RADIOLOGICAL ASSESSMENT REPORTS SERIES

REPORT BY AN INTERNATIONAL ADVISORY COMMITTEE

THE RADIOLOGICAL SITUATION AT THE ATOLLS OF MURUROA AND FANGATAUFA

MAIN REPORT

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STI/PUB/1028
ISBN 92–0–101198–9
ISSN 1020–6566
Printed by the IAEA in Austria
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VIC Library Cataloguing in Publication Data

The radiological situation at the atolls of Mururoa and Fangataufa : main report / report by an International Advisory Committee. — Vienna : International Atomic Energy Agency, 1998.
p. ; 29 cm. — (Radiological assessment reports series, ISSN 1020–6566)
STI/PUB/1028
ISBN 92–0–101198–9
Includes bibliographical references

1. Radioactive pollution—Mururoa Atoll (French Polynesia) 2. Radioactive pollution—Fangataufa Atoll (French Polynesia) 3. Nuclear weapons—Mururoa Atoll (French Polynesia)—Testing 4. Nuclear weapons—Fangataufa Atoll (French Polynesia)—Testing I. International Atomic Energy Agency. II. Series

VICL 98–00194

EDITORIAL NOTE

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FOREWORD

At the present time there are various locations around the world affected by radioactive residues. Some of these residues are the result of past peaceful activities, others result from military activities, including residues from the testing of nuclear weapons. Stimulated by concern about the state of the environment, the steps taken towards nuclear disarmament, and improved opportunities for international co-operation, attention in many countries has turned to assessing and, where necessary, remediating areas affected by radioactive residues.

Some of these residues are located in countries where there is an absence of the infrastructures and expertise necessary for evaluating the significance of the radiation risks posed by the residues and for making decisions on remediation. In such cases, governments have felt it necessary to obtain outside help. In other cases, it has been considered to be socially and politically desirable to have independent expert opinions on the radiological situation caused by the residues. As a result, the International Atomic Energy Agency (IAEA) has been requested by the governments of a number of Member States to provide assistance in this context. The assistance has been provided by the IAEA in relation to its statutory obligation "to establish...standards of safety for protection of health...and to provide for the application of these standards...at the request of a State".

On 22 September 1995, a resolution of the General Conference of the IAEA called on all States concerned "to fulfil their responsibilities to ensure that sites where nuclear tests have been conducted are monitored scrupulously and to take appropriate steps to avoid adverse impacts on health, safety and the environment as a consequence of such nuclear testing".

The Study reported upon here was requested by the Government of France, which asked the IAEA to assess the radiological situation at the atolls of Mururoa and Fangataufa in French Polynesia, where France had conducted a nuclear weapon testing programme between 1966 and 1996. The IAEA convened an International Advisory Committee (IAC), under the chairmanship of Dr. E. Gail de Planque of the United States of America, to supervise the Study.

The IAC, which was given the tasks of providing scientific guidance and direction to the IAEA in the conduct of the Study, and of reporting on the Study's findings, conclusions and recommendations, met formally for the first time on 13–14 April 1996; this signalled the start of the Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa. The Study has now been completed and a number of documents have been prepared. These documents are: the Main Report (which includes the Executive Summary); a Summary Report; and a Technical Report in six volumes.

I am pleased to have received these reports, which are being made available through the IAEA to a wider audience.

Mohamed ElBaradei

Director General
International Atomic Energy Agency

IAEA PROJECT MANAGEMENT NOTE

The Government of France covered most of the direct costs of the Study and provided invaluable logistic assistance throughout. Significant in-kind contributions were made by Argentina, Australia, Austria, Belarus, Belgium, Cuba, Denmark, Fiji, Germany, Indonesia, Japan, the Republic of Korea, New Zealand, Norway, the Russian Federation, Slovenia, Spain, Sweden, Switzerland, the United Kingdom, the United States of America, the European Commission, the South Pacific Forum, the South Pacific Regional Environment Programme, the Office of the Sub-Regional Representative for the Pacific of the Food and Agriculture Organization of the United Nations, the World Health Organization and the United Nations Scientific Committee on the Effects of Atomic Radiation.

In addition, significant in-kind contributions were made by the laboratories and other institutions involved in the Study, whose activities were co-ordinated by the Agency's Laboratories at Seibersdorf, Austria, and the IAEA Marine Environment Laboratory, Monaco. The laboratories and other institutions were. the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, and the Australian Radiation Laboratory, Melbourne, Australia, the Institute for Inorganic Chemistry and the Federal Institute for Food Control and Research, Vienna, Austria; the Institute of Radiobiology, Minsk, Belarus, the Centro de Isótopos, Havana, Cuba; the Risø National Laboratory, Roskilde, Denmark; the Physikalisch-Technische Bundesanstalt, Braunschweig, and the Federal Fisheries Research Centre, Hamburg, Germany, the National Radiation Laboratory, Christchurch, and the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand; the Norwegian Radiation Protection Authority, Østerås, Norway, the Jožef Stefan Institute, Ljubljana, Slovenia, the Instituto del Medio Ambiente, CIEMAT, Madrid, Spain, the Radiochemistry Group, Central Veterinary Laboratory, Addlestone, Surrey, and the Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, Suffolk, United Kingdom, and the Environmental Measurements Laboratory, US Department of Energy, New York, N Y., and Lawrence Livermore National Laboratory, Livermore, California, United States of America

The IAEA wishes to thank the large number of people who were involved in different ways in the Study. They are all acknowledged in the various reports of the IAC

PREFACE

Between 1966 and 1996, France conducted 193 'expériences nucléaires' (nuclear experiments — a term used by the French authorities to include the full testing of nuclear weapons and the conduct of certain safety trials) above and beneath the atolls of Mururoa and Fangataufa in the Tuamotu Archipelago of French Polynesia. All French testing ceased on 27 January 1996. Before the completion of the last series of tests the Government of France requested the International Atomic Energy Agency (IAEA) to conduct a study to assess the radiological impact of the tests.

The IAEA agreed to carry out a study — the Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa — for the purpose of ascertaining whether, as a consequence of the tests, radiological hazards exist now or will exist in the future, and making recommendations on the form, scale and duration of any monitoring, remedial action or follow-up action that might be required. An International Advisory Committee (IAC) was convened by the Director General of the IAEA to provide scientific direction and guidance to the IAEA in the conduct of the Study and to prepare a report on the Study's findings, conclusions and recommendations.

The IAC's first formal meeting took place in Vienna on 13–14 April 1996 and its final one, also in Vienna, on 3–5 February 1998. This publication constitutes one of several reports of the IAC to the Director General describing the conduct of the Study and its findings, conclusions and recommendations.

The terms of reference of the Study called for an evaluation of the radiological situation at the atolls (and in other involved areas). It is important to emphasize that it is the radiological situation at the atolls, both as it is at present and as it might develop in the long term, including its consequences for human health, that the Study was required to address, and not any past radiological consequences of the French nuclear testing programme. This had two implications for the Study.

First, it was not within the terms of reference of the Study to attempt to assess retrospectively doses received by inhabitants of the region as a result of the atmospheric nuclear tests at the time when those tests were carried out. Those doses were due in part to short lived fallout — for example, radioactive iodine (especially ^{131}I, which has a half-life of eight days). However, the Secretariat of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) did provide the IAC with the results of a review of such doses that had been received by people in the South Pacific region in the past. The IAC believes that readers will be interested in these results, and it has therefore included them in an annex to the Main Report on the Study. The results are accepted by the IAC as providing an objective and balanced view of the situation.

Second, the IAC felt that the most informative indicator of the radiological situation at the atolls would be the present and future individual annual effective doses that people (real and hypothetical) at the atolls and in other involved areas might receive as a consequence both of the radioactive material that is now in the accessible environment and of that which might be released into the accessible environment over time from underground. It should be noted that while UNSCEAR has invoked other dosimetric quantities — the 'effective dose commitment' and the 'collective effective dose commitment' — in assessing the global impact of nuclear weapon testing, the IAC did not consider it appropriate to use these quantities in any reports of the Study for the reasons discussed in Section 1 of the Main Report.

The French Government provided much of the information used in the Study. This information was independently evaluated by Study participants and, where practicable, validated. For example, to provide a basis for the evaluation of French environmental monitoring data, the IAEA carried out an environmental sampling and surveillance campaign to measure independently contemporary levels of radioactive material present in the environment of the atolls. Also, with the co-operation of French scientists, samples of underground water were collected by Study participants from two test cavity–chimneys beneath the rim of Mururoa, and from deep in the carbonate layer beneath the two lagoons. These samples were analysed for a number of radionuclides, and the results provided an independent check on the validity of assumptions made in some of the Study's calculations, for example of radionuclide concentrations in the cavity–chimney of each test. The French Government allowed complete access to the atolls for these surveys and provided the necessary logistic support.

In addition to the information provided by the French Government, a small amount of information had been published in the open literature on measured levels of certain radionuclides (^{60}Co, ^{90}Sr, ^{137}Cs and

$^{239+240}$Pu) in the environment of the atolls, and reports of three scientific missions to the atolls — the Tazieff Mission of June 1982, the Atkinson Mission of October 1983 and the Cousteau Mission of June 1987 — were in the public domain. Issues raised by these missions guided the IAC in the choice of certain topics to be addressed in the Study.

It is not possible to place reliable quantitative limits on the errors associated with the dose assessments carried out by the Study. The estimated upper limits to contemporary doses can be accepted with confidence as they are based on measurements of the concentrations of residual radioactive material at present in the environment of the atolls. However, considerable uncertainty is possible in the estimation of future doses because of the complexities of the physical processes involved in releases from underground sources and the limitations of the geological migration models used. Therefore, in the absence of definitive information, conservative assumptions have been made and the estimated future doses can be regarded as upper limit values. In any event, they are so small that large errors in the assumptions made would not affect the IAC's basic finding that possible radiation doses to people now, and potential doses at any time in the future, arising from the conditions at the atolls are a very small fraction of the doses people already receive from natural radiation sources.

The Main Report (which includes the Executive Summary) is a distillation of the large amount of scientific work carried out in the course of the Study, which is described in detail in the accompanying six volume Technical Report. The Summary Report presents a comprehensive summary of the Main Report, including its findings, conclusions and recommendations.

ACKNOWLEDGEMENTS

The Main Report and the Technical Report, compiled essentially between September 1997 and March 1998, represent an enormous effort by many people. All Study participants contributed, but the major load was borne by the Task Group Chairmen (A. McEwan and D.M. Levins) and the Working Group Chairmen (F. Schönhofer, D. Woodhead, L.-E. De Geer, C. Fairhurst and E. Mittelstaedt). The members of the IAEA management team, particularly A.J. González and R.M. Fry, also worked tirelessly. The Summary Report was compiled by D. Delves of the IAEA. The IAC wishes to acknowledge their dedication and that of all other participants, and also to thank the many IAEA staff members without whose efforts the Study would not have been possible. In addition, the co-operation of the French Government and the efforts of members of the French Liaison Office — G. Goutière and P. Delcourt and, in the past year, J.-F. Sornein and G. Corion — must be commended.

The IAC thanks those laboratories — all listed in the Main Report and the Technical Report — which were involved in the analysis of samples collected during the sampling and surveillance campaign, and the underground water sampling exercise, at the atolls and commends the efforts of the staff of the Agency's Laboratories at Seibersdorf, Austria, and the IAEA Marine Environment Laboratory, Monaco, who helped to co-ordinate, manage and conduct those campaigns.

The IAC expresses its appreciation for the support and encouragement of the former Director General of the IAEA, H. Blix, and the current Director General, M. ElBaradei, and for their willingness to provide the IAEA resources necessary for carrying out the Study.

The Chairman further wishes to thank all the members of the IAC for their thoughtful and competent guidance throughout the course of the Study.

E. Gail de Planque

Chairman
International Advisory Committee

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PART D: CONCLUSIONS AND RECOMMENDATIONS

EXECUTIVE SUMMARY

INTRODUCTION

(1) In April 1996, following a request from the Government of France, the International Atomic Energy Agency (IAEA) embarked on a *Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa,* in French Polynesia, where France conducted 193 'expériences nucléaires' (nuclear experiments) above and beneath the atolls between July 1966 and January 1996.

(2) Mururoa and Fangataufa Atolls are situated at 21°50′ S, 138°54′ W and 22°14′ S, 138°45′ W, respectively, in the middle of the South Pacific Ocean, halfway between Australia and South America, they belong to the Pitcairn–Gambier island chain at the southeastern extremity of the Tuamotu Archipelago. An atoll is a ring shaped coral reef enclosing a lagoon. The reef is a narrow rim — jutting a few metres at most above the surrounding ocean — which may be cut in many places by irregular channels, termed 'hoas', with the resulting formation of a string of islets, termed 'motus'. Mururoa and Fangataufa Atolls have evolved from extinct submarine volcanoes, and each rests upon a massive volcanic substratum capped by a coral reef platform and surrounded by ocean water thousands of metres deep. Therefore, in vertical structure each atoll consists essentially of two rock sequences: an igneous volcanic basalt basement and, capping it, sedimentary carbonate formations hundreds of metres thick.[1] The carbonate formations are heterogeneous and fairly porous and the basalt basements are of lower permeability, but all are saturated with sea water. There is slow migration of water from the ocean inwards, rising through the basalt basements and carbonate formations towards the lagoons.

(3) The expériences nucléaires were of two types: 178 were nuclear tests, in which nuclear devices were exploded with large releases of fission energy, and 15 were safety trials, in which more or less fully developed nuclear devices were subjected to simulated accident conditions and the nuclear weapon cores were destroyed by means of conventional explosives, with no or — on a few occasions — very small releases of fission energy Forty-one of the nuclear tests were atmospheric nuclear tests which took place — 37 at Mururoa Atoll and 4 at Fangataufa Atoll — between July 1966 and September 1974, and 137 were underground nuclear tests which took place — 127 at Mururoa Atoll and 10 at Fangataufa Atoll — between June 1975 and January 1996. Of the 15 safety trials, all of which were carried out at Mururoa Atoll, 5 were atmospheric safety trials and 10 were underground safety trials. Three underground safety trials had small releases of fission energy associated with them.

(4) The expériences nucléaires were carried out as follows:

— Most of the atmospheric nuclear tests were carried out with the device suspended from a balloon some hundreds of metres above the surface of the lagoon, in three cases, the devices were dropped from aircraft In all cases the detonation altitude was sufficient for the fireball not to reach sea level, thereby minimizing the production of local fallout. There were, however, four atmospheric nuclear tests — three at Mururoa Atoll and one at Fangataufa Atoll — in which the device was mounted on a barge floating in the lagoon; most of the residual radioactive material presently in the accessible environment of the atolls was produced by these nuclear tests The five atmospheric safety trials were conducted on the northern part of Mururoa Atoll, on three motus Colette, Ariel and Vesta.

— The underground nuclear tests were conducted in the basalt basement at depths between about 500 and 1100 m, in shafts drilled vertically beneath the rims or the lagoons. Each explosion generated intense heat and high pressures, melting the basalt rock in the immediate vicinity of the detonation point and forming a roughly spherical cavity and a lens shaped pool — or meniscus — of molten basalt rock at the bottom of the cavity. Upon cooling, the molten basalt rock solidified as a glass-like lava. Several hours after the explosion, the fractured basalt rock above the cavity

[1] Each coral reef platform consists of carbonate rocks of organic origin — limestones and dolomites For the purposes of the Study, the classification of the carbonate rocks is not important and they will therefore be simply referred to as 'carbonate formations'.

collapsed, creating a cavity–'chimney'[2] filled with rubble. The cavity–chimney eventually filled with water infiltrating from the surrounding basalt rock. Much of the residual radioactive material associated with the underground nuclear test was trapped in the lava, but some radionuclides were deposited on the rubble and are available for exchange with water in the cavity–chimney. The ten underground safety trials were carried out in shafts drilled vertically beneath the rim on the northeastern part of Mururoa Atoll. Seven of the underground safety trials were carried out in the carbonate formations, at depths in excess of 280 m, and three were carried out in the basalt basement. The three underground safety trials which involved some fission energy release took place in the carbonate formations.

The French programme of expériences nucléaires ceased on 27 January 1996.

OBJECTIVE

(5) The Study was designed to assess the residual radiological conditions at the atolls after the end of all the expériences nucléaires and covered both the present radiological situation and the potential long term radiological situation. Specifically, the aims of the Study were as follows:

— To assess the situation at the two atolls and in involved areas from the point of view of radiological safety;

— To ascertain whether there are any radiological hazards to people;

— To make recommendations on the form, scale and duration of any remedial action, monitoring or other follow-up action that might be required.

The Study was therefore prospective in nature. Nevertheless, it took note of and summarized the extensive retrospective radiological assessments of the nuclear tests which have been carried out over the years by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

FRAMEWORK

(6) The Study used as its principal international authority on radiation protection matters the *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources*, which are jointly sponsored by the Food and Agriculture Organization of the United Nations (FAO), the IAEA, the International Labour Organisation, the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, the Pan American Health Organization and the World Health Organization (WHO) and were published by the IAEA in 1996 (Safety Series No. 115).

ORGANIZATION AND SUPPORT

(7) The organizational basis for the Study consisted of: an International Advisory Committee (IAC)[3]; two task groups and five working groups set up by the IAC; a Project Management Office set up by the IAEA; and a Liaison Office set up by the French Government (see the following diagram and the annexed list of participants). The first meeting of the IAC took place in Vienna on 13 and 14 April 1996, marking the commencement of the Study.[4]

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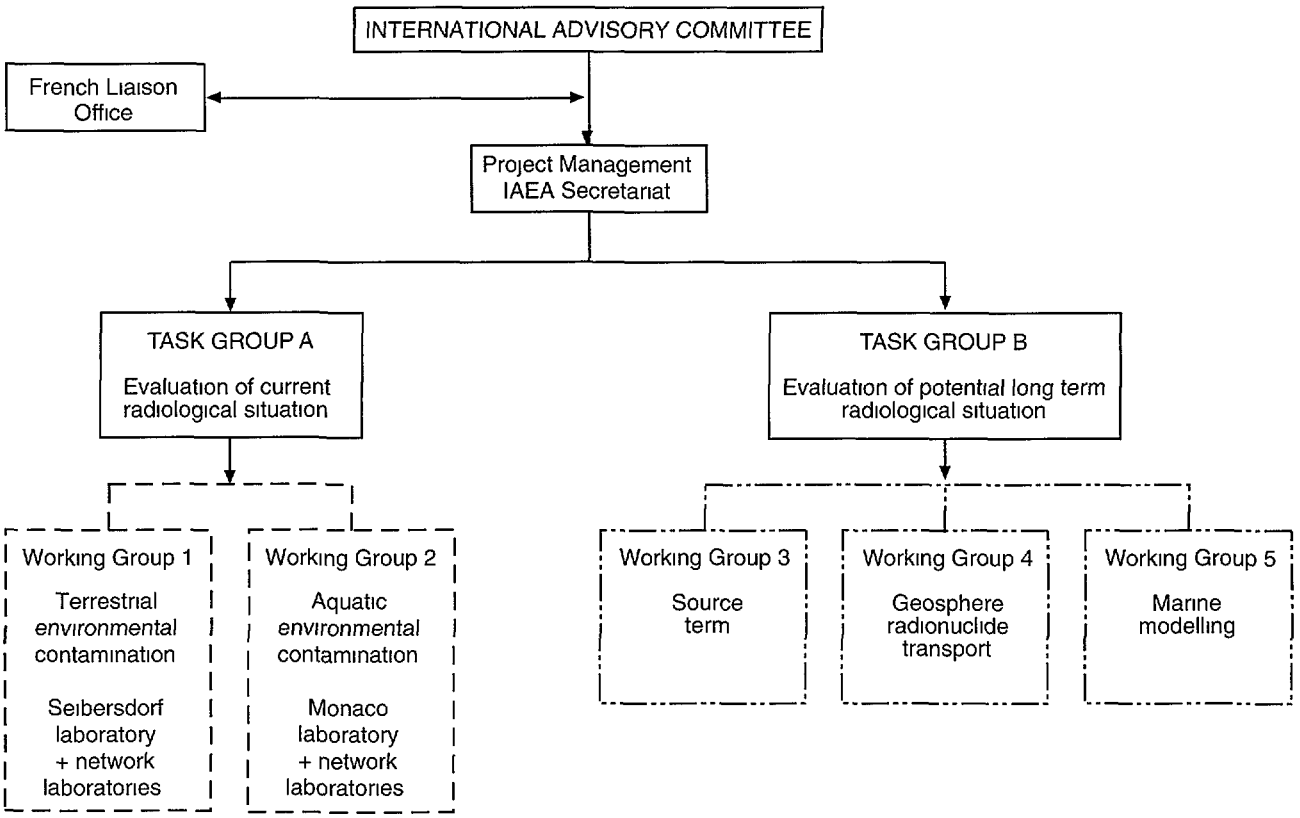
[2] The term (cavity–)'chimney' has been used extensively in the United States literature to refer to the rubble cone formed after the collapse of the cavity formed by an underground nuclear test Although the term is incorrect, as it evokes the idea of a duct leading to the free atmosphere rather than a closed cavity, it has become common jargon in the technical literature and was used throughout the reports resulting from the Study

[3] The IAC was chaired by Dr E Gail de Planque of the United States of America and comprised ten prominent scientists from ten IAEA Member States plus experts representing ex officio WHO, UNSCEAR, the South Pacific Forum and the European Commission.

[4] The Government of France covered most of the direct costs of the Study. Significant in-kind contributions were made by Argentina, Australia, Austria, Belarus, Belgium, Cuba, Denmark, Fiji, Germany, Indonesia, Japan, the Republic of Korea, New Zealand, Norway, the Russian Federation, Slovenia, Spain, Sweden, Switzerland, the United Kingdom, the United States of America, the European Commission, the South Pacific Forum, the South Pacific Regional Environment Programme, the Office of the FAO Sub-Regional Representative for the Pacific, WHO and UNSCEAR In addition, substantial in-kind contributions were made by the various laboratories involved in the Study The Government of France provided invaluable logistic assistance throughout the Study



The Working Groups of Task Group A were supported by a network of laboratories and other institutions co-ordinated by the Agency's Laboratories at Seibersdorf, Austria, and another co-ordinated by the IAEA Marine Environment Laboratory, Monaco The network of laboratories and other institutions co-ordinated by the Agency's Laboratories at Seibersdorf, Austria, consisted of the Institute for Inorganic Chemistry and the Federal Institute for Food Control and Research, Vienna, Austria, the Institute of Radiobiology, Minsk, Belarus, the Centro de Isótopos, Havana, Cuba, the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, the Norwegian Radiation Protection Authority, Østerås, Norway, the Jožef Stefan Institute, Ljubljana, Slovenia, the Instituto del Medio Ambiente, CIEMAT, Madrid, Spain; the Radiochemistry Group, Central Veterinary Laboratory, Addlestone, Surrey, United Kingdom, and the Environmental Measurements Laboratory, US Department of Energy, New York, N Y., United States of America The network of laboratories and other institutions co-ordinated by the IAEA Marine Environment Laboratory, Monaco, consisted of the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, and the Australian Radiation Laboratory, Melbourne, Australia, the Risø National Laboratory, Roskilde, Denmark; the Federal Fisheries Research Centre, Hamburg, Germany, the National Radiation Laboratory, Christchurch, and the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand, the Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, United Kingdom, and the Lawrence Livermore National Laboratory, Livermore, California, United States of America

CONDUCT OF THE STUDY

General approach

(8) The Study activities were divided between two Task Groups (see the diagram):

— Task Group A (supported by the "Terrestrial environmental contamination" and "Aquatic environmental contamination" Working Groups) evaluated the current levels of residual radioactive material in the environment of the atolls and their surrounding waters and assessed the present and future radiation doses attributable to this residual radioactive material. Using the information provided by Task Group B, it also assessed the potential future radiation doses attributable to the residual radioactive material which is presently located in the cavities of the safety trials and in the cavity–chimneys of the nuclear tests beneath the atolls.

— Task Group B (supported by the "Source term", "Geosphere radionuclide transport" and "Marine modelling" Working Groups) estimated the rate at which the residual radioactive material in the safety trial cavities and the nuclear test cavity–chimneys might migrate through the geosphere and be released into the surrounding ocean, either directly or through the atoll lagoons, and ultimately dispersed through the South Pacific Ocean — thereby providing the basis for the assessment of long term doses attributable to this material.

Environmental sampling and surveillance campaign

(9) The Study involved an environmental sampling and surveillance campaign at Mururoa and Fangataufa Atolls, which provided the basis for evaluating a large amount of available data (mostly from French sources). The campaign was split into a terrestrial part, covering the surface soils and corals and the flora of the atolls, and an aquatic part, covering the atoll lagoons, the surrounding ocean and their biota. The terrestrial part involved the collection of about 300 samples (vegetation, coconuts, sand, soil, corals, cores of coral bedrock and aerosols), a large analytical effort (over 1000 radioanalytical determinations) and more than 100 in situ gamma spectrometry measurements. The aquatic part involved gamma spectrometric surveys of the seabed, in order to optimize sampling, and the collecting of over 300 samples of lagoon water, ocean water, sediment pore water, sediment, corals and biota. Some 13 000 litres of water and about 1000 kilograms of solid samples were analysed, also representing a large analytical effort. No restrictions were placed by the French authorities on the sampling and surveillance campaign

The present radiological situation

(10) The aim of the assessment of the present situation was to estimate the radiation doses that people would receive from the radionuclides in the residual radioactive material that is already present in the accessible environment of Mururoa and Fangataufa Atolls and their surrounding waters. The values used for the present activity levels of radionuclides were based on the available data evaluated and supplemented through the sampling and surveillance campaign carried out at the atolls.

(11) There are no records of previous permanent indigenous habitation of Mururoa and Fangataufa Atolls, although there has been some intermittent habitation of Mururoa Atoll in addition to the habitation of both atolls by personnel involved in the programme of expériences nucléaires. However, the Study postulated hypothetical dwellers on the atolls and assessed the radiation doses that might be received by them The hypothetical dwellers were presumed to eat largely local seafood and locally grown produce. By making conservative assumptions about diet and mode of living, the Study estimated an upper limit to the doses that might be experienced if the atolls were actually to be inhabited. Also, the Study provided a conservative estimate of the doses being received by the present population of Tureia Atoll, the nearest inhabited land to Mururoa and Fangataufa Atolls, located at about 130 km from them.

The potential future radiological situation

(12) The aim of the long term assessment was to estimate the hypothetical doses that people anywhere in the South Pacific region might receive (in addition to the doses attributable to the residual radioactive material that is now already present in the accessible environment of the atolls) as a result of the release of residual radioactive material presently underground at Mururoa and Fangataufa Atolls into the atoll lagoons or directly into the surrounding ocean. Such a release could be caused by the normal migration of the residual radioactive material through the geosphere (modified by the hydrogeological effects of the nuclear testing) or by the occurrence of disruptive events. The assessment involved four steps.

(13) The initial step was an assessment of the yield of each nuclear test using seismic monitoring information from various sources — mainly from New Zealand. The specific characteristics of each nuclear device and each nuclear test were not provided by the French Government for the Study, but it was possible to assess independently the total 'inventory source term', i.e. the activity presently underground at Mururoa and Fangataufa Atolls of all radionuclides in the residual radioactive material generated by each nuclear test, by making assumptions about the design of the nuclear devices on the basis of their yields and the materials used in their assembly.

(14) The second step was to assess the 'effective source term' to be used in calculating the dispersion of the released residual radioactive material into the ocean, i.e. the rate at which the radionuclides in each nuclear test cavity–chimney might escape into the lagoons or directly to the ocean. This was a two stage process: first, the concentration of each radionuclide dissolved in the saline water filling each cavity–chimney was estimated; second, the rate of migration of the dissolved material through the surrounding basalt basement and through the carbonate formations was modelled. An independent check on the validity of the assumptions made in the Study's calculation of nuclear test cavity–chimney water concentrations was carried out by comparing the Study's estimates with independently measured concentrations in water samples collected from two nuclear test cavity–chimneys.

(15) Modelling of the migration of radionuclides through the basalt basements into the carbonate formations was carried out using a dual porosity model developed for the assessment of underground waste repositories. The modelling calculations took account of flow in the fractures[5] and of the retention of some radionuclides on surfaces within the basalt rock matrix. The velocity of water flow, assumed constant, was determined by hydrological modelling Calculations were carried out for 32 radionuclides, but particular attention was paid to 3 radionuclides of potential radiological significance — ^{239}Pu, ^{137}Cs and ^{90}Sr — and to ^{3}H, which was a useful tracer for model validation The predicted inventory in the carbonate formations was compared with estimates based on concentrations of radionuclides in the underground waters of the carbonate formations as determined by French scientists, supplemented by the Study's independent measurements. Future rates of radionuclide release from the carbonate formations, either upwards to the lagoons or laterally to the ocean at depth, were estimated using a semiempirical mixing model.

(16) In order to simplify the assessment of the total effective source term, i.e. the releases as a function of time from all underground nuclear tests, the Study divided the nuclear tests into categories and then determined the integrated release rate for each category. Three categories of nuclear test were the most important contributors to the overall release rates 12 nuclear tests (carried out at Mururoa Atoll early in the nuclear test progamme) in which the top of the cavity–chimney penetrated into the carbonate formations; four nuclear tests (three at Mururoa Atoll and one at Fangataufa Atoll) in which the basalt basement surrounding the cavity, though apparently thick enough, was inadequate to ensure complete confinement; and four safety trials (carried out in the carbonate formations at Mururoa Atoll — with no release of fission energy) which were found to be the major sources for the long term release of plutonium

(17) The Study also examined a number of hypothetical disruptive events, including extreme events and events due to climatic changes, that could lead to enhanced rates of release of the material presently in the cavity–chimneys or to enhanced rates of exposure to material in the environment (e.g. to the plutonium in the sediments). The consequences of only one disruptive event were considered worth investigating further: a hypothetical extreme event consisting of a major breakaway and slide of the carbonate formations in the northern zone of Mururoa Atoll, in the area where the underground safety trials and some of the nuclear tests that produced cavity–chimneys penetrating into the carbonate formations were carried out. It was assumed that this slide would intersect a safety trial cavity and also a nuclear test cavity–chimney which had penetrated into the carbonate formations, and pessimistic assumptions were

[5] The effects of the underground nuclear tests on the geological structures and on the stability of Mururoa and Fangataufa Atolls were not within the terms of reference of the Study, except insofar as geological pathways for radionuclide transport to the biosphere may have been affected by the explosions The possibility that migration may have been enhanced by the explosions was examined. The geological consequences of the nuclear test programme for Mururoa and Fangataufa Atolls, including the issue of geological stability, were the subject of a detailed investigation carried out at the request of the French Government by a group of earth scientists (an ad hoc International Geomechanical Commission, IGC) The IGC investigation was independent of the Study, although three scientists participated in both.

made about the fraction of the exposed material that might be released instantaneously.

(18) The third step was to use the effective source term at different times in modelling the dispersion of the released material through the South Pacific Ocean and in calculating the future concentrations of the radiologically significant radionuclides at a number of selected sites in the South Pacific Ocean at various times.

(19) The final step in the evaluation was to estimate the dose rates to which critical groups of people would be exposed at those places and times for which future concentrations of radionuclides had been calculated. It was through consideration of the implications of the present and future estimated dose rates that the IAC came to its findings about the radiological situation at the atolls and to its conclusions and recommendation about remedial and other actions.

REPORTS RESULTING FROM THE STUDY

(20) In March 1998, the IAC approved its reports on the Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa, which are being issued by the IAEA in its Radiological Assessment Reports Series. These reports are: the *Main Report*, which incorporates this *Executive Summary*, a *Technical Report* in six volumes ("Radionuclide Concentrations Measured in the Terrestrial Environment of the Atolls", "Radionuclide Concentrations Measured in the Aquatic Environment of the Atolls", "Inventory of Radionuclides Underground at the Atolls", "Releases to the Biosphere of Radionuclides from Underground Nuclear Weapon Tests at the Atolls", "Transport of Radioactive Material within the Marine Environment" and "Doses due to Radioactive Materials Present in the Environment or Released from the Atolls"); and a *Summary Report* for the benefit — in particular — of persons with executive, managerial and administrative responsibilities The IAEA is also issuing a public information booklet and 'at a glance' poster relating to the Study.

FINDINGS

Residual radioactive material already present in the accessible environment of the atolls

(21) The Study found that the terrestrial and aquatic environments of Mururoa and Fangataufa Atolls that are accessible to people contain residual radioactive material attributable to the expériences nucléaires, but at generally very low concentrations which the Study concluded were of no radiological significance. There are, however, some features of note whose radiological implications are examined in paragraph (24):

(a) Several kilograms of plutonium resulting from the atmospheric nuclear tests carried out at the atolls remain in sediments under the lagoon of each atoll. Some of the plutonium in the sediments of the Mururoa Atoll lagoon came from the atmospheric safety trials.

(b) The concentration of tritium in each lagoon was found to be higher than in the open ocean, as the result of leakages from a number of the cavity–chimneys created by underground nuclear tests.

(c) Particles containing plutonium and small amounts of americium resulting from atmospheric safety trials remain in the area of the trial sites — the motus of Colette, Ariel and Vesta on Mururoa Atoll. The Study analysed these types of particles, found in samples of sand and coral collected from the surface of the motu of Colette and in sand taken from a sandbank adjacent to it.

(d) Elevated levels of ^{137}Cs were found over small areas totalling several hectares on the Kilo–Empereur rim of Fangataufa Atoll

Residual radioactive material underground at the atolls

(22) The Study found that the results of the assessments of the nuclear explosive yields of all underground nuclear tests and of the resulting inventories of residual radioactive material contained underground at the atolls are in good agreement with information made available for the Study from French sources.[6]

[6] The Study estimated the total yields, calculated from the sum of the yields of individual nuclear tests, to be 2400 kilotons (one kiloton being equivalent to one thousand tons of trinitrotoluene (TNT)) for Mururoa Atoll and 770 kilotons for Fangataufa Atoll; the values provided by the French Liaison Office were 2400 and 800 kilotons. (Most experimental and theoretical values for the explosive energy released by TNT range from 900 to 1100 calories per gram At one time, there was uncertainty as to whether 'kiloton' of TNT referred to a 'short' kiloton, a 'metric' kiloton or a 'long' kiloton In order to avoid ambiguity, it was agreed that the term 'kiloton' should refer to the release of 10^{12} calories of explosive energy.)

(23) From the measurements of the activity in underground water samples taken from the two cavity–chimneys selected for the in situ sampling, the Study found that the concentrations of highly refractory radionuclides, in particular of $^{239+240}$Pu, are extremely low, indicating a high level of retention of such radionuclides in the glass-like lava formed in the cavities by basalt rock melted in the underground explosions

Potential radiation doses due to residual radioactive material already present in the accessible environment of the atolls

(24) Although it is doubtful whether Mururoa Atoll — still less Fangataufa Atoll — could sustain a permanent population dependent solely on local resources for food, the Study assessed the radiation doses to hypothetical inhabitants that could result from the residual radioactive material at present in the terrestrial and aquatic environments of the two atolls. The Study found that a population permanently resident on the atolls, and living on a diet of local produce and seafood, would not generally receive a radiation dose attributable to the residual radioactive material exceeding 0.01 mSv per year, which is equivalent to a very small fraction (less than one part in 200) of the annual background radiation dose that such a resident population would unavoidably receive from natural radiation sources. The Study found it necessary, however, to examine specifically the four features of note identified in paragraph (21).

(a) *Plutonium in the lagoons.* The Study found that the inventory of plutonium in the sediments of the two lagoons, while large, is of little radiological significance, mainly because of the low rate of transfer of plutonium to people via feasible pathways. Also, the Study noted that the availability of the plutonium will decrease over time owing to (i) the removal of the lagoon sediments to the ocean and (ii) the gradual burial and dilution of lagoon sediments by the accumulation of fresh sediment.

(b) *Tritium in the lagoons:* Similarly, the Study found that concentrations of tritium in the lagoons are of no radiological significance even though they are at present higher than in the open ocean

(c) *Plutonium-containing particles:* The Study noted that, if an individual were to visit the motus of Colette, Ariel or Vesta at Mururoa Atoll, there is a possibility that a particle containing plutonium with small amounts of americium could be incorporated into that individual's body — for example, through a cut caused by a fall. The Study assessed the probability of the incorporation of such a particle and its long term retention within the body. It also assessed the associated radiation dose and the probability of harm as a result of the dose received. On this basis, the Study found that the probability that a hypothetical individual visiting and spending some time on any of the three motus would ultimately incur a fatal cancer attributable to the incorporation of a particle containing plutonium is less than one in one million per year

(d) *Caesium-137 on the Kilo–Empereur rim.* The Study found that, if any population were to subsist entirely on produce grown on small areas of the Kilo–Empereur rim of Fangataufa Atoll, the estimated maximum radiation dose attributable to the ^{137}Cs in the rim would be about 0 25 mSv per year, equivalent to about one tenth of the total radiation dose which that population would unavoidably receive as a result of natural radiation sources. The Study considers, however, that this hypothetical situation is highly unlikely to arise, since — inter alia — the Kilo–Empereur rim is almost barren and virtually uninhabitable by people adopting a traditional semisubsistence lifestyle.

(25) The Study found that the highest dose attributable to the residual radioactive material already present in the accessible environment of Mururoa and Fangataufa Atolls, which is estimated to be currently received by residents of Tureia Atoll, is less than 0.0001 mSv per year, which is a completely insignificant fraction (about one part in 10 000) of the annual background radiation dose that these residents will unavoidably receive from natural radiation sources It should be noted, however, that Tureia Atoll did receive some immediate fallout from the atmospheric nuclear tests carried out at Mururoa and Fangataufa Atolls, in addition to the fallout globally experienced as a result of all atmospheric nuclear testing The radiation doses currently being received by residents of Tureia Atoll as a result of residues from earlier fallout and due to the nuclear testing at Mururoa and Fangataufa Atolls were assessed and found to be about 0.005 mSv per year, which is an extremely small fraction (about two parts in 1000) of the annual background radiation doses that the residents will unavoidably receive from natural radiation sources.

(26) The radiation doses due to the residual radioactive material already present in the accessible environment — principally arising from ^{137}Cs and plutonium isotopes — will persist, but they will decline owing to

both radioactive decay and other processes that reduce the availability of these radionuclides in the environment. According to the Study estimates, the rate of leaching of the ^{137}Cs and the plutonium isotopes present in the lagoon sediments will continue to decrease with time, as will the estimated radiation doses associated with these radionuclides. The Study found that the highest estimated potential annual doses attributable to the residual radioactive material already present in the accessible environment of Mururoa and Fangataufa Atolls and their surrounding waters will decline from the present hypothetical maximum of no more than 0.01 mSv per year to about 0.001 mSv per year within 100 years.

Migration of residual radioactive material from underground

(27) The Study estimated the rate of migration of the radionuclides in the radioactive material produced by the underground nuclear tests from the cavity–chimneys, through the geological media, into the lagoons and directly into the ocean over periods of more than 100 000 years The Study found that, over the first few decades, most of the released radionuclides would come from the small number of underground nuclear test sites where the basalt basement above the nuclear test point provided inadequate confinement of the nuclear tests.[7] In terms of amounts of activity, tritium would dominate the early releases, but with activity concentrations that are of no radiological significance. Other radionuclides, including ^{137}Cs and ^{90}Sr, would be effectively retained underground within the basalt basement, most of their activity decaying and only small amounts of activity being released. Plutonium would continue to be released over long periods of time but at very low rates. The modelling predicts that concentrations of ^{137}Cs and $^{239+240}Pu$ in the lagoon water are unlikely to exceed present levels at any time in the future. The concentrations of ^{90}Sr and ^{3}H could rise marginally above current levels, but only during the next few decades.

Dispersion of residual radioactive material throughout the ocean

(28) The Study used regional and far field oceanographic models to estimate the concentrations in sea water at various locations and times of radionuclides released into the ocean from Mururoa and Fangataufa Atolls The Study found that, except as a consequence of a hypothetical extreme disruptive event (see paragraph (29)), the predicted long term concentrations of radionuclides decrease to background oceanic levels beyond about 100 km from the atolls; thus, at Tureia Atoll the predicted concentrations will be around background levels and of no radiological significance.

Consequences of postulated disruptive events

(29) The only disruptive event that was found by the Study to warrant a thorough assessment was the hypothetical major breakaway and slide of the carbonate formations in the northern zone of Mururoa Atoll, in the area where the underground safety trials and some of the nuclear tests producing cavity–chimneys which penetrated into the carbonate formations were carried out. If such a hypothetical extreme event were to occur, ocean currents would carry the released radioactive material away from Mururoa Atoll and the highest potential annual dose would therefore be received by residents of nearby atolls For the residents of Tureia Atoll, the dose in the first year following such a slide would not be more than a few thousandths of a millisievert — which is an extremely small fraction (a few parts in 1000) of the annual background radiation dose that the residents will unavoidably receive from natural radiation sources — even pessimistically assuming that all the plutonium involved in the slide went into solution.

Potential doses in the future

(30) The Study found that — except in the hypothetical situation discussed in paragraph (24) — no population group is likely to receive at any time in the future a dose attributable to the residual radioactive material at Mururoa and Fangataufa Atolls which exceeds approximately 1% of the background radiation dose that the group will unavoidably receive from natural radiation sources

CONCLUSIONS

Implications for human health

(31) The Study concluded that there will be no radiation health effects which could be either medically diagnosed in an individual or epidemiologically discerned in a group of people and which would be attributable to the estimated radiation doses that are now being received or that would be received in the future by people as a result of the residual radioactive material at Mururoa and Fangataufa Atolls.

[7] This inadequate confinement is caused by fractures in the basalt basement which reach from the cavity–chimneys to the carbonate formations above

(32) Nevertheless, the Study noted that the reported cancer incidence in populations in the South Pacific region and throughout the world is changing for a number of reasons, including: the improved diagnosis and registration of cancer cases; modifications in environmental exposure to cancer causing agents and in personal habits (such as dietary and smoking habits); population migrations that alter baseline cancer incidence rates; and changes in the incidence of other diseases. The Study emphasized, however, that at the very low levels of dose estimated in the Study there will be no changes in cancer incidence rates in the region attributable to radiation exposure caused by the residual radioactive material at Mururoa and Fangataufa Atolls.

Implications for biota

(33) The Study assessed the dose rates to native biota resulting from the residual radioactive material at Mururoa and Fangataufa Atolls and, in the great majority of cases, found them to be similar to or lower than dose rates due to natural radiation sources. An exception is the potentially high dose rates that could be experienced by individual members of some species owing to plutonium contained in particulates — for example, from the sediment of the sandbank adjacent to the Colette motu in the northern part of Mururoa Atoll. Overall, the Study concluded that the expected radiation dose rates and modes of exposure are such that no effects on biota population groups could arise, although occasionally individual members of species might be harmed, but not to the extent of endangering the whole species or creating imbalances between species.

Remedial actions

(34) Given the measured and predicted radionuclide activity levels, and the low dose levels estimated for the present and for the future, and with account taken of international guidance, the Study concluded that no remedial action at Mururoa and Fangataufa Atolls is needed on radiological protection grounds, either now or in the future.

Monitoring

(35) Similarly, the Study concluded that no further environmental monitoring at Mururoa and Fangataufa Atolls is needed for purposes of radiological protection.

Robustness of the conclusions

(36) Although many assumptions were made in the modelling of systems, the findings are robust: i.e. the Study concluded that the expected extent of changes in the conclusions due to uncertainties in the parameters used in the modelling is slight. Furthermore, the predicted doses are so low that large errors (even of an order of magnitude) would not affect the conclusions.

RECOMMENDATION

(37) The Study noted that a scientific programme of monitoring of the radionuclide concentrations in the carbonate formations and in the nuclear test cavity–chimneys is under way at Mururoa and Fangataufa Atolls. Should this programme continue, the Study recommends that emphasis be placed on monitoring the migration behaviour of long lived and relatively mobile radionuclides and radiocolloids because of its particular scientific interest. The scientific programme, supplemented by some monitoring of radionuclide levels in the biosphere, may also be useful in assuring the public about the continuing radiological safety of the atolls.

Note: Ciguatera

Ciguatera is a type of food poisoning brought about by eating fish contaminated by a neurotoxin generated by a marine microorganism often found in association with disturbed coral reefs. There have been some reports in news media that outbreaks of ciguatera may be linked to exposure to radiation from the residual radioactive material at Mururoa and Fangataufa Atolls The symptoms of ciguatera poisoning have been recognized for over a century and a range of anthropogenic and natural disturbances may contribute to ciguatera outbreaks. However, there is no evidence in the scientific literature of radiation exposure being a causal factor

Part A
BACKGROUND

1. THE STUDY

1.1. OBJECTIVES AND TERMS OF REFERENCE

1.1.1. Background

In June 1995, the Government of France announced that it would carry out a final series of eight underground nuclear weapon tests at its test site in the South Pacific Ocean before acceding to a comprehensive nuclear test ban treaty, at that time being negotiated at the United Nations Conference on Disarmament in Geneva. Throughout the world, particularly in the Pacific region, there was strong reaction to this announcement of a continuation of testing. As the testing programme got under way, United Nations resolutions were passed condemning the French testing and deploring nuclear testing in general. In the event, only six tests were carried out — five at Mururoa and one at Fangataufa in French Polynesia — before the French President announced on 29 January 1996 the complete cessation of French nuclear testing.

Following the June 1995 announcement, the French Minister for Foreign Affairs wrote to the Director General of the International Atomic Energy Agency (IAEA), informing him of France's irreversible commitment to the conclusion of a comprehensive nuclear test ban treaty in 1996 and of its intention to undertake a final series of nuclear tests before that date, and asking whether the IAEA would be willing to conduct a scientific mission to assess the radiological impact of the tests It was proposed that the radiological assessment be complemented by an assessment of the effects that the tests might have had on the geological stability of the atolls.[1] While the IAEA was considering its response to this request, the IAEA General Conference, on 22 September 1995, in a resolution entitled "Nuclear testing" (GC(39)/RES/23):

- Called on all States concerned "to fulfil their responsibilities to ensure that sites where nuclear tests have been conducted are monitored scrupulously and to take appropriate steps to avoid adverse impacts on health, safety and the environment as a consequence of such nuclear testing".
- Requested all States concerned "to inform the International Atomic Energy Agency of any adverse impact on health, safety and the environment as a consequence of such nuclear testing as necessary to assist the Agency to discharge its functions under the Statute".
- Called for "co-operation between the States concerned and the International Atomic Energy Agency in accordance with its Statute in the implementation of the two preceding paragraphs".

In the light of this resolution and the numerous services provided by the IAEA to its Member States in the fields of nuclear safety and radiological protection, and following consultation with Member States, the Director General informed the French Foreign Ministry that the IAEA was ready in principle to conduct a study of the radiological situation at the atolls resulting from all testing in the South Pacific Ocean, after the end of the testing programme. The Director General informed the Board of Governors of this decision on 12 December 1995

An informal technical consultation meeting of scientists nominated by several Member States and representatives of intergovernmental organizations was convened by the IAEA in Vienna from 29 to 31 January 1996 to consider the substance of the French request In its request, the French Government proposed an assessment addressing both the current radiological situation at the atolls and in surrounding areas, and the potential long term impact. The participants discussed the objectives and terms of reference of the proposed Study, and the organizational structure and resources needed to carry out the assessment It was proposed that two task groups be set up, one to assess the present situation, the other to study possible long term consequences associated with the residual radioactive material underground.

On the basis of this meeting, and in consultation with French representatives, formal terms of reference for the Study were developed and agreed between the French Government and the IAEA. The formation of the Study was officially announced at IAEA Headquarters on 1 March 1996.

[1] The geological consequences of the nuclear test programme for Mururoa and Fangataufa Atolls, including the issue of geological stability, were the subject of a detailed investigation carried out at the request of the French Government by a group of earth scientists (an ad hoc International Geomechanical Commission, IGC) The IGC investigation was independent of the Study described in this report, although three scientists participated in both The report of the IGC has recently been published (Fairhurst et al 1998).

CHRONOLOGY

13 June 1995	French Government announces final series of eight underground tests before signing comprehensive nuclear test ban treaty
9 August 1995	French Foreign Minister writes to IAEA Director General, asking IAEA to conduct scientific mission to assess radiological impact of tests
5 September 1995	First test
22 September 1995	IAEA General Conference resolution calls for nuclear test sites to be "monitored scrupulously" and "adverse impacts on health, safety and the environment" to be avoided
30 September 1995	Second test
27 October 1995	Third test
17 November 1995	United Nations adopts resolution condemning French tests
21 November 1995	Fourth test
6 December 1995	French Defence Minister announces that only six tests may be needed and testing will be completed by end of February 1996
12 December 1995	United Nations adopts resolution deploring all nuclear testing and demanding immediate cessation IAEA Director General informs Board of Governors that IAEA has agreed to French request to conduct mission after testing has ceased
27 December 1995	Fifth test
27 January 1996	Sixth test
29 January 1996	French President announces complete cessation of nuclear weapon testing
29–31 January 1996	First meeting of experts from Member States and representatives of intergovernmental organizations to discuss IAEA mission
1 March 1996	Formation of Study officially announced at IAEA Headquarters
13–14 April 1996	First formal meeting of International Advisory Committee marks commencement of Study

1.1.2. Terms of reference

The formal terms of reference of the Study were as follows:

1. With the cessation of nuclear testing on the atolls of Mururoa and Fangataufa, the IAEA will organize a study of the radiological situation at the atolls and involved areas (hereinafter referred to as 'the Study').
2 The Study will be objective, comprehensive and independent, will take account of the scientific work done by the French Government in the area and make use of other scientific data available. In addition it will undertake further studies as needed in order to achieve an independent assessment
3. The objective of the Study will be to assess the radiological situation (both present and future) at the two atolls and involved areas from the point of view of radiological safety. The technical framework for the Study will be provided by the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources[2]. The Study will include recommendations on the form, scale and duration of any monitoring, remedial action or other follow-up action that might be required.

The purpose of the Study is to ascertain whether there are any radiological hazards to people. In radiological protection it is customary to presume that the adequate protection of individual human beings should also ensure that no other species will be threatened as a population, even if individuals of the species may be harmed, this presumption will be examined by taking into account any known particular characteristics of the local biota at Mururoa and Fangataufa Atolls.

[2] Published by the IAEA in 1996 as Safety Series No 115 (Food and Agriculture Organization of the United Nations (FAO) et al. 1996)

4. The scope of the Study is twofold and comprises:
   (a) An evaluation of the current radiological situation,
   (b) An evaluation of the potential long term[3] radiological situation.
5. For the purpose of carrying out the Study, an International Advisory Committee of independent scientists — hereinafter referred to as 'the Committee' — comprising highly qualified experts, drawn from Member States and including ex officio experts selected by relevant intergovernmental organizations, will be convened by the Director General of the IAEA to provide scientific guidance and direction to the IAEA on all matters related to the conduct of the Study The Study's findings, conclusions and recommendations will be contained in a report of the Committee to be published by the IAEA.
6. Task Groups will be established to perform the following tasks·
   6 1 Task Group A will evaluate (a) the radioactive materials in the environment that may lead to radiation exposure of the public; and (b) the doses to members of the public as a result of this environmental contamination It will be supported by two Working Groups which will deal with terrestrial and aquatic contamination[4], as follows:
   — The Terrestrial Working Group will assess the terrestrial environmental contamination of the atolls and their biota by evaluating data to be provided from available sources including the French Government and independent sampling and measurements
   — The Aquatic Working Group will assess the aquatic environmental contamination of the atolls' lagoons and of the surrounding oceanic water and their biota by evaluating data to be provided from available sources including the French Government and independent sampling and measurements.
   6 2 Task Group B will evaluate the potential long term radiological impact of the radioactive material remaining in the geological cavities at the atolls. It will be supported by three Working Groups which will deal with the source term, the release and transport of radionuclides in the geological formation and subsequent transfer through pathways to the biosphere as follows
   (a) Working Group 3 will assess the radiologically significant radioactive materials remaining in the deep geological formation of the atolls, their physical–chemical composition in relation to their geological transportability and their predicted rates of release from the cavities
   (b) Working Group 4 will assess the geological stability and hydrology of the atolls In addition it will estimate other necessary physical and chemical parameters which influence the movement of radionuclides through the atolls. It will further model the transport of radionuclides from the vicinity of the test cavities to the biosphere.
   (c) Working Group 5 will assess marine transport of radioactive material that might be released from the geological formation[5]
7. The French Government will provide the IAEA with information and data required for performing the Study, *inter alia*, with the following specific information and data
   (a) Levels of radioactive materials in the environment of significance for purposes of radiation protection on the atolls, in particular radionuclide concentrations in:
   — soil, water, sediments and local flora and fauna and possibly in human beings who had inhabited the testing sites transitionally;
   — the various biological and environmental components in the critical pathways of exposure to radiation.
   (b) Radiation exposure data, including:
   — information on current critical pathways of radiation exposure,
   — environmental transfer factors for the specific local environment.
   (c) Geological source term information as needed for transport modelling, including:
   — the actual zone, time and upper order of magnitude of the yield of the various underground tests conducted at the atolls,
   — the location and inventory of the radionuclides relevant for radiation protection

[3] Long term is used to mean a period of time over which remedial actions can have any significant effect on the dose to people It is provisionally presumed that the customary time of around 10 000 years — with emphasis on the short term — may provide an appropriate margin for this purpose.

[4] The IAEA Seibersdorf and Monaco laboratories will assist and co-ordinate the activities of the Terrestrial and Aquatic Working Groups, respectively

[5] The IAEA Monaco laboratory will assist in these activities

purposes, at the various test sites and sites of other radiologically significant events;
— the environmental availability of these radionuclides, including leachability from vitrified materials and the extent of vitrification.

(d) Geological and marine data:
— sufficient to allow a geological and marine model for the radionuclide transport to be constructed, taking into account the effects of rock fracturing, past tests, and any interaction thereof, on the geological structure and relevant chemical, physical and hydrogeological processes.

(e) Pathway information
— to permit future additional critical and population exposure pathway analyses to be carried out.

(f) Overall predictions of the future radiological situation, including:
— the models and assumptions made.

(g) The criteria that had been set to ensure the radiological safety of the previous tests conducted at the atolls and the way in which it was established that these safety criteria were actually met

(h) Details of past and planned future monitoring programmes (providing an indication of the timescale foreseen for such future monitoring programmes).

8. The Study is expected to be completed within 18 months after the information and data referred to in Paragraph 7 above are provided to the relevant working groups.

9. The IAEA will provide appropriate management for the Study, the task groups, the working groups and any specialized group to be established for the purpose of the Study. The IAEA will receive specific information and data from the French Government as required to perform the Study

10. A permanent Liaison Office will be established by the French Government to facilitate technical communication, supply of required data and organization of the logistic support needed by the IAEA in connection with the Study.

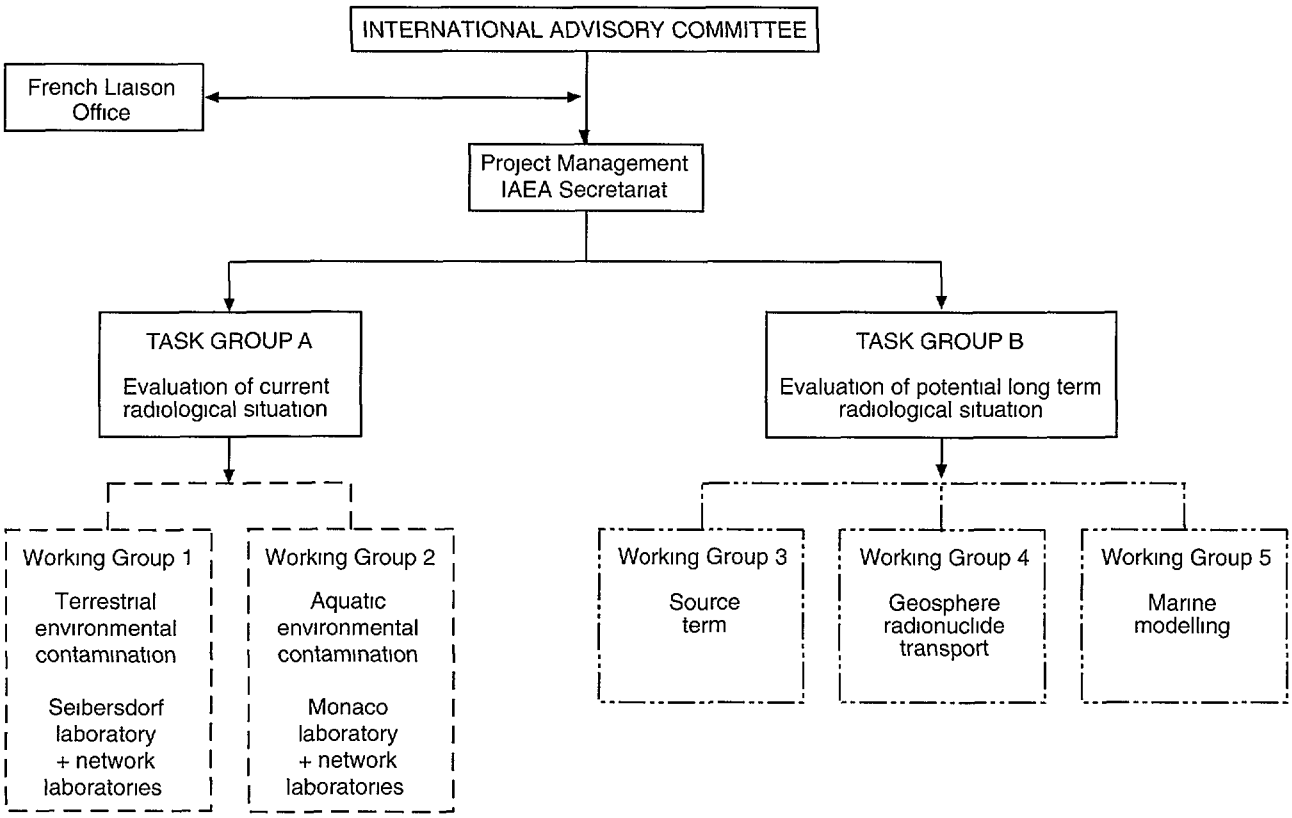


FIG 1 Organizational chart

1 2. ORGANIZATIONAL STRUCTURE

The organizational structure for the Study included the International Advisory Committee (IAC), the French Liaison Office, the Project Management Office set up by the IAEA and the Task Groups and Working Groups (Fig. 1) referred to in the terms of reference.

1.2.1. International Advisory Committee

The IAC comprised ten experts nominated by IAEA Member States and four experts representing ex officio the World Health Organization (WHO), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the South Pacific Forum and the European Commission It consisted essentially of those scientists who had attended the preliminary meeting in January 1996. The IAC was chaired by E. Gail de Planque, former Commissioner of the United States Nuclear Regulatory Commission. The members of the IAC, as well as the members and experts of the various Task Groups and Working Groups, are listed at the end of this report.

The first formal meeting of the IAC was held at IAEA Headquarters in Vienna on 13–14 April 1996, with the participation of the chairmen of the Task Groups and Working Groups. This meeting marked the commencement of the Study. The IAC reviewed its terms of reference and the proposed membership of the Task Groups and Working Groups and endorsed the action plans proposed by the chairmen of the groups

The IAC noted that it was not within its remit to assess retrospectively the exposure experienced by the inhabitants of the region during the atmospheric tests carried out by France between 1966 and 1974. Nevertheless, it was aware that there was considerable public concern about the effects of the atmospheric tests and therefore an expectation that the final Study report would contain some reference to these exposures. Accordingly, the IAC decided that the report should contain some discussion of the doses received at the time of the atmospheric tests and that the Secretariat of UNSCEAR should be asked to provide an assessment. This is presented in Annex I.

While the major purpose of the Study was to ascertain whether the conditions at the atolls constituted a radiological risk to people, the IAC was asked also to examine whether there may be radiological effects on other species It was agreed that the Aquatic Working Group would address this matter Though not directly related, and not in its terms of reference, the IAC noted public concern about the occurrence at the atolls of ciguatera, which was thought by some to be a direct consequence of radiation associated with the weapon tests. Ciguatera is a type of food poisoning brought about by eating fish contaminated by a neurotoxin generated by a marine microorganism. The IAC agreed that it would examine the evidence for a connection between the occurrence of ciguatera and radiation and include a statement on the results of its examination with the Main Report. This is presented in Annex II.

The second formal meeting of the IAC was held during December 1996, partly (2–4 December) at the headquarters of the South Pacific Forum in Suva, Fiji, and partly (4–6 December) in Papeete, Tahiti. Delegations from the States belonging to the South Pacific Forum — Australia, the Cook Islands, Fiji, Kiribati, the Marshall Islands, Micronesia, Nauru, New Zealand, Niue, Palau, Papua New Guinea, the Solomon Islands, Tonga, Tuvalu, Vanuatu and Western Samoa — were briefed in Suva on the Study and its status. Press conferences dealing with the progress of the Study were held in Suva and Papeete by the Chairman of the IAC, supported by the Task Group chairmen and members of the IAEA Project Management Office

The final meeting of the IAC was held at IAEA Headquarters from 3 to 5 February 1998 to review and approve the final draft of the Main Report.

1.2.2. Information provided by French Liaison Office

At the first meeting of the IAC, the French Liaison Office presented a list of documents that it intended to provide to cover the information topics listed in paragraph 7 of the terms of reference. The first four documents had already been provided at the March 1996 meeting of Task and Working Group chairmen in Montlhéry, France. Six more documents were delivered in October 1996 and the final three in February, April and December 1997. The documents are listed at the end of Section 1.

1.3. APPROACH AND METHODS

Figure 2 illustrates the general approach adopted in the Study. The sections of this report in which the various tasks of the Study are discussed are indicated in the figure for ease of reference. A more detailed explanation is provided below

1.3.1. Sampling and monitoring campaign

The sampling and monitoring campaign planned by Task Group A was carried out in July and August 1996.

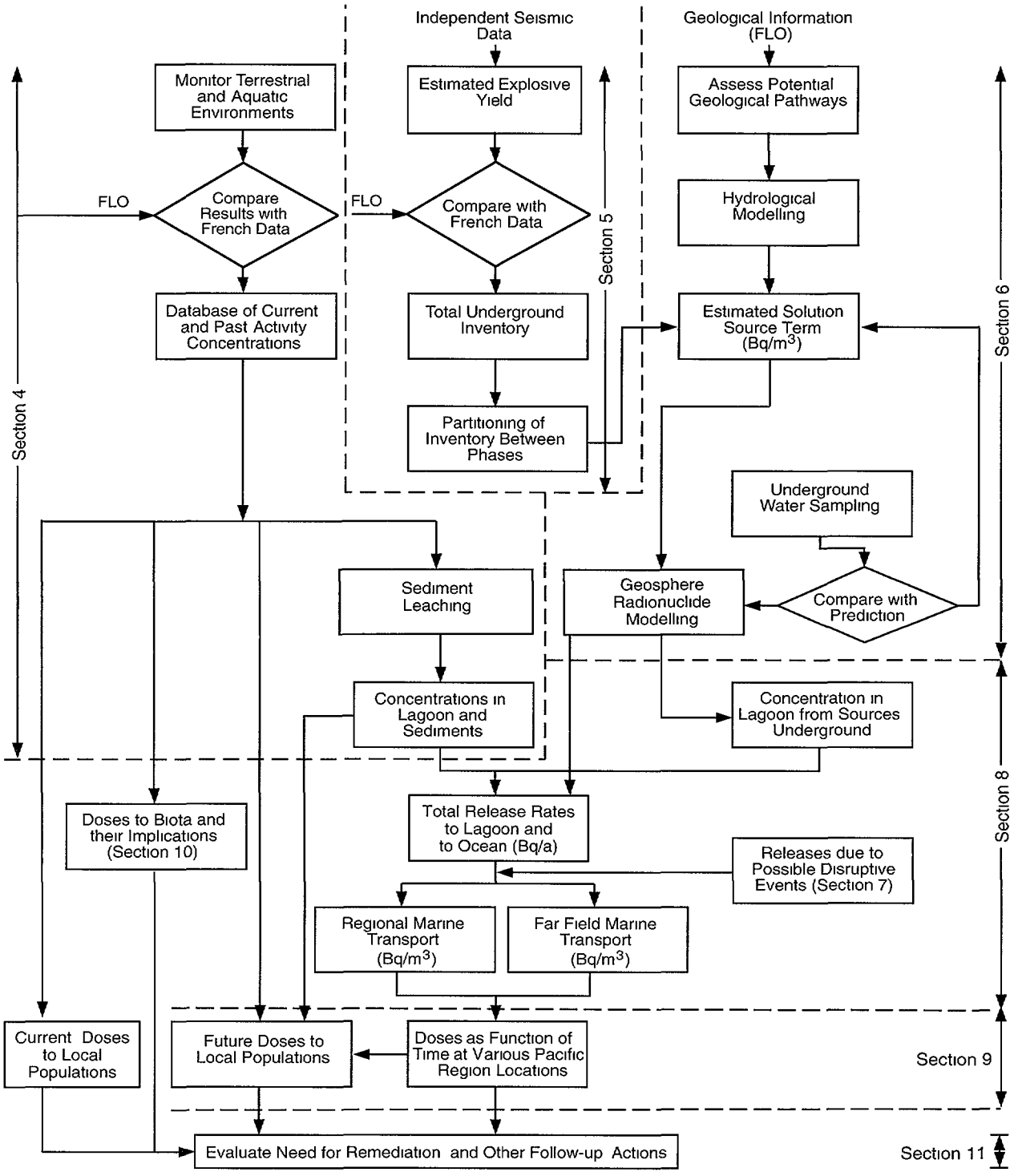


FIG 2 Study tasks and their interrelationships. The sections of this report in which they are discussed are indicated (FLO French Liaison Office.)

Its purpose, as defined by the IAC, was to evaluate the environmental data supplied by the French authorities and to ascertain, as far as practicable, whether the French monitoring programme had been sufficiently comprehensive to allow good estimates to be made of the amount of residual radioactive material in the environment of the region of the atolls.

The campaign comprised a terrestrial part, concentrating on the surface soils, corals and vegetation of the atolls, and an aquatic part, covering the lagoons, the

surrounding ocean and marine biota. The terrestrial part was co-ordinated by the Agency's Laboratories at Seibersdorf, Austria (hereinafter referred to as 'the Seibersdorf laboratory'); the sampling team comprised six scientists from five countries, supported by staff of the Seibersdorf laboratory The aquatic part was co-ordinated by the IAEA Marine Environment Laboratory (MEL) in Monaco, and the sampling team comprised five scientists from four countries supported by staff of the MEL.

The terrestrial programme involved the collection of about three hundred samples (vegetation, coconuts, sand, topsoil, soil profiles, corals, cores of coral bedrock and aerosols) and a considerable analytical effort (over a thousand radioanalytical determinations), which was spread among 11 institutes in nine countries plus the Seibersdorf laboratory (Section 4.3.1).

The network of laboratories and other institutions co-ordinated by the Seibersdorf laboratory consisted of: the Institute for Inorganic Chemistry and the Federal Institute for Food Control and Research, Vienna, Austria; the Institute of Radiobiology, Minsk, Belarus; the Centro de Isótopos, Havana, Cuba; the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany; the Norwegian Radiation Protection Authority, Østerås, Norway; the Jožef Stefan Institute, Ljubljana, Slovenia, the Instituto del Medio Ambiente, CIEMAT, Madrid, Spain, the Radiochemistry Group, Central Veterinary Laboratory, Addlestone, Surrey, United Kingdom; and the Environmental Measurements Laboratory, United States Department of Energy, New York, N Y., United States of America.

In addition, a number of gamma surveys and gamma spectrometric measurements were carried out, particularly in the Colette region of Mururoa Atoll, where five safety trials had been conducted in the atmosphere between 1966 and 1974. Surface scrapings and sand from this region were examined by the Seibersdorf laboratory in order to reveal the presence of residual particles of plutonium and plutonium oxide. Aspects of the biokinetic properties of a number of representative particles were examined at the laboratory of the National Radiological Protection Board, Chilton, United Kingdom, which had previously studied such particles associated with the UK weapon testing programme at Maralinga, Australia, during the 1950s.

The aquatic programme, carried out with the logistic support of five vessels provided by the French Government, involved gamma spectrometric surveys of the seabed, in order to optimize sampling, and the collection of over three hundred samples of lagoon water, ocean water, sediment pore water, sediment, corals and biota. About 13 000 L of water and 1 t of solid samples were processed, packaged and transported to Monaco. The analytical effort was spread among nine laboratories in seven countries plus the MEL in Monaco (Section 4.3.2).

The network of laboratories and other institutions co-ordinated by the MEL consisted of the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, and the Australian Radiation Laboratory, Melbourne, Australia; the Risø National Laboratory, Roskilde, Denmark; the Federal Fisheries Research Centre, Hamburg, Germany; the National Radiation Laboratory, Christchurch, and the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand; the Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, Suffolk, United Kingdom; and the Lawrence Livermore National Laboratory, Livermore, California, United States of America.

In addition to the main sampling and monitoring campaign, a special visit was made to the atolls between 26 May and 9 June 1997 to collect samples of underground water. Samples were taken from two of the Mururoa test 'cavity–chimneys', and the concentrations of a number of radionuclides in cavity–chimney water were determined to check the validity of independent assessments that had been made of these concentrations by Working Group 4. (The usage of the term cavity–chimney is discussed in Section 5 4.) Samples were also taken from a number of monitoring wells in the carbonate formations (the rock layers closest to the surface) of both atolls and analysed for concentrations of key radionuclides (^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ in particular). The sampling was conducted by one Study participant and two IAEA staff members with French logistic and technical support. Analyses of the samples were carried out by the MEL and ANSTO.

The French authorities, which placed no restrictions on the sampling operations, provided invaluable logistic assistance throughout the campaign

Details of the terrestrial and aquatic programmes, and evaluation of the French data on residual radioactive material in the environment of the atolls in the light of the results of the Study's sampling and monitoring campaign, are discussed in Section 4 The underground water sampling is discussed in Section 6.

1.3.2. Approach to assessment of the radiological situation

1.3 2.1. Current situation

Task Group A was responsible for assessing the current radiological situation at the atolls. This work involved estimating the individual doses to people living

near to Mururoa and Fangataufa Atolls — for example, on Tureia Atoll, some 130 km from Mururoa and with a population of about 120 — as well as the doses which could be incurred by hypothetical individuals if they were to live on the atolls themselves Data on residual radioactive material in the environment were needed for these dose assessments. The Study's sampling and monitoring campaign was intended to determine the adequacy of the existing French data for this purpose and to provide the necessary data where adequate French data were not available. A hypothetical population living on the atolls was assumed to eat local seafood and locally cultivated foodstuffs, although at present there is only very limited foodstuff cultivation on Mururoa Atoll and nothing edible, apart from some coconuts, is growing on Fangataufa Atoll. This assessment is discussed in Section 9.

In the case of Mururoa Atoll, there is an additional radiological exposure pathway due to the presence of plutonium contaminated particles from the safety trials conducted above ground in the region of Colette. This region had been extensively cleaned and scoured, but some residual radioactive material persists. The exposure pathways associated with this material, and the estimation of radiological risk, are discussed in Sections 4 3.1 and 9.6.1.

1.3.2 2. Potential long term situation

The approach of Task Group B was to estimate the long term migration of residual radioactive material from the underground cavity–chimneys through the surrounding geological media into the lagoon and/or the surrounding ocean, and its subsequent dispersion in the ocean throughout the South Pacific region. The possible exposure to such material of hypothetical local and regional population groups, and of people living farther away in the South Pacific, was then evaluated

In addressing the long term, Task Group B took account of the guideline of 10 000 years suggested in the terms of reference. However, because of the long radioactive half-life of plutonium, its slow rate of release from the underground cavity–chimneys and its long migration time through the geosphere to the accessible environment, the release rate of plutonium was followed for up to 100 000 years. Potential radiological consequences of a significant fall in sea level associated with a major ice age some 60 000 to 100 000 years from the present were also examined but it is recognized that assessments increasingly far into the future become more and more speculative and unreliable.

Working Group 3 estimated the yield of each of the underground test explosions using seismic monitoring information. From the yields, and by making assumptions about the design of the nuclear devices and the materials of which they were made, it was possible to calculate the inventory of residual activity due to fission, fusion and activation products (and the remnants of the nuclear fuel itself) in the cavity–chimneys. The distribution of this residual material between lava and rubble in the cavity–chimneys was also estimated for each test. The material remaining in the boreholes used for underground safety trials was also considered; the four trials in the carbonate formations in which there was no fission yield (and therefore no lava formed in which the plutonium might be immobilized) were recognized as being potentially important as sources of plutonium.

Given the inventory and distribution of radioactive material underground, Working Group 4 estimated the rate at which this material would go into solution in the water flowing through the cavity–chimneys. The assumptions made and the model used in these calculations were checked by comparing modelling results with information provided by the French Liaison Office and with concentrations observed in the underground water sampling campaign of May–June 1997.

The rate of migration of this dissolved material through the surrounding geological media (some hundreds of metres of volcanic rock and the carbonate rock cap) was then estimated using a model that had been developed to assess the migration of radionuclides from underground repositories for high level radioactive waste. Migration was modelled from a number of notional cavity–chimneys on the basis of what was known about the locations of the tests and the depth and integrity of the rock cover. The total rates of release of radiologically significant radionuclides into the lagoons and the ocean from all cavity–chimneys at both atolls were estimated, thus providing the source terms for the modelling of dispersion in the lagoons and the ocean.

Working Group 5, with the assistance of the MEL, estimated the dispersion of the radioactive materials calculated to be released into the lagoons and the ocean. The group developed hydrodynamic models to assess the movement of dissolved and sediment-bound material in the lagoons and the rate of release of this material to the oceans, and compartment models for estimating dispersion on a wider scale, encompassing islands such as Tureia and Tahiti A large scale general circulation model was used to estimate how radionuclides might be transported as far as the east coast of Australia and the west coast of South America This modelling provided the concentrations of relevant radionuclides in the ocean at a number of places and at various times in the future. Calculations were then made by Task Group A of the

potential doses to people at those places and times (these are discussed in Section 9.6.2).

1 3.2.3 The radiological situation in context

The present and future radiological situations resulting from the French testing programme are discussed using the estimated annual effective doses which people could receive now and in the future as a measure of radiological impact It should be noted that other dosimetric quantities — the 'effective dose commitment' and the 'collective effective dose commitment' — are available to assess the impact of nuclear weapon testing. These quantities are invoked, for example, by UNSCEAR in its reporting on exposures resulting from nuclear explosions but they have not been used in any of the reports on the Study.

The effective dose commitment is a quantity that has been used in estimating the total dose likely to be received from radionuclides released into the environment from the testing of nuclear weapons. It represents the total of individual doses over all time, about 70% of the total being contributed by ^{14}C over a period of the order of 10 000 years. However, the IAC noted that in the situation at the atolls ^{14}C is a trivial contributor to individual doses The present underground inventory of ^{14}C at Mururoa and Fangataufa is estimated to be less than 30 TBq, which is less than 3% of the amount produced naturally in the Earth's atmosphere every year. In addition, the effective dose commitment is the hypothetical dose received by the present generation and all future generations and therefore does not represent the dose received by any individual either in a year or in his or her lifetime The IAC believed that for the Study it was more meaningful to quote annual effective doses (or lifetime doses) received by individuals now and in the future. The significance of estimated individual dose rates can then be more readily grasped and put into perspective by comparison with the dose rate due to background radiation from natural sources. Individual effective dose rates have therefore been used throughout the Main Report.

The collective dose (the sum of all doses received by all individuals in an exposed population) is a measure of the total impact of an exposure on that population as a whole. Again, UNSCEAR has used this quantity to assess the global impact of atmospheric testing by summing the individual doses estimated to be received by a world population of a few thousand million which increases with time. In the present case, where the potentially exposed population is made up of small groups scattered over the South Pacific region, the IAC considered that the doses which individuals in the various groups in the region might receive would be of more interest and importance than the collective dose for all inhabitants of the region. The most informative index of the significance of the exposure of a group would then be the estimated maximum dose that individual members of that group could receive. While it can be calculated from the Study results, the collective dose for the whole region or for each group would not seem helpful, particularly as calculation of the future collective dose would require multiplying the assessed individual doses by an arbitrary and highly uncertain estimate of the number of people constituting each group.

The dose rates calculated in the Study's assessments are compared with the doses received by people in the region from natural sources and from radioactive material distributed widely around the Earth as global fallout from past atmospheric nuclear weapon testing. If the assessed dose rates are found to be some small fraction of the rates of exposure associated with normal background sources of radiation, the effects on human health may be judged to be a small fraction of the health effects that may be associated with background radiation.

To assist the non-specialist reader through some of the more technical parts of this report, some 'tutorial material' on radioactivity and radiation and the basic physics of nuclear weapons is provided in Annexes III and IV.

1.3.3. Reports of the IAC

The Main Report presents the primary technical arguments that have led to the Study's findings and conclusions. It is based on the detailed scientific assessments described in the Technical Report, which comprises six volumes:

Vol. 1: Radionuclide Concentrations Measured in the Terrestrial Environment of the Atolls
Vol. 2: Radionuclide Concentrations Measured in the Aquatic Environment of the Atolls
Vol. 3: Inventory of Radionuclides Underground at the Atolls
Vol. 4: Releases to the Biosphere of Radionuclides from Underground Nuclear Weapon Tests at the Atolls
Vol. 5: Transport of Radioactive Material within the Marine Environment
Vol. 6: Doses due to Radioactive Materials Present in the Environment or Released from the Atolls.

In addition, a Summary Report has been prepared for the benefit — in particular — of persons with executive, managerial and administrative responsibilities.

DOCUMENTS PROVIDED BY FRENCH LIAISON OFFICE

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French Liaison Office Document No 2 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Soil Radioactivity in Mururoa and Fangataufa,* March 1996

French Liaison Office Document No 3 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, Vol 1, *Environmental Monitoring in French Polynesia and on the Mururoa and Fangataufa Sites (1994),* March 1996, Vol 2, *Surveillance de l'environnement en Polynésie française et sur les sites de Mururoa et Fangataufa (1995),* January 1997

French Liaison Office Document No 4· Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Medium- and Long-Term Containment of Underground Nuclear Tests at the CEP Source Term Inventory and Worst-Case Impact Assessment,* March 1996

French Liaison Office Document No 5 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *The Geological, Mechanical and Hydrogeological Environment of the Underground Nuclear Tests at Mururoa and Fangataufa,* January 1997

French Liaison Office Document No 6 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Overall Distribution and Characteristics of the Underground Nuclear Tests Carried out at Mururoa and Fangataufa and their Effects on the Surrounding Media,* October 1996.

French Liaison Office Document No 7· Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Structural Integrity and Stability of the Atolls: Data and Modelling,* October 1996

French Liaison Office Document No 8· Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Experimental Data on the Mobility of the Radionuclides Deposited by the Underground Tests at Mururoa and Fangataufa,* October 1996

French Liaison Office Document No 9. Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Current Underground Distribution of Radionuclides at Mururoa and Fangataufa,* October 1996.

French Liaison Office Document No 10 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Overall Assessment of the Short, Medium and Long Term Radiological Situation of the Atolls of Mururoa and Fangataufa,* October 1996

French Liaison Office Document No. 11 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Marine Data and Modelling,* September 1996

French Liaison Office Document No. 12 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, Vol 1, *Guide de surveillance géomécanique des atolls de Mururoa et Fangataufa;* Vol 2, *Guide de surveillance radiologique des sites de Mururoa et de Fangataufa,* June 1997

French Liaison Office Document No 13 Ministère de la défense, Direction des Centres d'expérimentations nucléaires et Commissariat à l'énergie atomique, Direction des applications militaires, *Radiological Consequences of the Atmospheric Tests on the Islands of French Polynesia from 1966 to 1974,* April 1997

All of the above documents are included in the publication entitled *Geomechanical and Radiological Impact of Nuclear Tests at Mururoa and Fangataufa (French Polynesia),* published by La documentation française, Paris (1998)

2. GEOGRAPHY, GEOLOGY AND HISTORY OF THE ATOLLS

2.1. INTRODUCTION

Mururoa and Fangataufa are two small islands located in the South Pacific Ocean, in the French Overseas Territory of French Polynesia (Fig. 3). They are some 1200 km east-southeast of Tahiti and are administratively part of the Tuamotu Archipelago. The Tuamotu Archipelago comprises 76 islands, all of which are atolls. These are ring shaped coral reefs, enclosing a shallow lagoon, perched upon long extinct submerged volcanoes; they are formed by a long and complex interplay between geological and biological processes.

This area first became known to Europeans through the reports of seventeenth and eighteenth century navigators. The Tuamotu Archipelago became known for its hazards to shipping because of its many low lying coral islands; Louis de Bougainville called it the 'Dangerous Archipelago'. James Cook traversed the Tuamotus three times and was impressed by the narrow margin by which these coral islands escaped drowning. He described one typical Tuamotu atoll — the present day Hao — as "low and entirely drowned in the middle". Charles Darwin visited the region in 1835 and made a similar observation: "we saw several of those curious rings of coral land, just rising above the water's edge, which have been called Lagoon Islands…These low hollow coral islands bear no proportion to the vast ocean out of which they abruptly rise; and it seems wonderful, that such weak invaders are not overwhelmed by the all powerful and never-tiring waves of that great sea, miscalled the Pacific." Darwin went on to develop a theory of the origin and evolution of those rings of coral land which is remarkably close to present day understanding.

This section provides a brief description of the physical geography of Mururoa and Fangataufa, their evolution and specific geological features that are relevant to the Study. The history of human settlement and lifestyles in the area are also briefly described.

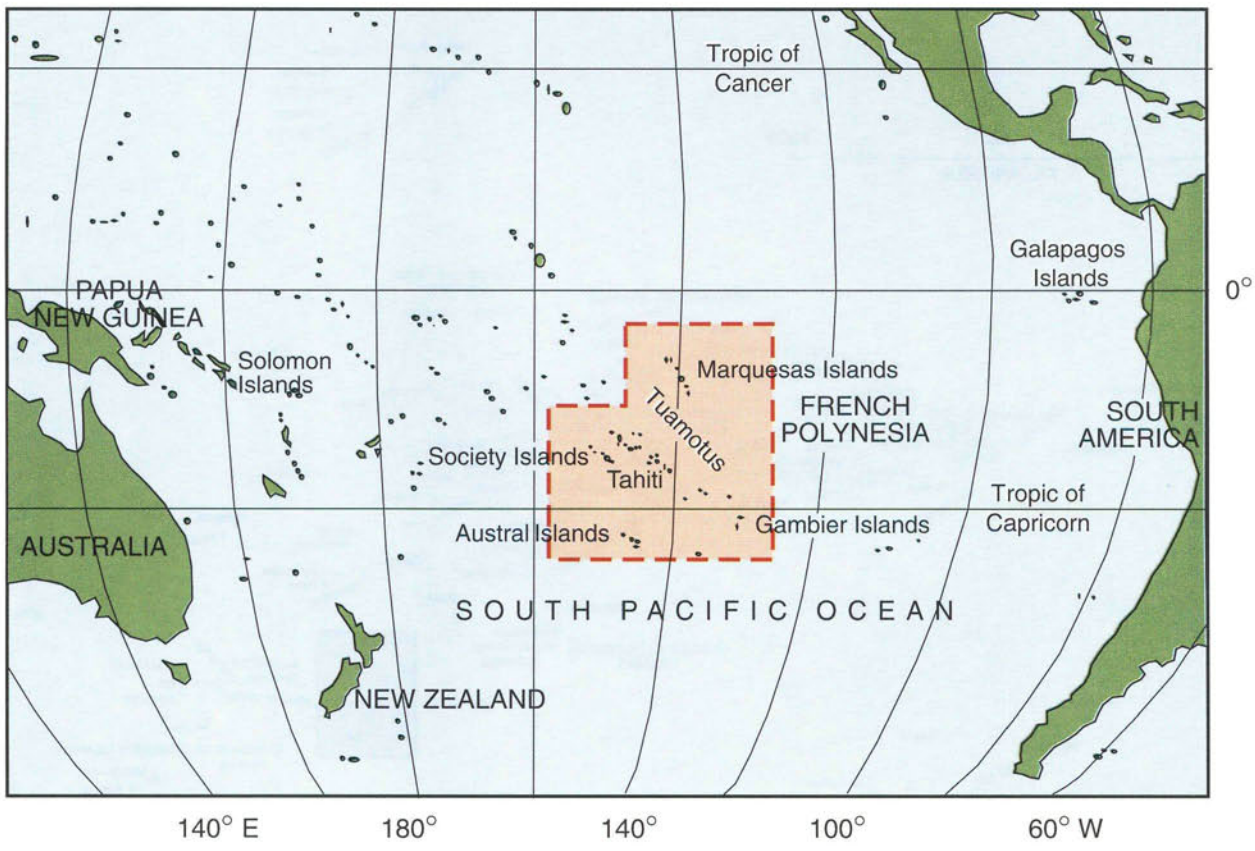


FIG. 3. Map of the South Pacific region showing the location of French Polynesia.

2.2. GEOGRAPHY OF FRENCH POLYNESIA

2.2.1. Location and geographical extent

French Polynesia consists of 118 small islands, with a total emerged land area of about 4000 km^2 enclosing some 7000 km^2 of lagoon, the whole covering an area of ocean roughly equivalent to that of Europe (2 500 000 km^2). It ranges in latitude between 8° and 27° S and in longitude between 131° and 156° W, as shown in Fig. 4. The territory comprises five main island groups: the Marquesas Islands, the Tuamotu Archipelago, the Society Islands (divided administratively into the Iles du Vent (Windward Group) to the east and the Iles sous le Vent (Leeward Group) to the west), the Iles Gambier (part of the Pitcairn–Gambier Archipelago) and the Austral (or Tubuai) Islands. Administratively, Mururoa and Fangataufa are part of the Iles Tuamotu–Gambier, but geologically they belong to the Pitcairn–Gambier Archipelago. Tahiti, the largest and possibly best known island in French Polynesia, is one of the Iles du Vent.

2.2.2. Islands of French Polynesia

Two categories of island can be distinguished in the Pacific, the high islands and the atolls. These represent two stages in the evolution of extinct volcanoes, as explained in Section 2.3. The high islands are younger volcanoes. There are 35 islands of this type in French Polynesia, with heights ranging from a few hundred metres to more than 2000 m above sea level (with, typically, another 4000 m below the sea). Many of the high islands are surrounded by a barrier reef which shelters an encircling lagoon. The older high islands show a more advanced degree of subsidence and erosion, representing a later stage in the evolution towards atolls. The other 83 islands are atolls, where all that is visible above the ocean surface is a narrow rim of coral up to a few hundred metres wide, covered patchily with coral derived sand, enclosing a central lagoon. The highest points of the atolls are no more than a few metres above sea level, and some areas are inundated at high tide. At 7000 km^2, the total surface area of these 83 lagoons far exceeds the total emerged land area of the atolls.

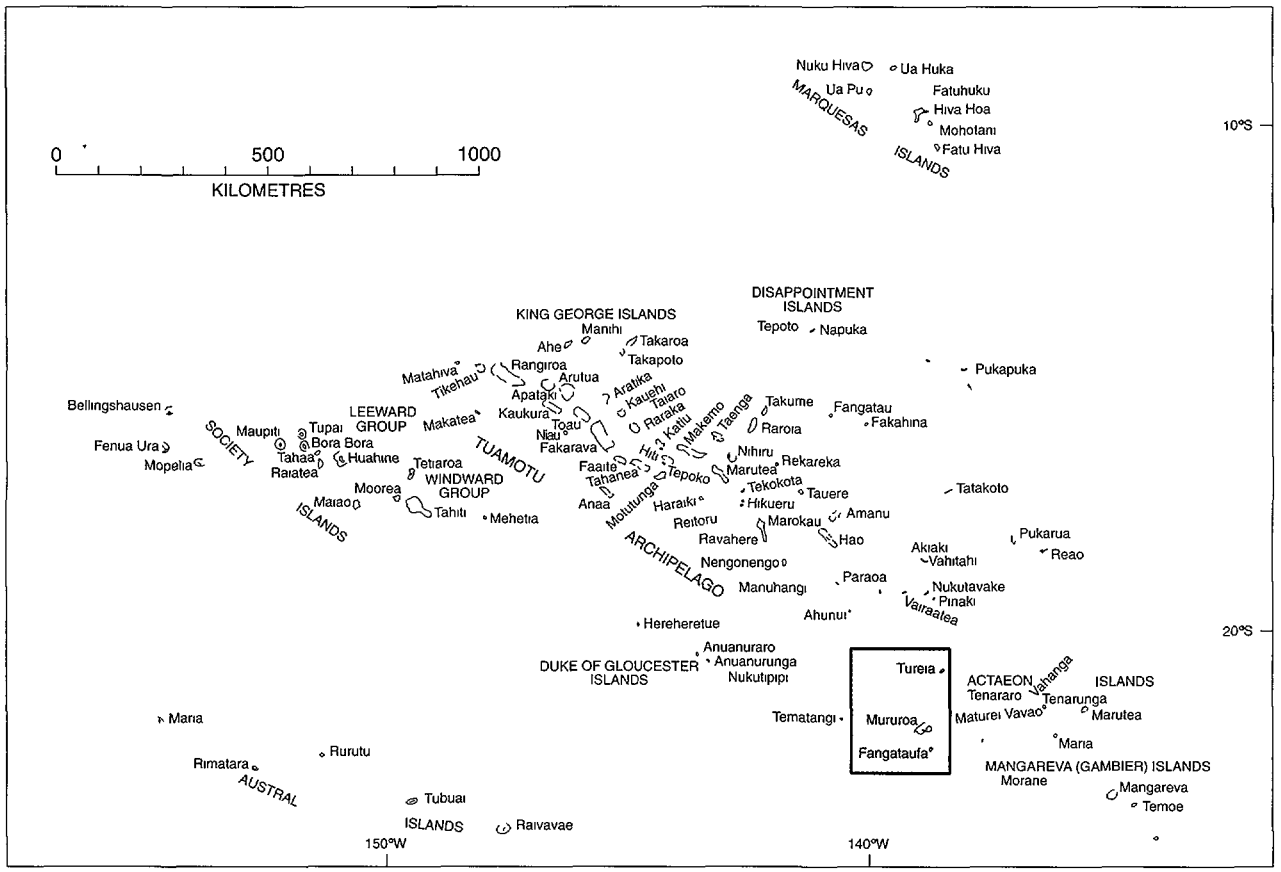


FIG 4 Map of French Polynesia showing the locations of Mururoa and Fangataufa Atolls.

The coral rim of an atoll is rarely continuous. There are generally channels or passes ('hoas') cutting through the rim, forming a chain of islets ('motus'). If there are numerous hoas, they constitute an important pathway for exchange of water between the lagoon and the ocean. In addition, there may be one or more major discontinuities in the rim At Mururoa, for example, there is a natural pass, while at Fangataufa an artificial pass has been created. Tureia, the closest inhabited island to Mururoa, is an example of an atoll with a completely enclosed lagoon; in such cases, exchange of lagoon water with the surface waters of the ocean occurs chiefly during storms. In general, accessibility of the lagoon from the ocean affects the suitability of an atoll as a dwelling place. Landing on an atoll from the ocean side is difficult because of the swell and the strong prevailing winds; being able to sail into a calm lagoon to a sheltered landing place is more conducive to habitation. However, as Mururoa (with a pass, but uninhabited) and Tureia (without a pass, but inhabited) demonstrate, the existence of a pass is by no means the only factor affecting habitability.

Sources of underground fresh water are virtually non-existent on these atolls. Drinking water must be obtained by the collection of rain, by importation or by desalination of sea water.

2.2.3. Physical description of Mururoa and Fangataufa

Mururoa and Fangataufa Atolls are located at the southeastern edge of the Tuamotu Archipelago. Mururoa, the larger of the two atolls, is at 21°50′ S, 138°54′ W, while Fangataufa, 40 km to the south of Mururoa, is at 22°14′ S, 138°45′ W. They lie about 150 km north of the Tropic of Capricorn.

2.2.3.1 Mururoa

Mururoa Atoll is somewhat elliptical in shape, as shown by the aerial photograph (Fig. 5) and the map of the atoll (Fig. 6) Its major axis, 28 km long, is aligned roughly east–west. The lagoon is about 10 km wide and the rim has a perimeter of 63 km. The emerged coral rim is not complete, having a pass 4.5 km wide and up to 9 m deep on the northwestern coast. There are over 280 hoas forming a chain of motus The rim at its highest point is no more than 3 m above the mean low water level. The width of the rim varies from 400 m in the northern sector to 600 m at the eastern tip (Anémone). It is 1100 m wide at the Faucon motu, an islet at the western tip of the atoll.

The area of Mururoa lagoon is 135 km^2. Its depth varies from 50–55 m at the eastern end to around 20 m at the western tip, with an average depth of about 33 m The lagoon volume is 4.7×10^9 m^3. The rate at which the lagoon is flushed by ocean water can be expressed in various ways but, on average, the entire lagoon volume is exchanged with the ocean every three months (Section 8). The majority of this exchange takes place through the main pass but the smaller hoas on the southern rim make an important contribution. About 70% of the floor of Mururoa lagoon is covered by a layer of unconsolidated, fine grained, sandy grade sediment derived from coral and the calcareous skeletons of marine organisms. A characteristic feature of the lagoon is the large number of pinnacles and coral 'heads'. These are pillars of coral, up to 100 m in diameter at their summit, which in some cases rise to the surface, where they can constitute a hazard to shipping. It is possible that they have developed in regions of the lagoon which have a particularly high influx of warm, nutrient rich water.

2.2.3.2. Fangataufa

Fangataufa is roughly rectangular in shape, with rounded corners and a diagonal axis about 10 km long (Figs 7 and 8) The lagoon is significantly smaller and shallower than that of Mururoa, with a volume of 5.5×10^8 m^3 and a surface area of 36 km^2, yielding an average depth of about 15 m, although it can attain a depth of 45 m in places In its natural state, Fangataufa had no clearly defined pass, although there are many hoas on the western coast. A pass was cut through the northern rim by French engineers in the mid-1960s and enlarged in the mid-1980s to a width of 100 m and depth of 8 m The flushing time for the lagoon is about 30 days and daily inflow through the hoas accounts for about 30% of this turnover. Compared with Mururoa, there are twice as many pinnacles per unit area reaching the lagoon surface, these being in places virtually joined up into a coral ridge.

2.2.4. Climate

The weather in French Polynesia is typical of tropical areas: warm and humid, tempered by the large expanse of surrounding ocean. There are effectively only two seasons: 'winter', from May to October, is slightly cooler (average air temperatures of 20–25°C) and drier than 'summer', from November to April (25–29°C). The average annual rainfall is around 1300 mm, the bulk of this falling in summer. Humidity ranges between 75 and 85% all the year round, being slightly less during the cooler winter months.

FIG. 5. Aerial photograph of Mururoa Atoll. (By courtesy of French Liaison Office.)

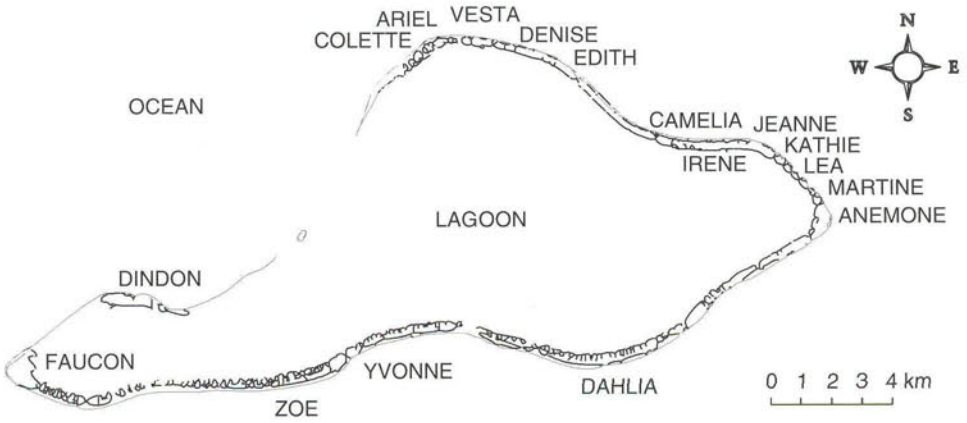


FIG. 6. Map of Mururoa Atoll showing frequently discussed locations and areas monitored during the Study's terrestrial monitoring programme.

The prevailing winds in the region are the easterly trade winds which, particularly between October and March, blow for about 70% of the time. Strong southeast winds can occur during the winter, and the percentage of calm days (wind speeds of less than 1 m/s) is very low, being less than 5%.

2.2.4.1. Cyclones

French Polynesia is near the edge of a region of the Pacific Ocean that is subject to tropical cyclones during which the winds typically exceed 120 km/h. North of the Marquesas, the expected cyclone frequency is between

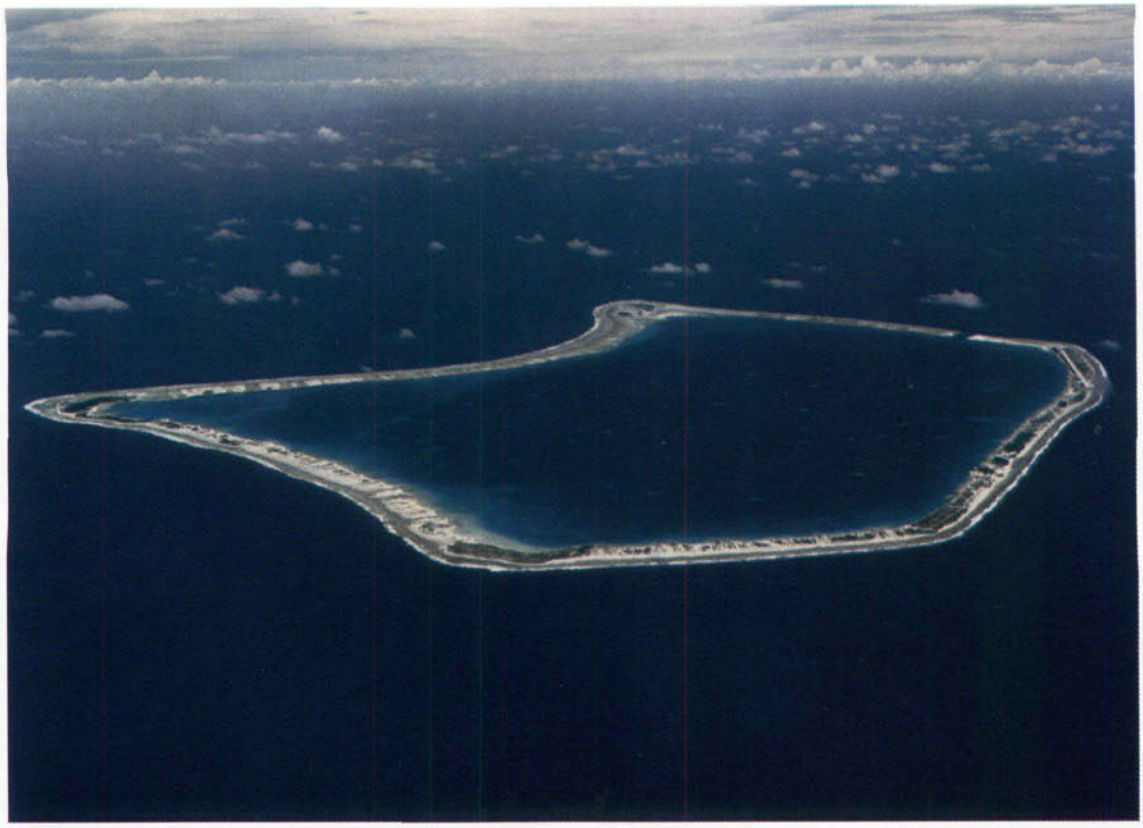


FIG. 7. Aerial photograph of Fangataufa Atoll. (By courtesy of French Liaison Office.)

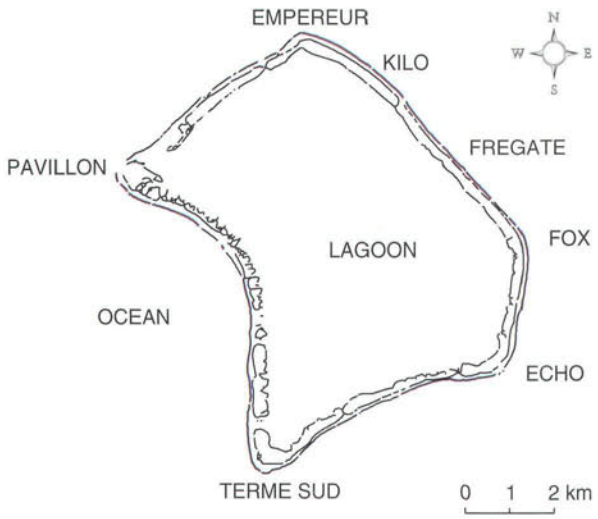


FIG. 8. Map of Fangataufa Atoll showing frequently discussed locations and areas monitored during the Study's terrestrial monitoring programme.

one and three every 100 years, between the Marquesas and the Tuamotus it is four to eight per 100 years, and south of the Tuamotus the expectation rises to one cyclone every two to three years. Although relatively infrequent, cyclones have a pronounced effect on the general habitability of the Tuamotu atolls. High winds and waves, coupled with the temporary rise in sea level as the cyclone passes, can cause complete flooding of the atoll. Dwellings are likely to be destroyed, along with trees, crops and freshwater supplies.

There were major cyclones in the region in 1878, 1903 and 1906. This was followed by a relatively quiet period of roughly 80 years (although there were a few strong depressions between 1966 and 1981), lasting until 1983 when five cyclones passed over the Tuamotus between January and April. Each inflicted heavy damage. For the Study, the most important effect of a cyclone on an atoll is the removal of sediment from the lagoon bed. A representative frequency for Mururoa and Fangataufa of one major cyclone every ten years is assumed in the Study for the estimation of the rate of removal of sediment from Mururoa lagoon (Section 8.3.2).

2.2.4.2. Climate change

Climate change arising from two causes has been considered in the Study: possible global warming in the (relatively) short term (~100 years), predicted to result

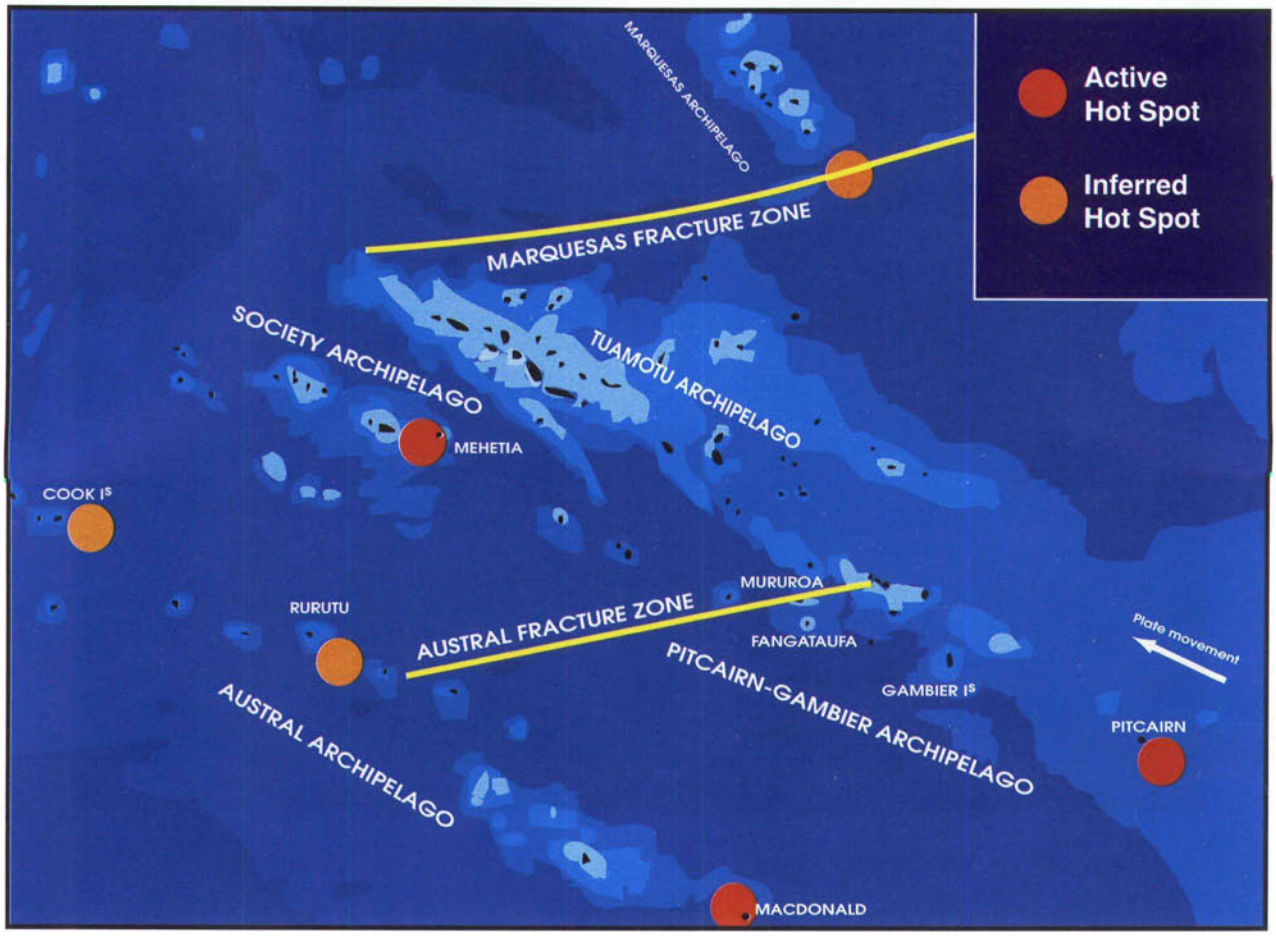


FIG. 9. Identified and inferred 'hot spots' in French Polynesia. (Source: Guille et al. (1995).)

from the buildup of 'greenhouse gases' in the upper atmosphere; and, in the longer term, extended glaciation, expected to occur as part of the natural glacial cycle. Global warming could lead to a rise in sea level, though this may be minor in the South Pacific Ocean; it is also possible that the rate of coral growth could keep pace with the sea level rise, so preventing the complete inundation of atolls such as Mururoa or Fangataufa.

Glaciation is certain to lead to a major fall in sea level, but on a timescale of tens of thousands of years. The potential consequences of glaciation are considered in Section 7, even though a major drop in sea level is unlikely to occur within the timescale suggested as being appropriate for this study (~10 000 years).

2.2.5. Oceanic environment

In the lagoons of Mururoa and Fangataufa as well as the surrounding oceans, the top 60 m or so of the water column — the depth to which sunlight can penetrate and in which coral can grow — is warm, with a maximum temperature of about 28°C in March and a minimum of 22°C in August. At Mururoa, the maximum tidal range is 120 cm; since the highest elevation of the rim above the low tide mark is less than 3 m, the highest points on the atoll rim at high tide are less than 2 m above sea level, and many parts of the rim are submerged. The tides and winds play a significant part in the flushing of the lagoon. This is discussed in Section 8.

2.2.5.1. General circulation in upper 500 m of South Pacific Ocean

The currents in subtropical areas of the world's oceans are dominated by the trade winds, which blow from east to west. Material that might be released from Mururoa and Fangataufa would be carried by prevailing currents and therefore drift mainly to the west. Dispersion in the ocean of material released from the atolls is discussed in detail in Section 8.

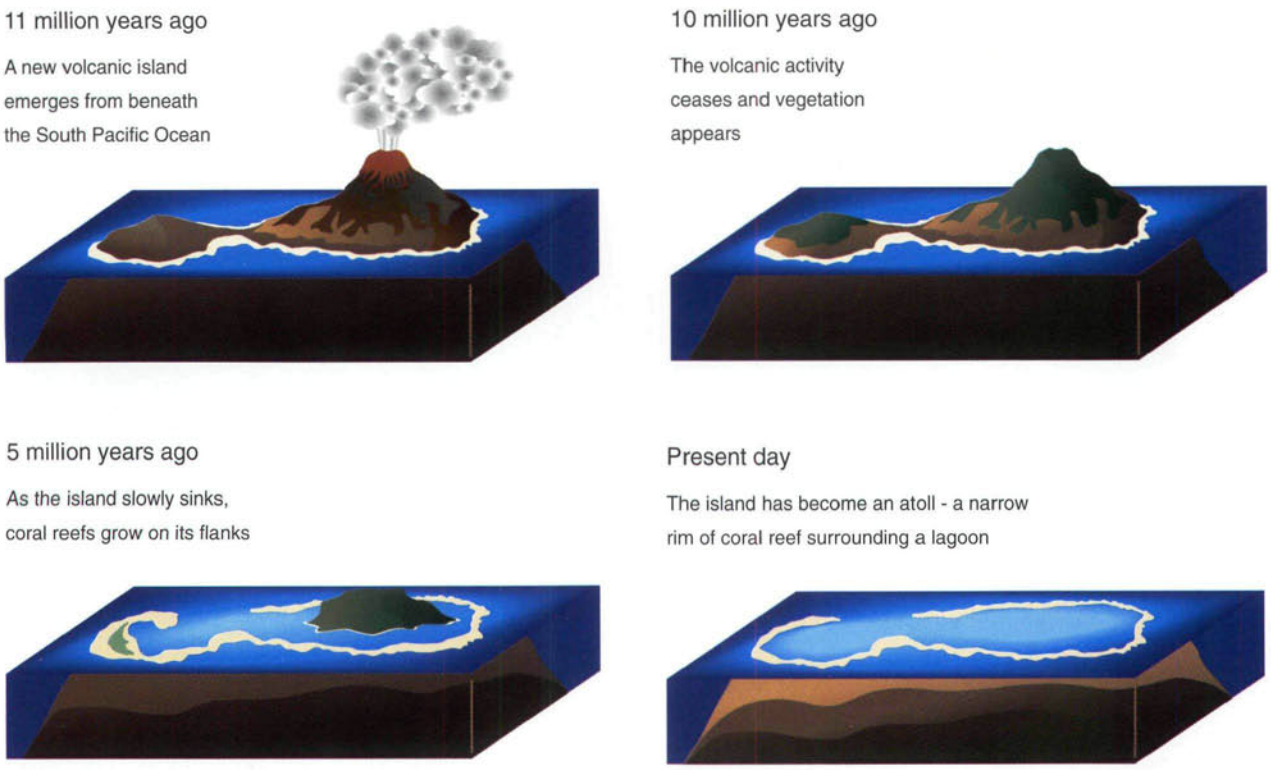


FIG. 10. Evolution of Mururoa Atoll.

2.3. EVOLUTION AND GEOLOGICAL STRUCTURE OF THE ATOLLS

2.3.1. Evolution

The atolls of Mururoa and Fangataufa have developed from extinct volcanoes. They are considerably younger than the oceanic crust on which they lie. Their evolution may be explained on the basis of the 'hot spot' theory, developed to explain the origin of the Hawaiian island chain. According to this simple model, magma generated at a fixed source in the upper mantle is able to ascend to form a volcano on the ocean floor. If the activity of the hot spot continues over time, new volcanic islands are established as the lithospheric plate moves over the hot spot (at a fixed position in the mantle). All the islands thus generated are aligned parallel to the movement of the plate, which is assumed to be unchanged. Figure 9 shows the known and inferred hot spots in French Polynesia. As a result of movement of the Pacific Plate, the hot spot that caused the formation of Mururoa and Fangataufa volcanoes is now 70 km southeast of Pitcairn (Bonati and Harrison 1976, Molnar and Stock 1987, Guille et al. 1995).

The hot spot model successfully explains the formation of the Hawaiian island chain and most of the islands of French Polynesia, which are oriented parallel to the southeast–northwest movement of the Pacific Plate. Some other, but not all, island chains in the South Pacific conform to this orientation. Mururoa Atoll and its underlying seamount, however, follow a N 80° E orientation. This is the orientation of the now extinct Austral Fracture Zone associated with the Farallon ridge. It is now considered that this fracture zone played a major role in the development of Mururoa Atoll (Buigues et al. 1992). At Fangataufa, just 40 km away, the influence of the Austral Fracture Zone is less apparent and the morphology reflects the general direction of movement of the Pacific Plate.

The volcanic rocks that form the basement of both atolls are approximately the same age (Mururoa 10.6–11.8 Ma, Fangataufa 9.6–11.5 Ma). They started their development as seamounts at the bottom of the South Pacific Ocean, which is some 4000 m deep at this point. The base of the volcano of Mururoa at the original sea floor measures approximately 130 km in length and 30 km in width.

Figure 10 illustrates the evolution of Mururoa Atoll. Fuelled by the hot spot, the volcano grew in size, eventually reaching the ocean surface, where it continued for some time as a subaerial volcano before the volcanic activity ceased. Magnetic surveys indicate, in fact, that

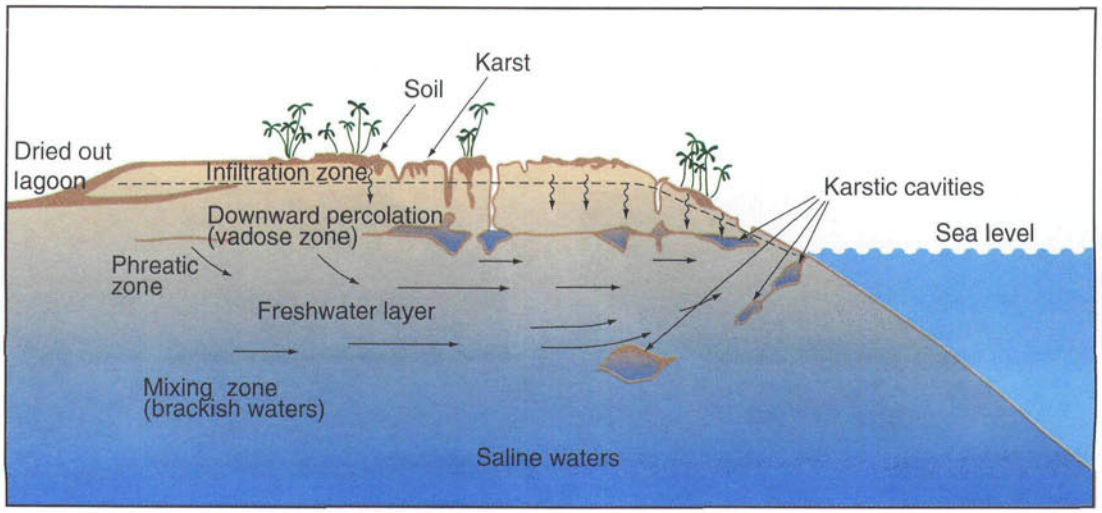


FIG. 11. Formation of karsts during glaciation periods. (Adapted from James and Choquette (1987).)

the atoll consists of at least two and probably three separate magma chambers (forming a flat volcano): one along the line of the northern rim, the other following the southern rim, with an isthmus between the two in the vicinity of the natural pass on the western extremity; and possibly a third, parallel to the rims, under the present lagoon. The enormous weight of the huge volcano then caused a slow sinking of the whole structure owing to the isostatic condition of the underlying Pacific Plate. Initially the rate of sinking was 1–2 mm/a but this later decreased to the current rate of about 0.15 mm/a.

Towards the end of the volcanic activity, coral growth commenced around the circumference of the volcano that was in contact with the sea and carbonate rocks were formed by coral and calcareous algae. Coral growth and the slow sinking of the volcano held pace with each other. Today the volcanic basement is capped by up to 450 m of consolidated carbonate sediments, the lowest parts of which have been changed to dolomite by diagenetic exchange processes with the surrounding sea water. The strongest growth of the coral reef occurs at the outer rim of the atoll in contact with the fresh sea water. Inside the lagoon the deposition of carbonate sediments predominates.

During glaciation periods, roughly every 100 000 years, the sea level drops worldwide by up to 150 m, owing to a huge accretion of ice at the polar ice caps. This kills the corals and exposes the carbonates to the effects of erosion and atmospheric conditions, with rainfall leading to the formation of groundwater bodies in the carbonates. Most probably the interconnected areas of high permeability within the carbonate rock (known as karsts) which have been observed originated during these glaciation periods. The karsts still have an important effect on the hydrogeological conditions of the atolls. Figure 11 depicts the formation of karstic cavities and mixing of the fresh and ocean water during periods when the sea level fell and the atolls rose to a significant height with dried out lagoons. During the interglacial periods the sea level increased again and corals grew back in concert with the rise of the ocean. Time and time again an equilibrium was established between the rise of the sea level and the growth of corals at the outer edge of the atolls, thus forming the beautiful ring shaped coral islands crowning the submerged volcanoes.

2.3.2. Structure and geology

An excellent general description of the structure, geology and petrology of Mururoa and Fangataufa Atolls is given in Guille et al. (1995).

Geological cross-sections through Mururoa and Fangataufa Atolls are given in Fig. 12. The main geological units are briefly described below; more detailed descriptions have been published by Buigues (1996, 1997) and the International Geomechanical Commission (IGC) (Fairhurst et al. 1998). Figure 13 shows the sequence of rock types and discontinuities apparent from drill cores from both atolls.

Submarine volcanics. The base of the submarine volcanics was built up from highly fluid lava flows that spread rapidly over gentle slopes to form tabular units. Subsequently lava erupted in the form of pillow shaped flows. The volcanic ejecta are characterized by intense

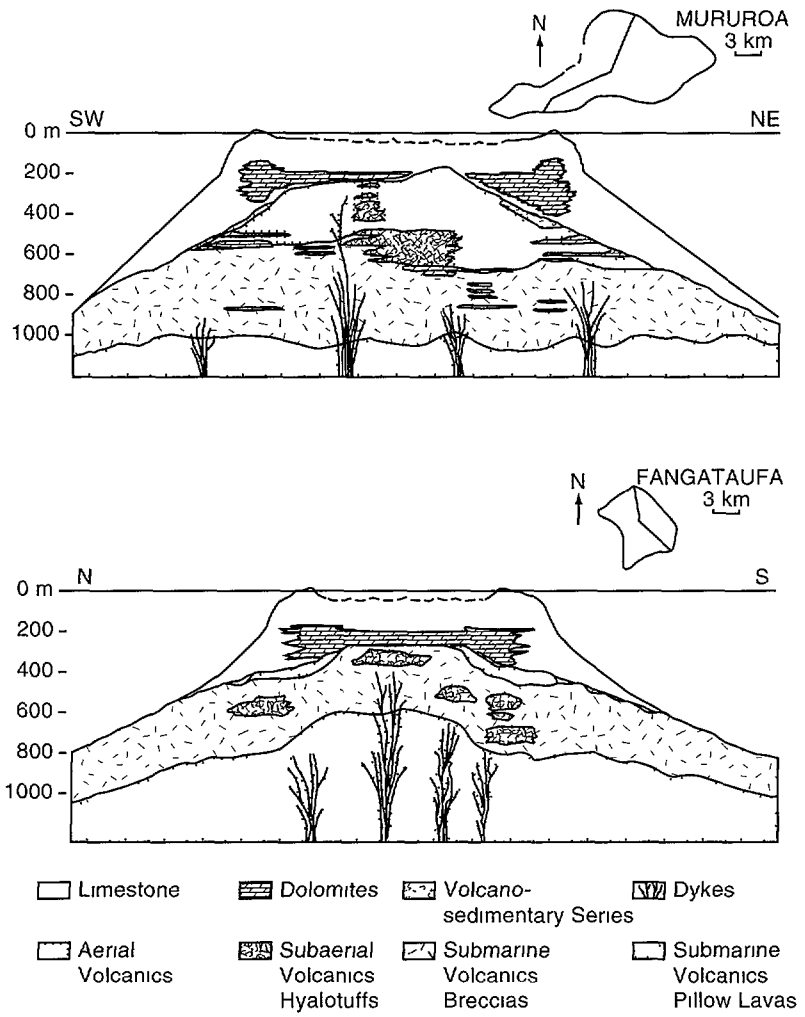


FIG 12. Geological cross-sections of Mururoa and Fangataufa Atolls (Adapted from Buigues (1997))

fragmentation due to thermal shock. In some locations, the finely brecciated volcanics mark the transition from the submarine to the subaerial series.

The volcanic sequence at Mururoa constitutes a typical moderated alkaline series with a range of products including basalts and trachytes, whereas at Fangataufa submarine basalts predominate (Guillou et al. 1990). At both atolls, the volcanic rocks have suffered early stage hydrothermal alteration due to basalt–seawater interactions.

Subaerial volcanics. At Mururoa, the subaerial volcanic series is well developed beneath the lagoon with a thickness exceeding 500 m in places. It consists of volcanic ejecta, massive but thin lava flows and highly vesicular lava of mildly alkaline composition. The flows are intercalated with red clayey layers that have been 'baked' by subsequent lava flows. At Fangataufa, the aerial volcanics are alkali basalts and are only present under the rim in thicknesses of up to 60 m

As with the submarine rocks, the primary mineral phases at both atolls have been transformed, not only by hydrothermal alteration, but also through leaching by meteoric waters.

Transition zones. The discontinuous nature of the buildup of the volcanic basement is apparent from erosion surfaces and carbonate rich layers in the submarine volcanics. The carbonate rich layers indicate that the volcanic basement was colonized before the cessation of volcanic activity. The deepest recorded occurrence of carbonate rocks is about 950 m below sea level at Mururoa

Transition zones are also apparent between the subaerial and carbonate zones. Where present, the transition zone is a conglomerate containing fragments and

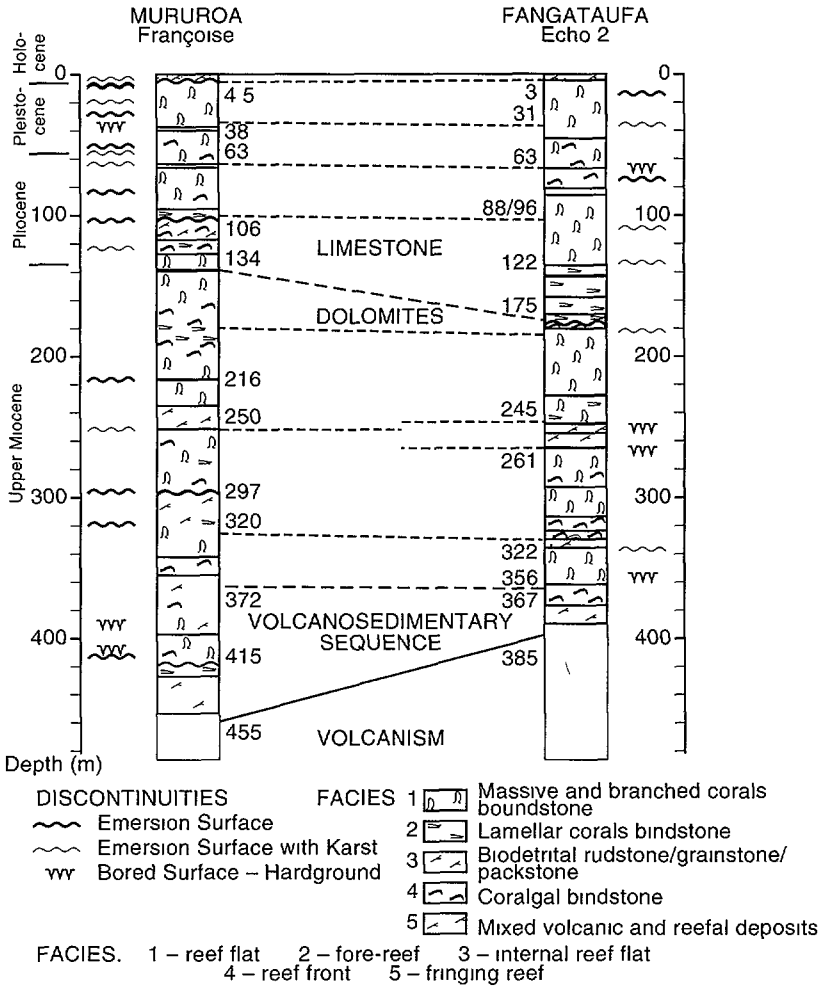


FIG 13 Sequence of rock types and discontinuities apparent from drill cores on Mururoa and Fangataufa Atolls (Adapted from Buigues (1997).)

alteration products of volcanic and carbonate rocks. Its thickness is variable and closely related to the morphology and degree of weathering of the volcanic relief. It is mostly absent beneath the lagoons

Carbonate cap The thickness of the sedimentary carbonate cap varies from 300–500 m at the atoll periphery to 120–220 m at the centre of the lagoons. A great diversity of sedimentary carbonate facies (i e discrete stratigraphic sequences) has been identified in drill cores taken from many locations on both atolls. These include a mixture of corals and coralline algae, detrital deposits and muddy facies At the periphery, slope deposits occur.

The calcareous deposits under the lagoons are generally poorly cemented The near surface deposits are sandy, the intermediate deposits are often lithified limestone interbedded with loosely cemented detrital deposits, and the lower sequence contains mostly hardened beds that are commonly karstified. On the atoll rim, the carbonate layers are strongly cemented down to about 400 m.

Significant chemical transformations have taken place owing to the influence at various times of fresh water and saline ocean water flowing through the carbonates. Limestones ($CaCO_3$) have been transformed to dolomites ($CaCO_3{\cdot}MgCO_3$), which are often well cemented and relatively strong mechanically. In other areas, dissolution by deep sea water has increased the porosity, leading to a characteristic chalky limestone, which is relatively weak mechanically

FIG. 14. Photograph of Mururoa during a storm. The sea wall is 4 m high.

2.4. SETTLEMENT IN FRENCH POLYNESIA

2.4.1. Early settlement

The order in which the islands of Eastern Polynesia were settled by the Polynesian peoples is not known with any certainty. New archaeological evidence suggests that the high islands now known as the Southern Cook Islands (west of the Society Islands) were settled first, followed by the high islands which make up the Iles du Vent, including Tahiti. From this core area, it appears that the population expanded eastwards to the rest of Eastern Polynesia and Easter Island, north to Hawaii and south-west to New Zealand. If this were the case, the high islands of the Marquesas and the low islands of the Tuamotus would probably have been settled by voyagers from Tahiti or its nearby islands. The nature of coral atolls makes carbon dating difficult, with the result that there is uncertainty in the times when the Tuamotu Archipelago was settled. However, the high islands of Mangareva and Pitcairn, farther to the east, are thought to have been settled by A.D. 800. Given the pattern of settlement described above, it seems likely that the Tuamotus would also have been inhabited before this time. However, the relative infertility of the coral derived soil has ensured that atoll populations were never as great as those of the high islands; indeed, there is no evidence that Fangataufa, for example, was ever inhabited.

2.4.2. Habitation of Mururoa

The first documentary evidence of population patterns in the area comes from the records of the European explorers of the eighteenth and nineteenth centuries. It is clear that the eastern Tuamotu Archipelago was then only sparsely populated and that occupation of the atolls was not continuous; an atoll reported as populated at one time would be found by a subsequent explorer to be deserted. It appears that the local populations made expeditions to otherwise uninhabited islands at certain times of the year, to harvest coconuts and to fish.

There is also circumstantial evidence of the effect of cyclones on atoll vegetation. For instance, Weatherhead reported only rocks on Mururoa in 1792, but in 1826 Beechey observed tall trees. Beechey found no one living on either Mururoa or Fangataufa. In the case of Mururoa, there could have been no significant population for many years previous to his exploration. A visit in 1832 found

dwellings but no inhabitants In 1834, only three of the few recorded inhabitants survived a skirmish with the crew of a visiting vessel. In 1847, when Queen Pomare accepted the French Protectorate, and a land survey was carried out, nobody claimed Mururoa, and it became French territorial land in 1881 (Beslu 1985).

In the latter part of the nineteenth century, there were attempts to set up a copra plantation on Mururoa Various concessions were granted and, for brief periods, there were workers living on the island and tending the plantations The coconut groves were destroyed in the devastating cyclones of 1903 and 1906 and any workers on the island either died or were evacuated Certainly, no one was seen on Mururoa by visitors in 1930, 1934 and 1936. A few people lived on the island between 1942 and 1943 and between 1950 and 1952. Since that time there had been no permanent settlement on Mururoa until it was ceded, along with Fangataufa, to the French Government in 1964 for the Centre d'expérimentations du Pacifique (CEP). The base for personnel conducting the nuclear testing programme was located at Mururoa and was opened in 1966.

During the thirty years or so of the French testing programme, about 3000 people were housed on Mururoa. This population was supported almost entirely by imported food and desalinated sea water. Because of the low relief of the atoll, the personnel base (including the living area, airstrip and industrial sector) was highly vulnerable to damage by waves resulting from storms or generated by rock slides on the flanks of the atoll, as demonstrated in Fig. 14 In the early 1980s, walls 4 m high were built, mainly on the ocean side of the Mururoa rim, to protect vulnerable areas The walls were designed to withstand a wave loading of 5 t/m^2.

At the conclusion of testing, decommissioning of the site began. Virtually all structures and facilities are being removed except the airstrip, some of the port facilities, the protective sea wall and the three massive concrete blockhouses built as observation posts for the atmospheric tests. It is not possible to say what the future occupation of Mururoa will be but, if past history is a guide, it is not likely to prove attractive to dwellers living a traditional Polynesian lifestyle.

2.4.3. Current population of the islands of French Polynesia

Estimates of the populations of the archipelagos and islands of French Polynesia in 1996 are given in Table I,

TABLE I. 1996 POPULATION ESTIMATES OF ARCHIPELAGOS AND ISLANDS OF FRENCH POLYNESIA AND (POPULATION WEIGHTED AVERAGE) DISTANCES FROM MURUROA

Island or archipelago	Distance from Mururoa (km)	Estimated population
Mururoa	0	700[a]
Tureia	133	120
Tematangi	178	40
Nukutavake	285	350
Iles Gambier (Mangareva)	423	730
Reao	460	530
Hao	461	1 570
Tatakoto	512	260
Hikueru	623	250
Rest of Tuamotus	1 020	8 300
Austral Islands	1 149	7 600
Iles du Vent	1 209	165 000
Marquesas Islands	1 367	8 600
Iles sous le Vent	1 428	26 000
Total, French Polynesia		220 000

[a] CEP personnel.

TABLE II. 1996 POPULATION ESTIMATES OF SOUTH PACIFIC STATES AND ISLANDS AND (POPULATION WEIGHTED AVERAGE) DISTANCES FROM MURUROA

State or island group (capital)	Distance from Mururoa (km)	Estimated population
Pitcairn	970	65
French Polynesia (Papeete)	1 161	220 000
Cook Islands (Rarotonga)	2 156	19 900
Easter Island	3 027	2 000
Niue (Alofi)	3 244	2 300
American Samoa (Pago Pago)	3 386	58 900
Western Samoa (Apia)	3 576	165 100
Tokelau (Fakaofo)	3 726	1 500
Tonga (Nuku'alofa)	3 745	90 000
Wallis and Futuna (Futuna)	4 214	14 800
Fiji (Suva)	4 460	800 500
Tuvalu (Funafuti)	4 720	9 600
New Zealand (Wellington)	4 816	3 500 000
Hawaii (Honolulu)	5 218	1 200 000
Vanuatu (Vila)	5 516	173 900
New Caledonia (Noumea)	5 596	196 800
Kiribati (Tarawa)	5 824	78 400
Nauru	6 303	11 200

along with their distances from Mururoa Where the population refers to a group of islands, a population weighted average distance is given. The population quoted for Mururoa reflects the number of personnel involved in decommissioning the CEP, and does not represent a permanent settlement.

Table II lists the 1996 population estimates of South Pacific States and islands, together with their (population weighted average) distances from Mururoa. Where appropriate, the name of the capital is also given

These tables demonstrate that there are great distances between islands and island groups in the South Pacific and that their populations are small; there are only around 5000 people living within 1000 km of Mururoa. New Zealand, with a population of 3 5 million, is the only State with a population of more than 1 million within 5000 km of Mururoa, the next nearest population of this magnitude is that of Hawaii, about 5200 km from Mururoa.

2 5. LIFESTYLES IN FRENCH POLYNESIA

2.5.1. Tureia: Example of an isolated atoll

Tureia Atoll is the closest inhabited island to Mururoa It has a population of around 120, who live in the village of Fakamaru on the northern coast. Tureia extends 15 km north to south and 9 km east to west; much of the reef is above sea level, with an average width of 300 m and a land area of 800 ha The highest point of land is a few metres above high tide level. The area of the enclosed lagoon is about 50 km^2 There is an airstrip on the island, but there are no regular flights and all goods and people coming to the island arrive at landings near the village The people live a semisubsistence lifestyle and depend on a combination of foods, some gathered from the ocean and the lagoon, some harvested from a very limited area of cultivated land and the remainder imported from Tahiti. Coconuts are widely cultivated, both for food and to produce copra for export, and papaya trees and vegetables are grown in small house gardens. The climate allows dwellings to be of simple construction, and the corrugated iron roofs of the houses and main buildings provide an important means of catching rainwater, which is then stored in cisterns.

The dwellers on this atoll are the closest Polynesian population group to Mururoa and their habits and lifestyle are the most likely to correspond to those of a Polynesian group that might settle on Mururoa in the future. Information on the habits and diets of the population of Tureia has therefore been used in assessing possible radiation doses to a hypothetical group that might live on Mururoa, as described in Section 9.

3. NUCLEAR TESTING PROGRAMME

3.1. INTRODUCTION

The French Government began testing nuclear weapons in 1960 at a site in the Sahara Desert in Algeria. In July 1962, the decision was made to establish a new test site in the South Pacific — the Centre d'expérimentations du Pacifique (CEP) — in the French sovereign territory of French Polynesia. The site chosen for the CEP was the uninhabited atoll of Mururoa, 460 km to the south of the major airbase at Hao, and with reasonable access to the main logistic base of Tahiti, 1200 km to the northwest. From the point of view of the French authorities, Mururoa had the advantage of lying within a sparsely populated area, with the good meteorological conditions needed to conduct high yield atmospheric tests. Fangataufa, 40 km south of Mururoa, was originally envisaged as an observation post, but was also used for some testing. The legislation to establish the CEP was enacted by the French Parliament on 29 March 1963 and development of the Mururoa site began almost immediately. The first troops arrived in May 1963 and the first civilian workers, from Anaa Atoll in the northeastern region of the Tuamotu Archipelago, were engaged on 7 September 1964. Altogether, some thousands of civilians, mostly Polynesians, worked on Mururoa during the testing programme.

Management of the CEP was the joint responsibility of the Ministry of Defence and the Commissariat à l'énergie atomique (CEA, the French Atomic Energy Commission). A managing body, the Direction des Centres d'expérimentations nucléaires (DIRCEN), was established in January 1964 and comprised a military general, responsible directly to the Defence Minister, and two deputies, one from the Ministry of Defence and the other from the CEA. The CEA was responsible for the scientific planning and execution of the tests, while the Ministry of Defence was in charge of operational and logistic support for the testing programme.

France conducted 193 'expériences nucléaires' (nuclear experiments) above and beneath Mururoa and Fangataufa Atolls between July 1966 and January 1996. The expériences nucléaires were of two types: 178 were nuclear tests ('essais nucléaires'), in which nuclear devices were exploded with large releases of fission energy, and 15 were safety trials ('expériences de sécurité'), in which more or less fully developed nuclear devices were subjected to simulated accident conditions and the nuclear weapon cores were destroyed by means of conventional explosives, with no or — on a few occasions — very small releases of fission energy.

3.2. ATMOSPHERIC TESTS AND SAFETY TRIALS

The first nuclear test at the CEP, performed on 2 July 1966, was of a 28 kiloton (TNT equivalent yield) device mounted on a barge in the lagoon of Mururoa Atoll (where one kiloton (1 kt) of TNT is defined to be equivalent to the release of 10^{12} calories of explosive energy). Three more barge mounted tests were carried out, two at Mururoa and one in the lagoon of Fangataufa Atoll. Over the next eight years, a further 34 devices were exploded in the atmosphere, suspended from balloons tethered above the atolls (31 at Mururoa and 3 at Fangataufa), and a further 3 were dropped from aircraft in the vicinity of Mururoa. The largest test was of a 2.6 megaton (Mt) thermonuclear device, Canopus, which was detonated 520 m above Fangataufa lagoon on 24 August 1968. The last atmospheric test, Verseau, carried out on 14 September 1974, was a 0.3 Mt device exploded 433 m above Mururoa.

The French Government has recently released some details of the nuclear testing conducted in the atmosphere at the CEP. This information is given in Table III (Doury and Musa 1996). Of the 46 expériences nucléaires listed, 41 were nuclear tests — 37 at Mururoa and 4 at Fangataufa — and 5 were safety trials. The safety trials were conducted between 1966 and 1974 on the three motus Colette, Ariel and Vesta on the northern tip of Mururoa Atoll west of Denise (Fig. 6) This recent information indicates that there was a small amount of fission energy released in two of the safety trials, Ariel and Persée. A summary of the atmospheric testing programme at the CEP is given in Table IV

3.3. UNDERGROUND TESTS AND SAFETY TRIALS

Underground testing was introduced in 1975 and continued until January 1996. Altogether there were 137 underground nuclear tests — 127 at Mururoa and 10 at Fangataufa — and 10 underground safety trials, all of which were conducted at Mururoa. Until 1981, all of the testing was carried out in shafts drilled vertically deep into the volcanic rock beneath the coral rim. Thereafter,

TABLE III. NUCLEAR TESTS AND SAFETY TRIALS AT MURUROA AND FANGATAUFA: ATMOSPHERIC

Date	Name	Type	Height (m)	Yield (kt)	
				Fission	Total
2 Jul. 1966	Aldébaran	Barge	0	28	28
19 Jul 1966	Tamouré	Air drop	1000	50	50
21 Jul 1966	Ganymède	Safety trial	12	0	0
11 Sep 1966	Betelgeuse	Balloon	470	110	110
24 Sep 1966	Rigel[a]	Barge	3	125	125
4 Oct 1966	Sirius	Barge	10	205	205
5 Jun 1967	Altair	Balloon	295	15	15
27 Jun 1967	Antares	Balloon	340	120	120
2 Jul 1967	Arcturus	Barge	0	22	22
7 Jul 1968	Capella	Balloon	463	115	115
15 Jul 1968	Castor	Balloon	650	450	450
3 Aug 1968	Pollux	Balloon	490	150	150
24 Aug 1968	Canopus[a]	*Balloon*	*520*	—[b]	*2600*
8 Sep 1968	Procyon	Balloon	700	—	1280
15 May 1970	Andromède	Balloon	220	13	13
22 May 1970	Cassiopée	Balloon	500	—	224
30 May 1970	Dragon[a]	Balloon	500	—	945
24 Jun. 1970	Eridan	Balloon	220	12	12
3 Jul. 1970	Licorne	Balloon	500	—	914
27 Jul 1970	Pégase	Balloon	220	0.05	0.05
2 Aug 1970	Orion[a]	Balloon	400	—	72
6 Aug. 1970	Toucan	Balloon	500	—	594
5 Jun 1971	Dione	Balloon	275	34	34
12 Jun. 1971	Encelade	Balloon	450	—	440
4 Jul 1971	Japet	Balloon	230	9	9
8 Aug. 1971	Phoebe	Balloon	230	4	4
14 Aug. 1971	Rhéa	Balloon	480	—	955
25 Jun. 1972	Umbriel	Balloon	230	0 5	0 5
30 Jun 1972	Titiana	Balloon	220	4	4
27 Jul 1972	Obéron	Balloon	220	6	6
31 Jul. 1972	Ariel	Safety trial	10	0 001	0.001
21 Jul 1973	Euterpe	Balloon	220	11	11
28 Jul 1973	Melpomène	Balloon	270	0.05	0.05
18 Aug. 1973	Pallas	Balloon	270	4	4
24 Aug 1973	Parthenope	Balloon	220	0.2	0.2
29 Aug 1973	Tamara	Air drop	—	6	6
13 Sep. 1973	Vesta	Safety trial	4	0	0
16 Jun 1974	Capricorne	Balloon	220	4	4
1 Jul 1974	Bélier	Safety trial	5 6	0	0
7 Jul. 1974	Gémaux	Balloon	312	—	150
17 Jul. 1974	Centaure	Balloon	270	4	4
25 Jul 1974	Maquis	Air drop	250	8	8
28 Jul 1974	Persée	Safety trial	5.6	0 001	0.001
14 Aug 1974	Scorpion	Balloon	312	—	96
24 Aug. 1974	Taureau	Balloon	270	14	14
14 Sep. 1974	Verseau	Balloon	433	—	332

[a] The four tests carried out at Fangataufa, all others were performed at Mururoa

[b] A dash indicates that data were not given

the limited space available on the Mururoa rim, and developments in drilling techniques, led to the nuclear tests being carried out under the lagoons, with the first of them at Mururoa on 10 April 1981. All tests from 1987 onwards were conducted under the lagoons, though one further underground safety trial was carried out under the Mururoa rim in November 1989.

No very high yield devices were exploded underground — none exceeded 150 kt — and the total energy release associated with all underground testing was reported by the French Government to be 3 2 Mt. The final test was detonated under Fangataufa lagoon on 27 January 1996, after which all nuclear testing at the CEP ceased. The complete list of underground tests is given in Table V; this information, with indications of the approximate yield of each device, was provided by the French Government (Bouchez and Lecomte 1996). The total yield of all underground tests as advised by the French Liaison Office (Document No. 4) was 2.4 Mt at Mururoa and 0.8 Mt at Fangataufa A summary of this information is provided in Table VI.

The ten underground safety trials were all carried out in shafts drilled vertically from the rim in the north-eastern region of Mururoa. The French Liaison Office reported that all the safety trial shafts were located 300–500 m inwards from the external edge of the rim (measured from the face of the coral cliff at a depth of 150 m) Seven of the shafts ended in the carbonate zone, though none was less than 280 m deep, and three entered the volcanics. The three trials that involved some fission energy release were in the carbonate zone The preparation for a trial was similar to that for a test, i e the device

TABLE IV. SUMMARY OF ATMOSPHERIC NUCLEAR TESTS AND SAFETY TRIALS AT MURUROA AND FANGATAUFA

	Mururoa	Fangataufa	Total
Barge	3	1	4
Balloon	31	3	34
Air drop	3	0	3
Total tests	37	4	41
Safety trials	5	0	5
Total (tests and trials)			46
Approximate total yield			10 Mt

TABLE V NUCLEAR TESTS AND SAFETY TRIALS AT MURUROA AND FANGATAUFA: UNDERGROUND

Date	Name	Location	Yield category[a]	Date	Name	Location	Yield category[a]
5 Jun 1975	Achille	Fangataufa rim	A	14 Nov 1978	Aphrodite	Mururoa rim	S
26 Nov 1975	Hector	Fangataufa rim	B	30 Nov 1978	Priam	Mururoa rim	C
3 Apr 1976	Patrocle	Mururoa rim	A	17 Dec 1978	Etéocle	Mururoa rim	A
11 Jul 1976	Ménélas	Mururoa rim	B	19 Dec. 1978	Eumée	Mururoa rim	B
22 Jul 1976	Calypso	Mururoa rim	S	1 Mar 1979	Penthésilée	Mururoa rim	B
30 Oct 1976	Ulysse A	Mururoa rim	A	9 Mar 1979	Philoctète	Mururoa rim	B
5 Dec 1976	Astyanax	Mururoa rim	A	24 Mar 1979	Agapénor	Mururoa rim	B
19 Feb. 1977	Ulysse B	Mururoa rim	B	4 Apr 1979	Polydore	Mururoa rim	B
19 Mar 1977	Nestor	Mururoa rim	C	18 Jun 1979	Pyrrhos	Mururoa rim	B
2 Apr 1977	Oedipe	Mururoa rim	A	29 Jun. 1979	Egisthe	Mururoa rim	C
28 Jun 1977	Andromaque	Mururoa rim	S	25 Jul. 1979	Tydée	Mururoa rim	C
6 Jul 1977	Ajax	Mururoa rim	B	28 Jul 1979	Palamède	Mururoa rim	A
12 Jul 1977	Clytemnestre	Mururoa rim	S	19 Nov 1979	Chrysothémis	Mururoa rim	A
12 Nov 1977	Oreste	Mururoa rim	A	22 Nov 1979	Atrée	Mururoa rim	A
24 Nov 1977	Enée	Mururoa rim	C	23 Feb 1980	Thyeste	Mururoa rim	A
17 Dec 1977	Laocoon	Mururoa rim	A	3 Mar. 1980	Adraste	Mururoa rim	A
27 Feb 1978	Polyphème	Mururoa rim	A	23 Mar. 1980	Thésée	Mururoa rim	C
22 Mar. 1978	Pylade	Mururoa rim	A	1 Apr 1980	Boros	Mururoa rim	B
25 Mar 1978	Hécube	Mururoa rim	A	4 Apr 1980	Pélops	Mururoa rim	B
1 Jul 1978	Xanthos	Mururoa rim	A	16 Jun 1980	Euryple	Mururoa rim	C
19 Jul. 1978	Arès	Mururoa rim	B	21 Jun. 1980	Ilus	Mururoa rim	B
26 Jul 1978	Idoménée	Mururoa rim	A	6 Jul. 1980	Chrysès	Mururoa rim	B
2 Nov 1978	Schédios	Mururoa rim	A	9 Jul 1980	Léda	Mururoa rim	S

TABLE V. (cont.)

Date	Name	Location	Yield category[a]	Date	Name	Location	Yield category[a]
19 Jul. 1980	Asios	Mururoa rim	C	6 May 1986	Céto	Mururoa rim	A
25 Nov. 1980	Laerte	Mururoa rim	A	27 May 1986	Sthénélos	Mururoa rim	B
3 Dec. 1980	Diomède	Mururoa rim	C	30 May 1986	Galatée	Mururoa lagoon	C
27 Feb. 1981	Brotéas	Mururoa rim	A	10 Nov. 1986	Hésione	Mururoa rim	A
6 Mar 1981	Tyro	Mururoa rim	A	12 Nov. 1986	Nauplios	Mururoa lagoon	B
28 Mar 1981	Iphiclès	Mururoa rim	B	6 Dec 1986	Pénéléos	Mururoa rim	A
10 Apr 1981	Clymène	Mururoa lagoon	B	10 Dec. 1986	Circé	Mururoa lagoon	C
8 Jul 1981	Lyncée	Mururoa rim	B	5 May 1987	Jocaste	Mururoa lagoon	B
11 Jul. 1981	Eryx	Mururoa rim	A	20 May 1987	Lycomède	Mururoa lagoon	C
18 Jul. 1981	Théras	Mururoa rim	A	6 Jun 1987	Dirce	Mururoa lagoon	B
3 Aug. 1981	Agénor	Mururoa rim	C	21 Jun. 1987	Iphitos	Mururoa lagoon	C
6 Nov. 1981	Léto	Mururoa rim	A	23 Oct 1987	Hélénos	Mururoa lagoon	C
11 Nov. 1981	Proclès	Mururoa rim	B	5 Nov. 1987	Pasiphae	Mururoa lagoon	B
5 Dec. 1981	Cilix	Mururoa rim	B	19 Nov 1987	Pelée	Mururoa lagoon	C
8 Dec 1981	Cadmos	Mururoa lagoon	B	29 Nov 1987	Danaé	Mururoa lagoon	B
20 Feb 1982	Aérope	Mururoa rim	A	11 May 1988	Nelée	Mururoa lagoon	C
24 Feb 1982	Déiphobe	Mururoa rim	A	25 May 1988	Niobé	Mururoa lagoon	C
20 Mar 1982	Rhésos	Mururoa lagoon	B	16 Jun 1988	Antigone	Mururoa lagoon	A
23 Mar. 1982	Evénos	Mururoa rim	A	23 Jun 1988	Déjanire	Mururoa lagoon	B
31 Mar. 1982	Aeson	Mururoa rim	S	25 Oct 1988	Acrisios	Mururoa lagoon	A
27 Jun 1982	Laodice	Mururoa rim	A	5 Nov. 1988	Thrasymèdes	Mururoa lagoon	C
1 Jul 1982	Antilokos	Mururoa rim	C	23 Nov 1988	Phères	Mururoa lagoon	C
21 Jul 1982	Pitane	Mururoa rim	A	30 Nov. 1988	Cycnos	Fangataufa lagoon	C
25 Jul. 1982	Laios	Mururoa lagoon	C	11 May 1989	Epéios	Mururoa lagoon	B
27 Nov. 1982	Procris	Mururoa rim	A	20 May 1989	Tecmessa	Mururoa lagoon	A
19 Apr 1983	Eurytos	Mururoa lagoon	C	3 Jun. 1989	Nyctée	Mururoa lagoon	C
25 Apr. 1983	Automédon	Mururoa rim	A	10 Jun. 1989	Cyzicos	Fangataufa lagoon	C
25 May 1983	Cinyras	Mururoa lagoon	C	24 Oct 1989	Hypsipyle	Mururoa lagoon	C
18 Jun. 1983	Burisis	Mururoa rim	A	31 Oct. 1989	Erigone	Mururoa lagoon	B
28 Jun 1983	Oxylos	Mururoa lagoon	B	20 Nov 1989	Tros	Mururoa lagoon	B
20 Jul. 1983	Battos	Mururoa rim	B	25 Nov. 1989	Daunus	Mururoa rim	S
4 Aug 1983	Carnabon	Mururoa lagoon	C	27 Nov 1989	Lycos	Fangataufa lagoon	C
3 Dec 1983	Linos	Mururoa rim	A	2 Jun 1990	Télèphe	Mururoa lagoon	B
7 Dec 1983	Gygès	Mururoa lagoon	B	7 Jun 1990	Mégapenthès	Mururoa lagoon	B
8 May 1984	Démophon	Mururoa rim	A	26 Jun. 1990	Cypsélos	Fangataufa lagoon	C
12 May 1984	Midas	Mururoa lagoon	C	4 Jul. 1990	Anticlée	Mururoa lagoon	B
12 Jun 1984	Aristée	Mururoa rim	B	14 Nov 1990	Hyrtacos	Fangataufa lagoon	C
16 Jun. 1984	Echémos	Mururoa lagoon	C	21 Nov 1990	Thoas	Mururoa lagoon	C
27 Oct. 1984	Machaon	Mururoa rim	B	7 May 1991	Mélanippe	Mururoa lagoon	A
2 Nov. 1984	Acaste	Mururoa lagoon	C	18 May 1991	Alcinoos	Mururoa lagoon	C
1 Dec. 1984	Milétos	Mururoa rim	A	29 May 1991	Périclyménos	Fangataufa lagoon	C
6 Dec. 1984	Memnon	Mururoa lagoon	C	14 Jun 1991	Pitthée	Mururoa lagoon	C
30 Apr. 1985	Cercyon	Mururoa rim	B	5 Jul. 1991	Coronis	Mururoa lagoon	A
8 May 1985	Nisos	Mururoa lagoon	C	15 Jul 1991	Lycurgue	Mururoa lagoon	C
3 Jun 1985	Talaos	Mururoa rim	B	5 Sep 1995	Thétys	Mururoa lagoon	B
7 Jun 1985	Erginos	Mururoa lagoon	B	1 Oct 1995	Ploutos	Fangataufa lagoon	C
24 Oct. 1985	Héro	Mururoa rim	A	27 Oct 1995	Aepytos	Mururoa lagoon	C
26 Oct. 1985	Codros	Mururoa lagoon	C	21 Nov. 1995	Phégée	Mururoa lagoon	C
24 Nov 1985	Zétès	Mururoa rim	B	27 Dec 1995	Thémisto	Mururoa lagoon	C
26 Nov. 1985	Mégarée	Mururoa lagoon	C	27 Jan. 1996	Xouthos	Fangataufa lagoon	C
26 Apr 1986	Hyllos	Mururoa rim	B				

[a] Yield categories are as follows A, <5 kt; B, 5–20 kt, C, 20–150 kt, S, safety trial with no fission yield

TABLE VI. SUMMARY OF UNDERGROUND NUCLEAR TESTS AND SAFETY TRIALS AT MURUROA AND FANGATAUFA

	Mururoa	Fangataufa	Total
Rim	73	2	75
Lagoon	54	8	62
Total tests	127	10	137
Safety trials	10[a]	0	10[a]
Total (tests and trials)	137	10	147
Approximate total yield			3 2 Mt

[a] In three of these safety trials, some fission occurred. (Although the total yield for these three trials was only about 0 5 kt, they are classified as nuclear tests in French sources, which cite the number of underground nuclear tests at the CEP as 140)

was lowered in a steel container to the bottom of the shaft, basaltic sand and cuttings were packed around it and the shaft was sealed with cement.

According to information provided by the French Liaison Office, each safety trial involved 10 TBq $^{239+240}$Pu. If the material used in these trials had been 'weapons grade' plutonium, say 7% ^{240}Pu, then about 3.4 kg ^{239}Pu and 0 3 kg ^{240}Pu would have been left behind in the cavity at the end of each trial. Virtually the same mass of plutonium would have remained in those trials in which some fissioning occurred, because very little of the mass of the original core would have been consumed. The difference is, however, that even such a relatively small release of fission energy would have been sufficient to melt the surrounding basalt backfill, so producing a lava in which most of the residual plutonium would have been trapped, thereby substantially reducing its potential for migration.

3.4. OTHER NUCLEAR EXPERIMENTS

Although not normally categorized as 'nuclear tests', the Study was informed by the French Liaison Office that a number of non-critical laboratory experiments with nuclear fuel were also undertaken at Mururoa. The residual plutonium, amounting to 10 TBq, was disposed of in two deep disposal shafts together with 10 TBq of plutonium collected during cleanup of the Colette region following the atmospheric safety trials (Section 4.2.2).

Part B
PRESENT AND PREDICTED RADIOLOGICAL SITUATIONS

4. INVENTORY OF RESIDUAL RADIOACTIVE MATERIAL IN THE BIOSPHERE AT THE ATOLLS

Since the mid-1980s, the Service mixte de surveillance radiologique et biologique de l'homme et de l'environnement (SMSRB) at Montlhéry, France, and its predecessor organizations have conducted a comprehensive programme of environmental monitoring in French Polynesia, and particularly on the atolls of Mururoa and Fangataufa Results of this programme up to 1995 were provided to the Study (French Liaison Office Document No. 3). To provide the basis for evaluation of the data from the French monitoring programme, a much smaller independent environmental monitoring campaign was carried out at the atolls as part of the Study.

The French monitoring programme is described briefly in Section 4.1 and the origin of the radionuclides detected by the French monitoring programme is discussed in Section 4.2. The independent sampling and surveillance campaign carried out as part of the Study is described in Section 4.3, where the results are compared with the French data.

4.1 FRENCH ENVIRONMENTAL MONITORING PROGRAMME

The French monitoring programme is described under two general headings: the physical environment and the biological environment. Measurements of ambient radiation levels, airborne and deposited activity concentrations, and activity concentrations in sea water and sediments are presented in Section 4.1.1 on the physical environment, whereas measurements of terrestrial and aquatic flora and fauna are discussed in Section 4.1.2 on the biological environment.

4.1.1. Physical environment

A monitoring system was established at several locations within French Polynesia. In particular:

— At Mururoa, regular measurements were made of dose rate and absorbed dose, atmospheric and deposited activity, and activity concentrations in the lagoon (water and sediment) and the surrounding ocean waters. Particular attention was paid to the Mururoa living area
— At Fangataufa, the activity concentrations in lagoon and surrounding waters were measured, together with the ambient dose rate.
— A wide range of monitoring was also performed on Tahiti, to allow comparison of measurements from coral reef atolls with those from a high (volcanic) island.

The monitoring performed at each location is summarized in Table VII, and the radionuclides monitored in each medium are listed in Table VIII

Absorbed dose and dose rate measurements

Absorbed doses outdoors were measured using thermoluminescent dosimeters (TLDs), which were collected for reading at six-monthly intervals. Measurements were taken at 20 locations on Mururoa and five on Fangataufa, as shown in Figs 15 and 16, respectively, and at two locations on Tahiti and one on Tureia. Dose rates were measured continuously in the Mururoa living area and on Tahiti.

TABLE VII. PHYSICAL ENVIRONMENT MONITORING LOCATIONS

Location	Dose rate	Dose	Radionuclide concentrations in				
			Air	Deposition	Lagoon water	Lagoon sediment	Ocean water
Tahiti	×	×	×	×			
Tureia		×					
EEZ[a]							×
Mururoa	×	×	×	×	×	×	×
Fangataufa		×			×	×	×
LTW[b]							×

[a] Within the limit of the exclusive economic zone (200 nautical miles, or 370 km).
[b] Limit of territorial waters (12 nautical miles, or 22 2 km)

TABLE VIII. RADIONUCLIDES TESTED FOR IN THE PHYSICAL ENVIRONMENT

	Air	Deposition	Lagoon water	Lagoon sediment	Ocean water
Total α	*				
Total β	*				
^{3}H			*		*
^{7}Be	*				
^{22}Na	*				
^{40}K	*			*	
^{60}Co				*	
^{90}Sr		*	*	*	*
^{125}Sb				*	
^{137}Cs	*	*	*	*	*
^{155}Eu				*	
^{210}Pb	*			*	
^{226}Ra				*	
^{228}Th				*	
^{228}Ac				*	
^{234}Th				*	
^{235}U				*	
^{238}Pu	*	*	*	*	*
$^{239+240}Pu$	*	*	*	*	*
^{241}Am				*	

Atmospheric monitoring

Monitoring of aerosols was carried out in the Mururoa living area, at one location on Tahiti and at Montlhéry (near Paris). Material was collected on filters, which were replaced daily. Total alpha and beta activities were measured five days after filter collection (i e. after short lived radon progeny had decayed), and gamma spectrometry was performed on dissolved filters. Plutonium isotopes were radiochemically isolated and measured by alpha spectrometry.

Deposition monitoring

Deposition monitoring stations were located in the Mururoa living area, on Tahiti and at Montlhéry. Each station consisted of two collection units and each unit had a collecting area of 1 m^2. Deposited material was collected on a continuous basis in 30 L plastic containers to which acid was added. To provide sufficient material for analysis the samples were bulked over six month periods. Samples were filtered and the radionuclide content of the acid soluble fraction was determined using gamma spectrometry for ^{137}Cs, beta counting of ^{90}Y (the short lived decay product) for ^{90}Sr and alpha spectrometry for radioisotopes of plutonium.

Lagoon water sampling

Lagoon water samples were collected from the Mururoa and Fangataufa lagoons every two years (in the absence of weapon testing). This frequency of monitoring was considered sufficient because of the slow change in activity concentrations in lagoon waters. Samples were taken at eight locations in the Mururoa lagoon and five in the Fangataufa lagoon (Figs 17 and 16, respectively) at a depth of 5 m (or 2 m in shallow water) in relatively calm weather. Analysis of ^{137}Cs, ^{90}Sr and $^{239+240}Pu$ was performed using the same techniques as mentioned above for deposition monitoring, with additional measurements being made of radioactive, tritiated water (HTO).

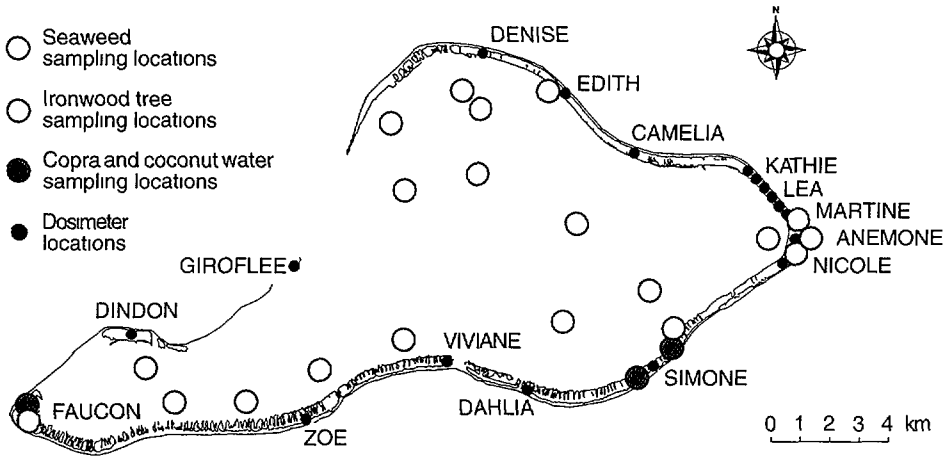


FIG 15 Locations of dosimeters and terrestrial and seaweed sampling points at Mururoa

Lagoon sediment sampling

Samples were taken from the top layer of the lagoon bed sediment at each atoll, wherever possible at the same location and date as the water samples. The distribution of bottom sediments in the lagoons is very non-uniform.

Ocean water sampling

A number of sites in the French Polynesian ocean, both close to and at some distance from Mururoa and Fangataufa, were monitored (Figs 16–18). Ocean water samples were collected from various depths, on a vertical line from the surface. In the deep ocean, where the water depth is more than 4000 m, samples of 500 L were taken at each depth, but closer to the atolls 250 L samples were collected. The analysis techniques mentioned above were used.

4.1.2. Biological environment

The biological environment was monitored by taking annual samples of fauna and flora which form part of the human food chain. Particular attention was paid to those species which are representative of a particular aspect of the environment or which tend to concentrate nuclides of concern

Terrestrial environment monitoring

Coconuts were of particular interest because of their importance in the Polynesian diet. They are consumed in two forms: the 'via-via' stage, at which the water is drunk, and the 'opaa' stage, when the pulp is consumed in the form of a fermented milk or gratings. Coconuts at both stages were monitored. Papaya is also commonly eaten and was therefore included in the sampling programme. The needles of the ironwood tree were sampled because the leaf (needle) structure is an effective collector of particulate materials from the atmosphere. Coenobites (terrestrial crustaceans) were also sampled. Some of the sampling locations at Mururoa are shown in Fig. 15.

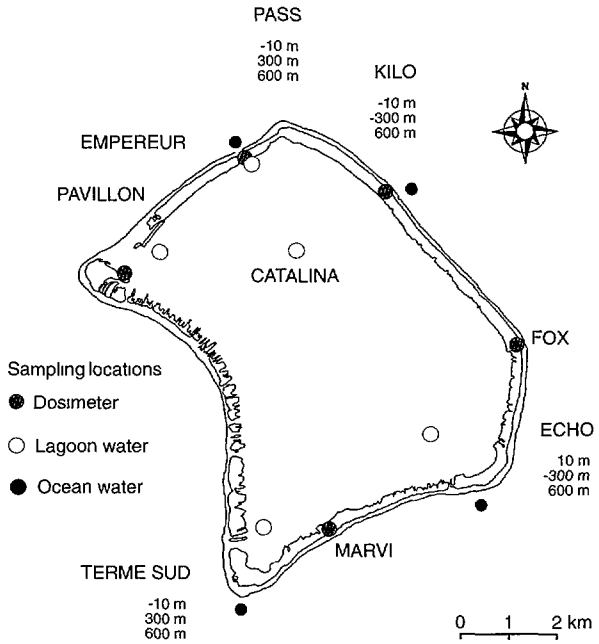


FIG 16 Locations of dosimeters and lagoon and ocean sampling points at Fangataufa

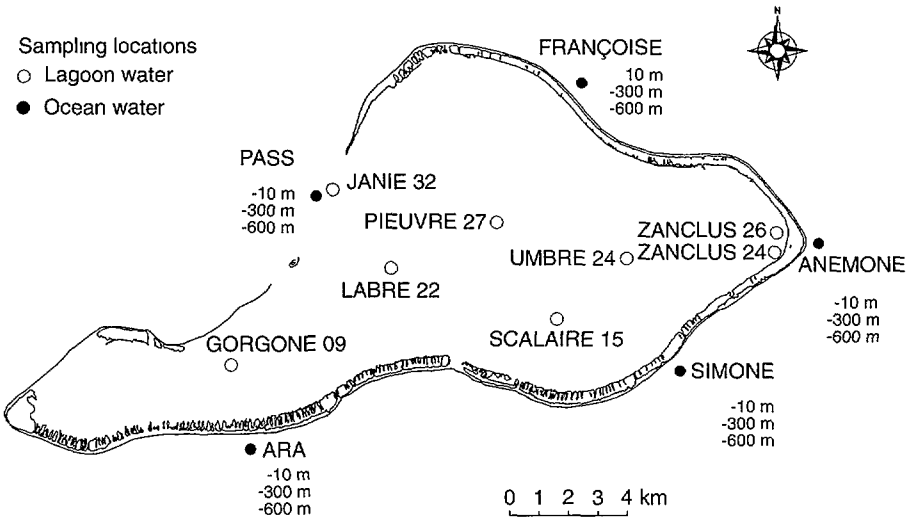


FIG 17 Locations of lagoon and ocean sampling points at Mururoa.

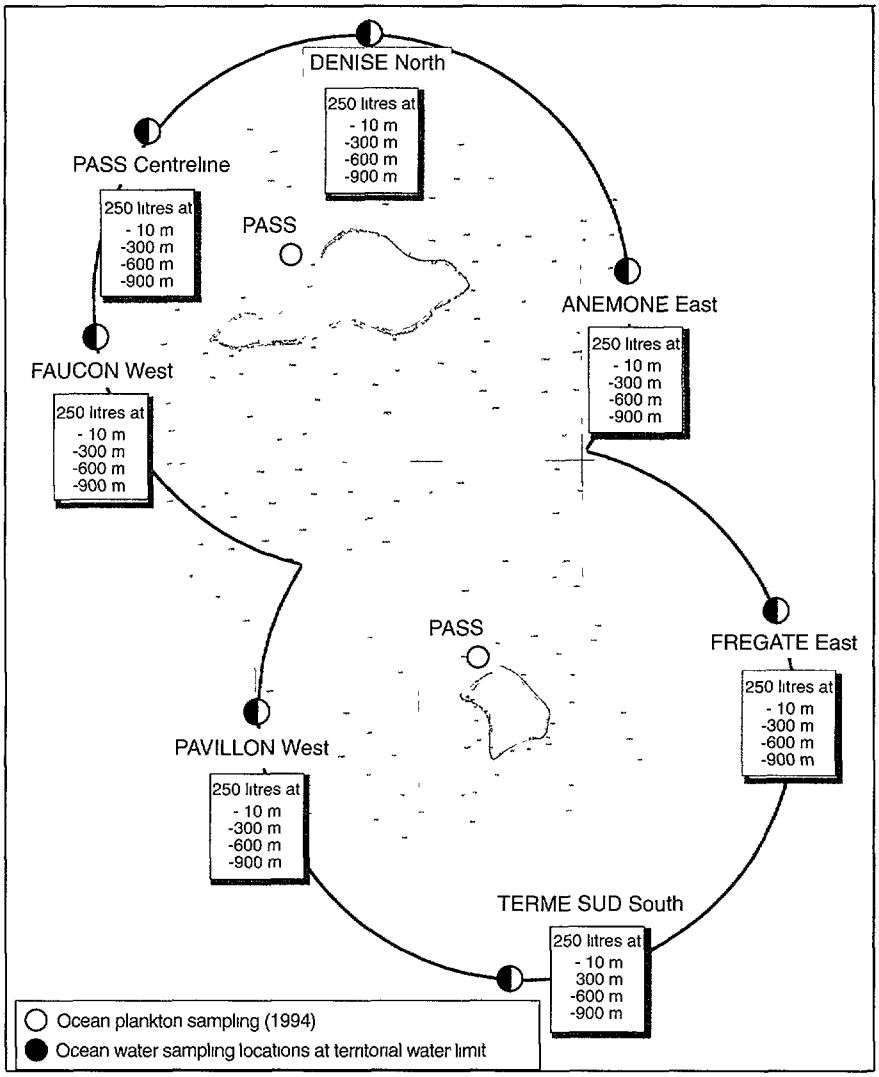


FIG 18. Locations of ocean and plankton sampling points around the test sites

Lagoon environment monitoring

Seaweed was collected three times a year from artificial supports at 16 locations in the lagoon at Mururoa, as illustrated in Fig. 15 Both phytoplankton (microscopic plants) and zooplankton (small animals) were sampled by in situ filtration of sea water. Surgeon fish and trochus (a mollusc), both of which consume seaweed, were sampled, together with a number of secondary consumers (consumers of zooplankton), such as coral, giant clams, chama and mother of pearl oyster The black sea cucumber (a benthic arenivore) was also sampled. The giant clam and the black sea cucumber were of particular interest for the monitoring programme, the giant clam because it consumes suspended particles and plankton present in water, and the black sea cucumber because it feeds on the microscopic sediment fauna and the organic coating of sand particles, and is in permanent contact with the sediment surface. Fish eaters, such as the grouper, goat fish and parrot fish, were also of interest Analyses performed on the turbo, spiny lobster and deep water shrimp, which live on the outer rim of the coral reef, provided information on this different type of environment.

Ocean environment monitoring

Ocean plankton were collected at points in the south and north of the French Polynesian ocean, close to Mururoa and Fangataufa and at the limits of their territorial waters (12 nautical miles, or 22.2 km) (Fig. 18). Ocean fish, particularly species of tuna, were caught at the surface or in deep water.

4.1.3. Long term monitoring

After decommissioning of the South Pacific test site, the French authorities intend to continue for an indefinite period a programme of environmental monitoring similar to that described above but at a somewhat reduced scale and frequency Logistic support will be provided by the French Navy with the CEA collecting the samples. Sample preparation and analysis will be carried out in laboratories in France In addition to the normal environmental monitoring, the monitoring of underground waters, as described in Section 6.6.2, is expected to continue.

The proposed long term environmental monitoring programme is presented in French Liaison Office Document No. 12, which also describes a continuing programme of geomechanical observations designed to monitor the geological stability of Mururoa.

4.2. ORIGIN OF ARTIFICIAL RADIOACTIVE MATERIAL IN THE ENVIRONMENT OF THE ATOLLS

The French environmental monitoring programme (Section 4.1) revealed the presence of a number of non-naturally-occurring radionuclides in the environment of the atolls. The results relating to the general environment are, as mentioned above, given in French Liaison Office Document No. 3, and separate reports are devoted to the levels of radionuclides in the lagoon sediments (Document No. 1) and in the soil of the atolls (Document No. 2). There are three sources of this residual radioactive material:

— *Atmospheric tests*: local fallout from the tests carried out by France on the atolls between 1966 and 1974, plus global fallout (largely ^{137}Cs and ^{90}Sr) from testing by the USA, the USSR, the UK and China between 1952 and 1980. This testing was mostly in the Northern Hemisphere, with major contributions coming from the USA and the USSR in the early 1960s (Annex I).
— *Safety trials*: five such trials were carried out on the surface of the northern rim of Mururoa between 1966 and 1974, resulting in the dispersion of finely divided plutonium.
— *Underground tests:* as discussed below, one or more of the underground tests is almost certainly a source of tritium found in the lagoons today (and may also be a source of ^{90}Sr).

4.2.1. Atmospheric tests

France's atmospheric testing programme in the South Pacific was described in Section 3. The amount of residual radioactive material deposited in or near the ground zero area by an atmospheric test depends on the height of the explosion. In general, the greater the altitude of the test, the more material will be injected into the troposphere and stratosphere, from where it will be widely distributed around the globe. Low altitude explosions, in which the fireball can interact with the surface of the Earth, give more local fallout

4.2.1.1. Tests at altitude

Apart from the four barge tests (Section 4 2.1.2), the devices used were detonated sufficiently high above the surface of the atolls that the fireball did not touch the ground. The tests conducted at altitude would therefore have contributed little to the residual radioactive material on Mururoa and Fangataufa. However, some of the material from these tests would have been deposited farther away. This fallout can be detected today on some nearby islands (e.g. Tureia), although it is deposited against a background of global fallout, most of which came from atmospheric tests carried out in the Northern Hemisphere. Only 13% of the ^{137}Cs and ^{90}Sr deposited in the general latitude band of Mururoa and Fangataufa came from the testing at the two atolls (Annex I).

Levels of ^{137}Cs and ^{90}Sr in the surface ocean water of French Polynesia in the mid-1990s were 2.1 and 1.4 Bq/m^3, respectively, as measured in the French monitoring programme at a sampling station about halfway between Tahiti and Hereheretue Atoll. This station is some 900 km from Mururoa, and the measured levels were about the same as, or lower than, the few results that have been reported in the literature for other areas in the South Pacific Ocean (Hamilton et al. 1996, Bourlat et al. 1996a). These levels therefore constitute a background concentration for these two radionuclides in the South Pacific Ocean against which measured concentrations in the lagoon waters of the atolls may be compared.

4.2.1.2 Barge tests

In the tests carried out on barges, the device was mounted as little as 1 m or so above the surface of the lagoon. The depth of water underneath the barges was 30–40 m. There were three barge tests at Mururoa, two in the Dindon area and one near Denise, and one at Fangataufa, in the Frégate area. The four barge tests, their yields and locations are given in Table IX.

TABLE IX. BARGE TESTS

Date	Name	Location	Height (m)	Yield (kt)
2 Jul. 1966	Aldébaran	Mururoa: Dindon	0	28
24 Sep 1966	Rigel	Fangataufa. Frégate	3	125
4 Oct 1966	Sirius	Mururoa Dindon	10	205
2 Jul 1967	Arcturus	Mururoa Denise	0	22

TABLE X TOTAL ACTIVITY (Bq) OF ARTIFICIAL RADIONUCLIDES IN UNCONSOLIDATED SEDIMENTS ON THE BOTTOM OF MURUROA LAGOON AS ESTIMATED BY FRENCH SCIENTISTS

Radionuclide	Dindon area (>1000 Bq/kg)	Denise area (>1000 Bq/kg)	Sandbank, Colette	North zone (without Colette and Denise) (>1000 Bq/kg)	Other lagoon zones	Total inventory (Bq)
^{60}Co	4.7×10^{11}	7.5×10^{9}	Negligible	Negligible	4.4×10^{10}	5.2×10^{11}
^{125}Sb	3.3×10^{10}	Negligible	Negligible	Negligible	Negligible	3.3×10^{10}
^{137}Cs	7.8×10^{11}	Negligible	Negligible	Negligible	Negligible	7.8×10^{11}
^{155}Eu	7.7×10^{11}	1.1×10^{10}	Negligible	Negligible	1.1×10^{11}	8.9×10^{11}
^{238}Pu	2.4×10^{12}	1.5×10^{11}	5.0×10^{10}	1.1×10^{11}	6.2×10^{11}	3.3×10^{12}
$^{239+240}$Pu	4.9×10^{12}	5.0×10^{11}	4.4×10^{12}	4.2×10^{12}	3.6×10^{12}	1.8×10^{13}
^{241}Am	4.2×10^{11}	Negligible	1.1×10^{11}	1.3×10^{11}	1.8×10^{11}	8.4×10^{11}

Note: Activities are given as of 1 January 1995, corrected only for radioactive decay, with no allowance made for possible sediment removal or for the fraction of each radionuclide that may have gone into solution in the lagoon waters since the date of sampling
Source French Liaison Office Document No 1

In contrast to the tests at altitude, the barge tests have left an unmistakable imprint on the atoll environments, especially immediately below the barges in the unconsolidated sediments of the lagoon bottoms. French monitoring showed localized high levels of plutonium isotopes in the sediments, together with measurable levels of ^{241}Am and the fission products ^{90}Sr, ^{125}Sb, ^{137}Cs and ^{155}Eu, and traces of the activation product ^{60}Co. According to the French results, the radionuclide concentrations were highest in the sediment beneath ground zero and decreased rapidly with distance from ground zero, ^{60}Co, ^{125}Sb and ^{137}Cs were barely measurable outside the test areas. At ground zero, the activity was distributed throughout the top few metres of sediment, with concentrations peaking between about 0.5 and 2 m, but farther from ground zero the activity was increasingly confined to the surface layers. Only 100 m from ground zero, the activity was found to be essentially limited to the top few tens of centimetres of sediment.

French estimates of the total quantities of a number of radionuclides remaining in the sediments of the two lagoons are presented in Tables X and XI (French Liaison Office Document No. 1). The estimates are based on extensive sediment core sampling campaigns carried out between 1984 and 1990. They are subject to considerable uncertainty because the depth distribution of each radionuclide in the sediments is only partly known and varies from place to place, the number of sites within the lagoon where sediments have been sampled is limited, and the depth and areal distribution of sediment over the bottom of the lagoons are only approximately known. A detailed discussion of the residual radionuclides and their levels in the bottom sediments of the two lagoons, as measured in the Study sampling programme, is given in Section 4.3 2.3 and the data are compared with the French values in Section 4.3.2 4.

The inventories of $^{239+240}$Pu in the lagoons resulting from the atmospheric nuclear tests (i.e. excluding the contribution from safety trials on Mururoa) are, according to French estimates, 13 TBq for Mururoa and 7.4 TBq for Fangataufa. This is equivalent to about 5 kg in the sediments of Mururoa and 3 kg at Fangataufa. If it is assumed that the core of each nuclear device contained 3.7 kg of plutonium, and that only 10% of this was fissioned (Section 5.6), there would be about 3.3 kg of plutonium remaining from each explosion, or a total of about 10 kg of plutonium for the three barge tests at Mururoa. Some of this will have been dispersed into the

TABLE XI. TOTAL ACTIVITY OF ARTIFICIAL RADIONUCLIDES IN UNCONSOLIDATED SEDIMENTS ON THE BOTTOM OF FANGATAUFA LAGOON AS ESTIMATED BY FRENCH SCIENTISTS

Radionuclide	Total inventory (Bq)
^{60}Co	4.2×10^{10}
^{125}Sb	7.1×10^{9}
^{137}Cs	1.9×10^{11}
^{155}Eu	5.9×10^{11}
^{238}Pu	2.9×10^{12}
$^{239+240}Pu$	7.4×10^{12}
^{241}Am	3.9×10^{11}

Note: Activities are given as of 1 January 1995, corrected only for radioactive decay, with no allowance made for possible sediment removal or for the fraction of each radionuclide that may have gone into solution in the lagoon waters since the date of sampling.

Source French Liaison Office Document No 1

atmosphere, but it appears that about 50% has been deposited on the bottom of the lagoon. The estimated residual inventory of 3 kg of plutonium in the Fangataufa bed sediments from one test is not inconsistent with this figure.

4.2.2. Safety trials

At Mururoa (but not Fangataufa), there was an additional source of plutonium in the lagoon sediments, namely the five atmospheric safety trials carried out on the northern rim of the atoll, west of Denise. In these trials, a virtually complete nuclear core, mounted on a tower a few metres high, was blown apart by the conventional explosive trigger of a nuclear weapon in such a way that little or no fission energy was released. The five safety trials (Ganymède, Ariel, Vesta, Bélier and Persée) are included in Table III.

One result of a safety trial was the dispersion over a wide area of plutonium and plutonium oxide in the form of particulates, ranging in size from plutonium vapour, through variously sized aerosols of plutonium and plutonium oxide (or, more likely, particles consisting of plutonium coated on, or incorporated in, a matrix of some other material), to sizeable lumps of contaminated structural material destroyed in the explosion.

The trials were carried out on Colette, Ariel and Vesta, motus which are essentially composed of exposed coral bedrock At the time of the trials, according to French Liaison Office Document No. 2, the motus were covered in places with a thin layer of sand. The area of permanently emergent land in this zone is about 190 000 m^2, comprising a strip of land about 300 m wide at its widest, with the Colette motu making up over half of the area. The trials were carried out first on Colette (Ganymède), then on Ariel (Ariel and possibly Bélier) and then on Vesta (Vesta and possibly Persée), with the wind blowing predominantly towards the ocean or towards the west, i.e. away from the road to the airstrip, as reported by the French Liaison Office. Most of the plutonium would therefore have been deposited in the ocean, although there is evidence, from variations in the $^{241}Am/^{239}Pu$ ratios measured on Colette, that some material was deposited there from the trials conducted on the other two motus.

French Liaison Office Document No. 2 describes how, after each trial, the larger pieces of contaminated debris were collected and sealed into drums for disposal and the remaining deposited plutonium was immobilized by covering it with emulsified asphalt. An area of 70 000 m^2 was covered in this way. The asphalt deteriorated with time, suffering damage by heavy seas, and a series of cleanup campaigns was undertaken by the French authorities between 1982 and 1987. A major radiation survey of the area involving 145 000 measurements was carried out in 1986, and established that the residual plutonium contamination, largely in spots of unremoved asphalt and in the coral bedrock, amounted to about 35 GBq (nearly 16 g ^{239}Pu). A final cleanup was carried out in 1987, when all 10 m × 10 m areas containing more than 100 MBq of plutonium were further scoured and scraped to reduce residual contamination to below an average of 1 MBq/m^2. After this cleanup the estimated residual plutonium on the three motus was 15 GBq (6.5 g ^{239}Pu), 80% of it on Colette (French Liaison Office Document No. 2).

According to the French Liaison Office, about 10 TBq of plutonium (3.7 kg) was collected from the three motus during cleanup and buried in two disposal shafts drilled deep (1180 m) into the volcanics underneath the atoll rim, near the Denise blockhouse Most of the activity appears to have been associated with quite large lumps of contaminated debris collected immediately after each trial.

It should be noted that additional plutonium waste produced on Mururoa was disposed of in these shafts. The Study was informed by the French Liaison Office that this waste was produced in a series of non-critical laboratory experiments with nuclear fuel (possibly hydrodynamic tests and/or hydronuclear tests; see Annex IV). The waste amounted to a further 10 TBq of plutonium, which was disposed of in the two disposal shafts near Denise. Hence, there is a total of 20 TBq of

plutonium buried in the two shafts which, not being incorporated in 'lava', constitutes an underground source of relatively mobile plutonium, though it is buried deep in the volcanics. This is the 'Category 7' source (Section 5.9) used in the assessment of the total rate of migration of plutonium from underground into the accessible environment.

The remainder of the plutonium involved in the safety trials (about 15 kg) would have been deposited in the lagoon and the sea, with the majority going to the sea. Of the material deposited on the motus, some of the less fixed would undoubtedly have been washed from the surface into the surrounding water by the action of the tides and waves. French scientists have reported a significant accumulation of plutonium, clearly originating from the trials, in a sandbank in the lagoon adjacent to the Colette motu According to French estimates based on the analysis of 200 top layer samples and nine cores taken through the entire depth of the sandbank (0.5–1 m), the total amount of plutonium in this sandbank is 4 4 TBq, or about 1 9 kg (Table X) (French Liaison Office Document No 1; see also Section 4.3.2.3).

4.2.3. Underground tests

In the above discussion, the radionuclides currently in the environment of the atolls have been assumed to be attributable to the atmospheric tests and safety trials. However, it is possible that, in the 23 years since the first underground tests, some of the radioactive material produced may have reached the surface. A major task of the Study was to determine whether or not such releases have already occurred, whether there will be releases in the future and, if so, when and at what rate. The question of releases in the future is discussed in Section 6; the possibility that such releases may already be occurring is discussed below.

With the exception of tritium and possibly ^{90}Sr, the French monitoring data do not indicate the presence of an underground source for the nuclides currently measurable in the environment. The plutonium, ^{241}Am and ^{137}Cs measurable in the environment of the atolls can be accounted for by the atmospheric tests and safety trials

The definite exception is tritium (^{3}H or T). In the environment, tritium is almost invariably incorporated in water molecules, replacing one of the normal hydrogen atoms to give HTO Tritium is produced naturally by nuclear interactions between cosmic ray neutrons and oxygen and nitrogen in the upper atmosphere, but the levels in the environment before nuclear explosions began were extremely low; for example, the concentration of tritium in the oceans before the nuclear age was certainly less than 100 Bq/m^3. As large quantities of tritium are present in nuclear weapons, and further tritium is produced in some of the nuclear reactions within such devices, the atmospheric testing of nuclear weapons introduced an additional, global source of tritium into the environment. Tritium is also released during the operation of nuclear power reactors and in the processing of nuclear fuel, so environmental levels of tritium in the vicinity of such nuclear facilities can be further increased. Tritium concentrations in the North Sea, for example, are around 2500 Bq/m^3. However, in areas remote from any nuclear activities, the present background levels of tritium in the surface waters of the open ocean can be taken to be about 150 Bq/m^3, essentially the 'pre-nuclear' background plus global fallout.

Tritium introduced into the environment of the atolls as a result of the French atmospheric testing would be found predominantly in the lagoon waters. The concentration in lagoon water from this source would be expected to have decreased quite rapidly over the years, through a combination of radioactive decay and the flushing of the lagoon water into the ocean. Tritium has a half-life of 12 4 years, so the concentrations at the cessation of French atmospheric testing in 1974 would have fallen by a factor of 4 over the subsequent 24 years from radioactive decay alone. It is immediately clear from inspection of the French monitoring data for tritium in the water of both lagoons that this is not the case (French Liaison Office Document No. 3). For some years, the concentration of tritium in Mururoa lagoon has remained fairly constant at around 1000 Bq/m^3 and, although fewer data are available for Fangataufa lagoon, the level there also seems to have remained fairly constant, at about half this value. An approximate calculation based on the flushing time and the volume of Mururoa lagoon shows that tritium must be entering the lagoon at the rate of about 10 TBq/a to maintain this concentration.

The source of the 'extra' tritium in the lagoons must be the residual material from the underground tests, migrating to the carbonate formations and from there to the lagoons (or possibly via the direct transfer of tritiated groundwater from the carbonate zone during the drilling of large boreholes through the karstic layers; such drilling was an almost continuous activity throughout the years of underground testing).

There is no clear indication from the French monitoring data of any escape of other radionuclides from underground testing into the lagoons, except possibly for ^{90}Sr, where the evidence is equivocal. Evidence for leakage into the lagoons, based on the French monitoring data and the results obtained during the Study's sampling and monitoring campaign, is examined in Section 4.3 2.

The migration of residual radioactive material from underground into the biosphere is discussed in detail in Section 6.

4.3. THE STUDY'S SAMPLING AND MONITORING CAMPAIGN

At its first formal meeting, the IAC agreed that the current radiological situation at the atolls would be assessed by estimating the annual doses that people living in involved areas were currently receiving, and the dose rates to which people could potentially be exposed if they chose to live on the atolls themselves. The exposures to be estimated were those attributable to the radioactive material present in the environment as a result of the French testing programme in the region, i.e. the contribution to local exposures resulting from general global fallout from the nuclear testing of other countries was, as far as reasonably practicable, to be excluded from the assessment.

The French Government has for many years been carrying out an environmental monitoring programme in the region and results of this programme were made available to the Study. The French monitoring programme and the nature of the data provided were summarized in Sections 4.1 and 4.2 Only a small amount of this information had been published in the open literature and most of the information had not therefore been available for peer review and assessment. It was thus necessary for this information to be critically reviewed. The IAC resolved at its first meeting that, to enhance the effectiveness of this evaluation, an independent environmental sampling and monitoring campaign should be carried out at the atolls.

The IAC believed that a large independent sampling and analysis programme was not warranted. After reviewing the information provided by the French Liaison Office, the IAC was of the opinion that the French monitoring programme appeared to be comprehensive and the data to be of high quality. Recognizing this, and the limited resources and time available to the IAEA for carrying out an independent survey, the IAC determined that the programme should be the minimum necessary to evaluate the credibility of the French data. It would also need to establish whether or not the French programme had been sufficiently comprehensive to provide an adequate estimate of the concentrations and inventories of relevant radionuclides in the environment, so that sound dose assessments could be made.

It had to be recognized, however, that such relatively limited sampling would inevitably lead to differences in radionuclide concentrations between the spot samples taken in the Study's campaign and the much more extensive data sets generated by the French monitoring programme. Previous intercomparison exercises (IAEA 1991, 1995) had indicated that analytical variability was unlikely to be a major source of differences between the Study data and French results and this was confirmed by analytical quality control measures included in the Study. However, differences could arise from many other potential sources, including the known small scale heterogeneity of the radionuclide distributions in the physical environment, the difficulty in obtaining suitable samples from the same locations as were used in the French monitoring programme, the known biological variability in the accumulation of radionuclides and the mobility of some of the marine species sampled. In these circumstances exact agreement would not be expected; overlaps in the ranges of values would be regarded as a good measure of agreement. For single samples, agreement to within a factor of 3 either way would probably be acceptable; outside that, it might be necessary to examine the potential influence of confounding factors.

It was foreseen at the technical consultation meeting in January 1996 that an independent survey might be necessary, and a technical team comprising four members of the IAEA's Seibersdorf and Monaco laboratories visited the atolls in March 1996 to assess the logistic requirements for such a campaign. They inspected potential sampling sites as well as the laboratory equipment and facilities available for sample collection and preparation, and discussed with members of the French Liaison Office and local staff the general infrastructure and logistic support that could be provided locally for carrying out the campaign in such a remote area.

Task Group A was responsible for the design of the sampling and monitoring programmes, which were organized and conducted in two parts, the Seibersdorf laboratory co-ordinating the sampling of the terrestrial environment and the Monaco laboratory organizing the sampling of the aquatic environment. The Terrestrial and Aquatic Working Groups were augmented to include a number of participating experts for the duration of the sampling campaign, and analysis of collected samples for radionuclide content was carried out by independent international laboratories. The action plan for Task Group A, therefore, had the following components:

— Examination of the existing French environmental monitoring data, and data from other relevant studies, and identification of gaps in the information that would be needed to assess the current radiological situation,

— Design and implementation of an independent sampling and measurement programme for the terrestrial and aquatic environments of the atolls that would assist in the evaluation of the data supplied by the French Government and provide such additional information as may be necessary to carry out the radiological assessments;
— Definition of the exposure pathways, habits and dietary intake of populations in involved areas, and of hypothetical populations, to be used in the dose assessments;
— Estimation of existing individual doses resulting from the measured radionuclide concentrations in the environment, and of doses to hypothetical groups, now and in the future, including those due to exposures resulting from radionuclides that may migrate from underground to the biosphere.

The terrestrial and aquatic sampling programmes and the results obtained are summarized in the remainder of this section. Environmental activity concentrations and inventories are discussed here; the conversion of these into rates of radionuclide intake by humans real and hypothetical and the assessment of doses are presented in Section 9.

4.3.1. Terrestrial environment

4.3.1.1. Introduction

This section describes the Study's terrestrial sampling and measurement campaign and its results. The sampling was carried out from 15 July to 2 August 1996. Technical details relating to all aspects of the campaign and the evaluation of the results can be found in the Technical Report, Vol. 1.

4.3.1.2 Participating laboratories and sample distribution

The samples collected during the campaign were analysed by members of the IAEA's co-ordinated international network of Analytical Laboratories for Measuring Environmental Radioactivity (ALMERA) and the Seibersdorf laboratory. A list of ALMERA members that provided results is given at the end of this report.

The programme was designed to obtain representative environmental samples. Care was taken in the preparation and processing of the samples to ensure that all radionuclides were distributed homogeneously in the final subsamples. Each sample was split into three parts: one was measured by a member of the ALMERA network or the Seibersdorf laboratory, one was sent to the SMSRB and the third was archived at Seibersdorf. The amount of material sampled took into account the mass needed to achieve adequate detection limits for the Study in each of the three subsamples

The SMSRB protocols were reviewed and found to be adequate. These protocols were therefore followed closely in all sampling procedures, in order to ensure reasonable comparability of results with the French data.

4.3 1.3 Geographical location and site description

Samples were collected from sites chosen to be as close as possible to those used by the environmental monitoring network described in French Liaison Office Document No. 3. A brief description of the location and characteristics of the sampling sites chosen for the Study's programme is given below. The sites on Mururoa are named below and their locations are identified in Fig 6; the descriptions below start from the living area, Anémone, at the easternmost tip of the atoll, and proceed in an anticlockwise direction.

Living area on Mururoa (Anémone, Martine, Léa)

The living area of Mururoa covers about 0.75 km^2 at the eastern end of the atoll, where the rim is 600 m wide. This area is the only part of the atoll that has deeper layers of soil and humus; most of the soil was transported there from other locations.

Airport zone (Kathie, Jeanne, Irène, Camélia)

Although adjacent to the living area, the airport zone shows a completely different structure. The soil is essentially coral debris and sand. The ground was levelled prior to building the airport and material was transported to this zone from different locations, including the more contaminated areas in the north (Colette). This has resulted in a heterogeneous soil structure, which is reflected in the variability of levels of activity found in this area.

North zone (Denise)

Denise is in the northern part of the atoll, well away from the living area. This is one of the zones where the barge tests were carried out and, according to the information supplied by the French Liaison Office, shows some localized high levels of residual activity. Denise consists mainly of coral debris, coral bedrock and sand, with little vegetation.

Safety trial sites (Colette, Ariel, Vesta)

The three motus Colette, Ariel and Vesta, shown in Fig. 19, are located west of the motu of Denise, in the northern part of Mururoa. They consist of exposed bedrock, covered in some places by a thin layer of sand or coral debris, and are at times partly flooded by sea water. Scattered vegetation is present on some parts of Colette. The residual plutonium on the motus originates from the five safety trials (Section 4.2.2). The motus, the surrounding lagoon sediments and a submerged sandbank in the lagoon adjacent to Colette were all contaminated with plutonium. According to French Liaison Office Document No. 1 and Bourlat et al. (1995), the $^{239+240}$Pu activity concentrations in the Colette sandbank reach 2.5 MBq/kg, mainly in the form of relatively large particles, which may be of the order of 1 mg in weight and have activities in excess of 10^5 Bq.

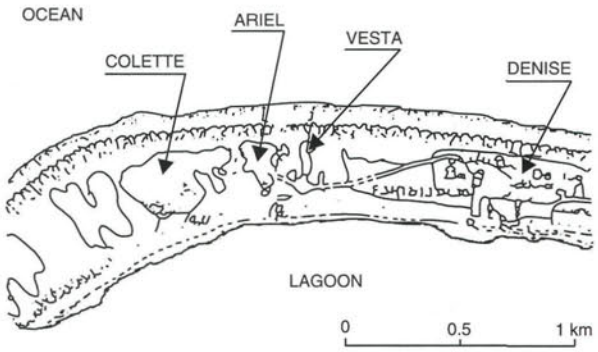


FIG. 19. Map of the three motus Colette, Ariel and Vesta of Mururoa Atoll.

Surface activity maps, shown in Fig. 20, were provided by the French Liaison Office after the IAEA monitoring had been completed. Sample collection and in situ gamma measurements by the Study team were focused on Colette, which is by far the largest of the three areas.

West zone (Dindon, Faucon)

Dindon and Faucon are at the western end of the atoll, far from the living area. Like Denise, these areas were used for barge tests and high, but variable, levels of residual activity were reported by the French authorities. A relatively large number of samples were collected from this zone to obtain more representative information. Dindon and Faucon are not accessible by land from the

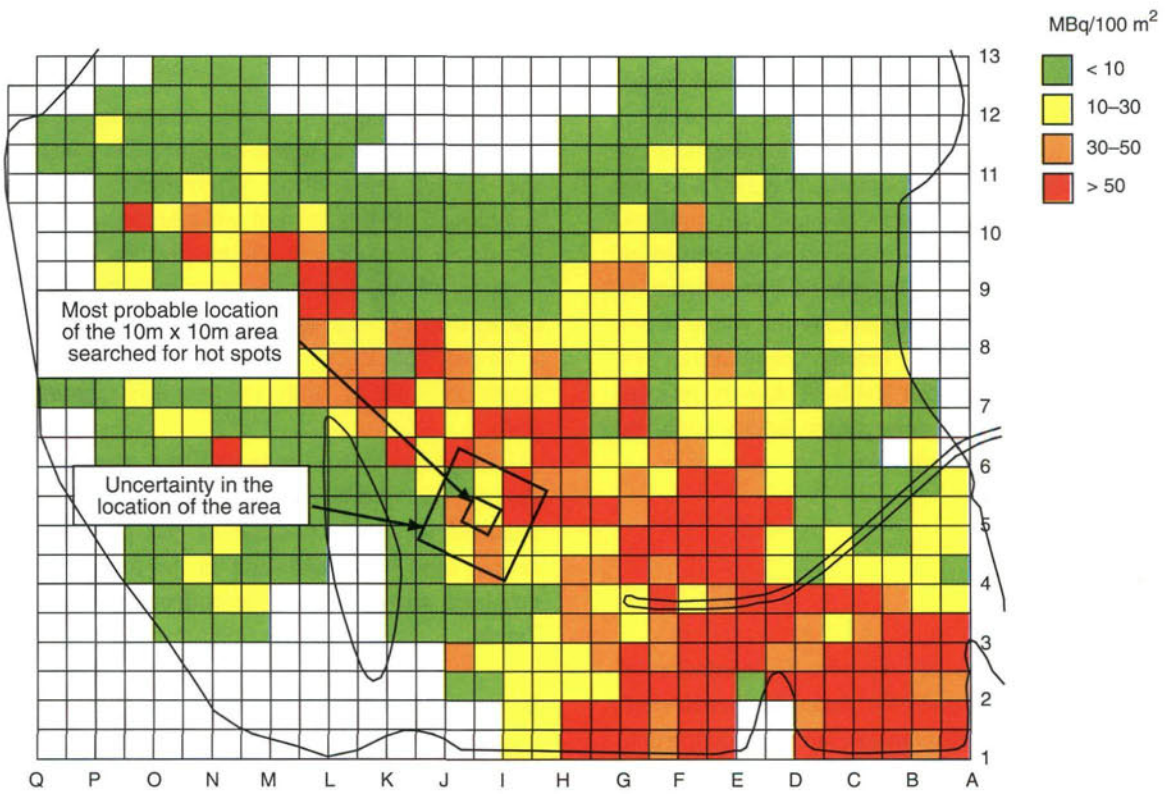


FIG. 20. Map of surface activity concentrations of ^{239}Pu on the Colette motu of Mururoa as provided by the French Liaison Office.

rest of the atoll The Dindon area consists mainly of coral debris, coral bedrock and sand, with little vegetation. Faucon is a broader motu at the western tip of the atoll and has young flora which has developed since the end of the atmospheric tests (all previous vegetation having been burned during these tests).

Because of the similarities between the west zone and the Denise area in the north, the results from Denise, Dindon and Faucon are discussed together in subsequent sections.

Fangataufa (Kilo, Empereur, Pavillon, Terme sud)

Fangataufa is smaller than Mururoa and has no living area. The sampling locations named above are included on the map of Fangataufa in Fig. 8. One barge test was carried out there, near the Frégate area. However, according to French information, most of the fallout from this test was deposited to the northwest, in the Kilo–Empereur area. This northwestern area shows evidence of local test fallout, but the rest of the atoll has low levels of residual activity. The landscape and vegetation are quite similar to those of Mururoa, although there are far fewer coconuts. The soil consists of coral bedrock, coral debris and sand.

Tureia (Fakamaru)

Tureia is the nearest inhabited atoll to Mururoa and Fangataufa. The village of Fakamaru is at the northern tip of the island. In order to assess the contemporary radiological situation at the atolls and involved areas, it was necessary to evaluate dose rates to the inhabitants of Tureia. French monitoring information was available, but a limited sampling programme (topsoil, soil profiles, vegetation and coconuts) was included in the campaign of the Study. Furthermore, a hypothetical population on Mururoa would be assumed to have similar living habits and diets to those of the Tureian population, and therefore any information on levels of activity in local foodstuffs, from which concentration factors could be deduced, was considered valuable.

4.3 1.4. Sample types

Aerosols

One potential route of exposure is inhalation of resuspended radioactive particles. As in the French environmental monitoring programme, air was sampled in the Mururoa living area and in the airport zone. Three high flow rate air samplers were used at each site The filters were collected daily and initially measured on Mururoa for gross alpha and beta activity (after a delay of five days in order to allow for the decay of the short lived progeny of radon). More extensive measurements on the filters were carried out later, at the Seibersdorf laboratory. The filters were measured for gamma activity and then ashed for alpha and beta activity determinations. Because of the very low concentrations of atmospheric activity, the set of 53 filters from the living area (Anémone) and the set of 27 filters from the airport zone were each combined, giving just one sample for each site for the alpha activity measurements.

A planned collection of aerosols on Fangataufa was not performed because of difficulties in maintaining electricity generators and aerosol samplers in operation for a duration of one week. Fangataufa is a deserted atoll, sometimes inundated by the sea, and the French logistics support could not provide electricity generators in this location

Soils

A knowledge of the total soil contamination makes it possible to estimate the deposition of various radionuclides, whereas the distribution of activity with depth provides information about the transfer of radionuclides through soil (and is also necessary for the calibration and self-shielding corrections of in situ gamma measurements). Depth profiles would be expected to change with time, so some difference between the Study results and those published earlier in the French reports could be anticipated.

Topsoil samples were collected using the procedure and the collection template designed and constructed for the French monitoring programme. This allowed samples of the top 2 cm of soil over an area of 20 cm × 30 cm to be collected Depth profiles were taken by scraping off the top 2 cm layer with the template and coring the next 40 cm with a French coring tool of 10 cm × 10 cm The 40 cm core was divided into four 10 cm layers in order to study radionuclide migration in the soil.

In some areas, including the airport zone and Faucon, the collection of soil cores was not possible at all intended locations, because of the presence of coral debris, sand or groundwater in the lower layers Such problems also hampered the collection of soil cores on Tureia.

Loose coral and sand

In areas where no soil was available, loose coral and sand samples were collected to obtain information about surface contamination. Sand and loose rocks on the

beach are continuously subject to disturbance and mixing by waves and storms. Random sampling was considered to be the most appropriate scientific procedure to obtain unbiased information on the contamination of a given area. Beach sand samples were therefore collected by taking a number of samples from points chosen at random within the area of interest and then mixing them to give one composite sample representing the area as a whole. Loose coral rock was also collected at the beach in a largely random way, but with a preference for the older rocks (indicated by their darker colour, resulting from their exposure to air and sun).

Coral bedrock cores

Cores of coral rock were taken to investigate the downward migration of radionuclides originally deposited on the surface This information was necessary to calculate the total radionuclide deposition per unit surface area. The vertical concentration profile is also an important parameter for the calculation of the overall radionuclide inventory from in situ gamma spectrometry. Although it was expected that most of the radionuclide activity would have remained in the top layers, migration through fine channels in the bedrock could not be excluded.

The cores were cut using a coring device designed for use with concrete Cores generally had a diameter of 14 cm and the core length ranged between 10 and 40 cm, depending on the location and structure of the bedrock. After gamma spectrometry measurements, all cores were sliced horizontally, two 1 cm long sections being removed from the top of the core (the top layers of the coral) and the remainder being cut into sections of 10 cm

Hot spots

On the safety trial sites (Colette and the neighbouring motus), a heterogeneous distribution of activity was expected, but the only information available prior to the sampling campaign was the average residual surface contamination of ^{239}Pu in the area. This was reported to be less than 1 MBq/m^2, averaged over areas of 20 m × 20 m, following the final cleanup operations on the motus of Colette, Ariel and Vesta (French Liaison Office Document No. 2).

From a short survey using a sensitive contamination monitor, a number of hot spots were detected which indicated a non-uniform distribution of ^{241}Am and ^{239}Pu (hot spots were defined as areas smaller than 20 cm^2 with ^{241}Am activity exceeding 50 Bq).

Two active particles were identified and isolated on Colette and collected for further analysis. Samples likely to contain other active particles (sand, loose coral rock, etc., from Colette) were carefully screened in the Seibersdorf laboratory The lower limit of detection of the screening technique was approximately 70 Bq ^{241}Am. The active particles identified were investigated separately by special methods, as described in detail in the Technical Report, Vol. 1.

To learn more about the spatial distribution of hot spots, a 10 m × 10 m area at Colette was chosen at random, and a more thorough survey was carried out within that area As time was available for only one survey of this kind, and the area chosen was not necessarily representative of the whole of the Colette motu, conclusions derived from this survey may not be of general applicability. However, any other area would have had the same associated uncertainty. The map of surface contamination levels (Fig. 20) was made available by the French Liaison Office only after the sampling campaign had been completed The map could have provided some guidance for the measurements, although the French location markers on the site had disappeared.

Vegetation

No vegetables or fruit trees are grown on Mururoa or Fangataufa, except for a few specimens in private gardens in the Mururoa living area, grown on soils shipped from other areas of French Polynesia, which would not be representative of plants grown under natural conditions Nevertheless, it was considered desirable to obtain information on radionuclide transfer characteristics from soils to plants that might be grown by a hypothetical population of atoll dwellers. In the absence of vegetables, tree and bush leaves were sampled as a substitute, but these could be expected to provide only a general indication of likely radionuclide uptake by edible plants. More specific data were obtained for coconuts.

The soil quality on the atolls is poor, with a high calcium content and a deficiency in potassium, iron and magnesium. Large amounts of salt come from the ocean and little humus is available These factors are responsible for the poor flora on the atolls. Only two types of high vegetation are found in most parts of the atolls: *Argusia argentea* and *Casuarina equisetifolia* (the ironwood tree). Leaf samples were taken from these trees. In addition, some types of low vegetation (*Pemphis acidula* and *Scaevola fructesens*) were collected in all areas *Guettarda speciosa*, *Pandanus tectorius* and *Cocos nucifera* (coconut) could be collected only in certain regions of the atolls.

Vegetation was either hand picked (e.g. leaves) or cut with a knife. Because of the frequent rains, and in

accordance with the French protocol, the samples were not washed before drying (the frequent and heavy tropical rains effectively wash any resuspended particles from the vegetation; the protocol was, therefore, considered to be adequate for the purpose of the Study). Because of this, no data are available on the contamination of leaves by resuspension of soil particles, but it was expected that the aerosol samples taken in the living area could provide some relevant information on this matter.

Coconuts

Coconut palms were introduced to Mururoa about a hundred years ago, but there has been no attempt to cultivate them on Fangataufa. As they play a very important role in the diet of Polynesians, coconuts were collected in several parts of Mururoa and Tureia, and a few isolated samples were taken from Fangataufa. The coconuts were chosen according to their ripeness, in order to have samples of both coconut water and flesh (copra).

The coconuts were hand picked and opened, and the fluid was transferred directly into a 10 L container. The flesh was separated from the shell and placed into plastic bags. Because of the high water content of the flesh (the weight ratio of ash to wet coconut flesh — the copra — ranges between 0.009 and 0.016), it was necessary to collect a large number of coconuts for one sample. One coconut water sample represents 15–20 coconuts, while one copra sample was derived from about 12–15 coconuts.

In situ measurements

Dose rate and contamination monitors were used on-site as a screening method to indicate places of interest for sampling, and particularly areas of high activity. For residual alpha activity measurements on surfaces, a hand-held probe with a detection efficiency for ^{241}Am of 35% was used.

In situ gamma spectrometry with high purity germanium detectors was used to collect information on surface and subsurface radionuclide inventories. The technique permits rapid and efficient identification and quantification of gamma emitting radionuclides in the soil at a specific site. A detector was positioned at a defined height (usually 1 m) above ground level and a spectrum was collected of gamma emitters in the ground A major source of uncertainty for this type of measurement is usually poor knowledge of the depth distribution of the radionuclide of interest within the soil. In this case, however, the distribution was known from the core profiles, and the measurements were corrected for the decrease of activity concentration with depth.

A total of 106 gamma spectra were recorded at selected locations on Mururoa and Fangataufa with three portable gamma spectrometers. Five control spectra were recorded at the laboratory on Mururoa and a few repeat measurements were carried out to assess reproducibility. A range of radionuclides — ^{60}Co, ^{137}Cs, ^{155}Eu, ^{239}Pu and ^{241}Am — were identified and quantified at various locations.

Summary of sample collection and analysis

During the terrestrial sampling campaign, a total of 299 samples were collected from Mururoa, Fangataufa and Tureia After screening of all samples for their activity content, 198 were analysed. The majority of the samples not analysed were of very low activity and came from the lower parts of core profiles The number of samples collected by the independent sampling campaign was much smaller than the number collected and analysed by the French monitoring programme over many years, but was considered sufficient to provide the basis for a reliable audit of the French data.

Gamma spectrometric analyses were carried out on 192 samples, 176 of which were measured by ALMERA network members and 16 by the Seibersdorf laboratory. Alpha and beta emitting radionuclides were analysed in 178 samples, 139 by the ALMERA network members and 39 at Seibersdorf. Well established radiochemical separation procedures and measurement methods were used by all laboratories involved in the analysis. A review of the analytical methods used for the different isotopes is provided in the Technical Report, Vol. 1 Measurements were performed in duplicate and triplicate as part of the validation and quality control measures. This resulted in a total of 941 individual determinations for the alpha emitting nuclides ^{238}Pu, $^{239+240}$Pu and ^{241}Am, 78 determinations for ^{90}Sr and 2520 results for the different gamma emitting radionuclides. A summary of the number of samples measured, categorized according to material and location, is given in Table XII.

4 3.1.5. Quality assurance

Sampling campaign

The whole sampling process, as well as the preparation, storage and distribution of the samples, was carried out under stringent quality assurance measures in order to maintain sample identity and integrity throughout the Study. Each sampling site, together with an information board showing the sample code and the date and time of

TABLE XII. SUMMARY OF MEASURED TERRESTRIAL SAMPLES

Location	Matrix	Number of measured samples
	Mururoa	
Anémone	Sand	2 samples
	Topsoil	8 samples
	Soil profile	1 profile (5 layers)
	Ironwood tree leaves	1 sample
	A argentea leaves	1 sample
	Coconut flesh	1 sample
	Coconut water	1 sample
	Air filter	2 samples
Kathie	Loose coral rocks	2 samples
	Low plant leaves	2 samples
	Ironwood tree leaves	1 sample
	A. argentea leaves	1 sample
Airport zone	Topsoil	13 samples
	Soil profile	1 profile (3 layers)
	Air filter	2 samples
Camélia	Loose coral rocks	3 samples
	Sand	1 sample
	Ironwood tree leaves	1 sample
	A argentea leaves	1 sample
Edith	Loose coral rocks	2 samples
Denise	Coral bedrock	1 profile (5 layers)
	Loose coral rocks	4 samples
	Ironwood tree leaves	1 sample
	A argentea leaves	1 sample
Colette	Coral bedrock	5profiles (17 layers)
	Loose coral rocks	4 samples
	Sand	2 samples
Dindon	Coral bedrock	1 profile (4 layers)
	Sand	2 samples
	Ironwood tree leaves	1 sample
	A argentea leaves	1 sample
	Coconut flesh	1 sample
	Coconut water	1 sample
Faucon	Loose coral rocks	2 samples
	Moss–sand	2 samples
	Sand	2 samples
	Topsoil	23 samples
	Soil profile	1 profile (5 layers)
	Low plant leaves	2 samples
	Ironwood tree leaves	1 sample
	A argentea leaves	1 sample
	Coconut flesh	1 sample
	Coconut water	1 sample
	Fangataufa	
Kilo	Coral bedrock	1 profile (3 layers)
		1 sample (mixed without cutting)
	Loose coral rocks	4 samples
	Sand	4 samples
	Topsoil	8 samples
	Soil profile	1 profile (5 layers)
	Low plant leaves	3 samples
	Ironwood tree leaves	1 sample
	A argentea leaves	1 sample
	Coconut flesh	1 sample
	Coconut water	1 sample
Pavillon	Loose coral rocks	2 samples
	Topsoil	4 samples
	Soil profile	1 profile (5 layers)
	A argentea leaves	1 sample
	G speciosa leaves	1 sample
	P tectorius leaves	1 sample
Terme sud	Topsoil	4 samples
	Low plant leaves	1 sample
	A argentea leaves	1 sample
	Tureia	
Fakamaru	Soil profile	1 profile (5 layers)
	Low plant leaves	1 sample
	A argentea leaves	1 sample
	Coconut flesh	1 sample
	Coconut water	1 sample
Total	141 samples + 14 profiles (57 layers)	

sampling, was photographed and the sampling operations were recorded with video cameras. On a daily basis, the data were transferred to a personal computer and also stored on floppy disks. During the sample collection and on-site preparation, special care was taken not to contaminate or cross-contaminate the samples, and

all sample collection and preparation details were documented

Measures were taken to avoid cross-contamination between samples at all stages of sample processing. On Mururoa the preparation of the samples was carried out in different laboratories, according to their expected activity level At the Seibersdorf laboratory, the samples were analysed in the order of increasing expected activity. Whenever possible, the samples distributed to the ALMERA network laboratories were selected from samples having a similar activity level in order to avoid cross-contamination during analysis.

A major concern was the homogeneity of the processed samples before their distribution to the different laboratories for analysis. Sample homogeneity is important in order to ensure comparability of the results. Special care was therefore devoted to the final homogenization The homogeneity was verified by gamma spectrometric analysis of several subsamples before shipment to the ALMERA network laboratories. In general the homogeneity proved to be satisfactory.

For the samples taken at Colette, the presence of active particles had to be expected Therefore, all laboratories were requested to perform double determinations and to check any undissolved parts of the samples, which could provide an indication of active particles.

In situ measurements

Each measurement was documented, unambiguous codes were assigned to record the spectra and measurement locations, and the locations were photographed for future reference and inspection. The energy calibration of the detector was checked on a daily basis. All spectra recorded were evaluated on-site, inspected for anomalies and saved in duplicate on computer disks.

The in situ response efficiency of the gamma spectrometer was modelled for a standard soil matrix using a Monte Carlo approach (Briesmeister 1993). The accuracy of this calculated efficiency curve was checked via a series of measurements with calibrated point sources containing ^{241}Am and ^{152}Eu (which has a gamma emission of similar energy to ^{239}Pu). The calculated efficiency agreed with that measured to within 5–7%, which is of the same order as their combined uncertainties

Sample measurements

The ALMERA network members involved in the analysis were selected on the basis of an intercomparison analysis on one soil and one sediment sample. These materials were well characterized, being taken from the IAEA's set of reference materials. The performance of the laboratories in this intercomparison was evaluated on the basis of their Z scores (the ratio of bias to uncertainty, according to the method of Thompson and Wood (1993)) for gamma spectrometric results and the measurement of ^{90}Sr and alpha emitting nuclides. The SMSRB laboratory, which performed the historical measurements in the South Pacific, participated in the intercomparison and achieved very good Z scores for all radionuclides. This provided evidence for the quality of the historical French results and a strong basis for their comparability with results of the current campaign.

The participating laboratories were requested to document fully their measurements on all samples They were also requested to include systematic measurements on reference materials and to report the results together with the results for the measured samples. Cross-checks between external laboratory results and those of the Seibersdorf laboratory were carried out

Except for the coconut flesh and coconut water, the results for all materials in all locations were based on measurements carried out on at least two samples

Data reporting and evaluation

The documentation provided by the participating laboratories and the measurement results, including those obtained for reference materials, were screened and any discrepancies, ambiguities or doubtful data were investigated and clarified. The activity concentration ranges reported here have been established from the individual results and independently cross-checked for consistency with the available documentation

4.3 1.6 Results and discussion

Reporting format

The French monitoring data obtained in the past were based on a large number of samples, providing either ranges of activity concentrations or, in the case of homogeneous data sets, average values. In most cases, the limited number of measurements in the campaign of the Study, and the observed differences from one sample to another, meant that average values were unlikely to be meaningful The ranges of observed values were therefore indicated and compared with the more extensive French data The results were arranged according to sample location to provide an overall picture of the local situation. Summary views of the ranges observed for $^{239+240}$Pu and for ^{137}Cs are presented in Figs 21 and 22, respectively. For the majority of the combinations of location and sample type, the ranges

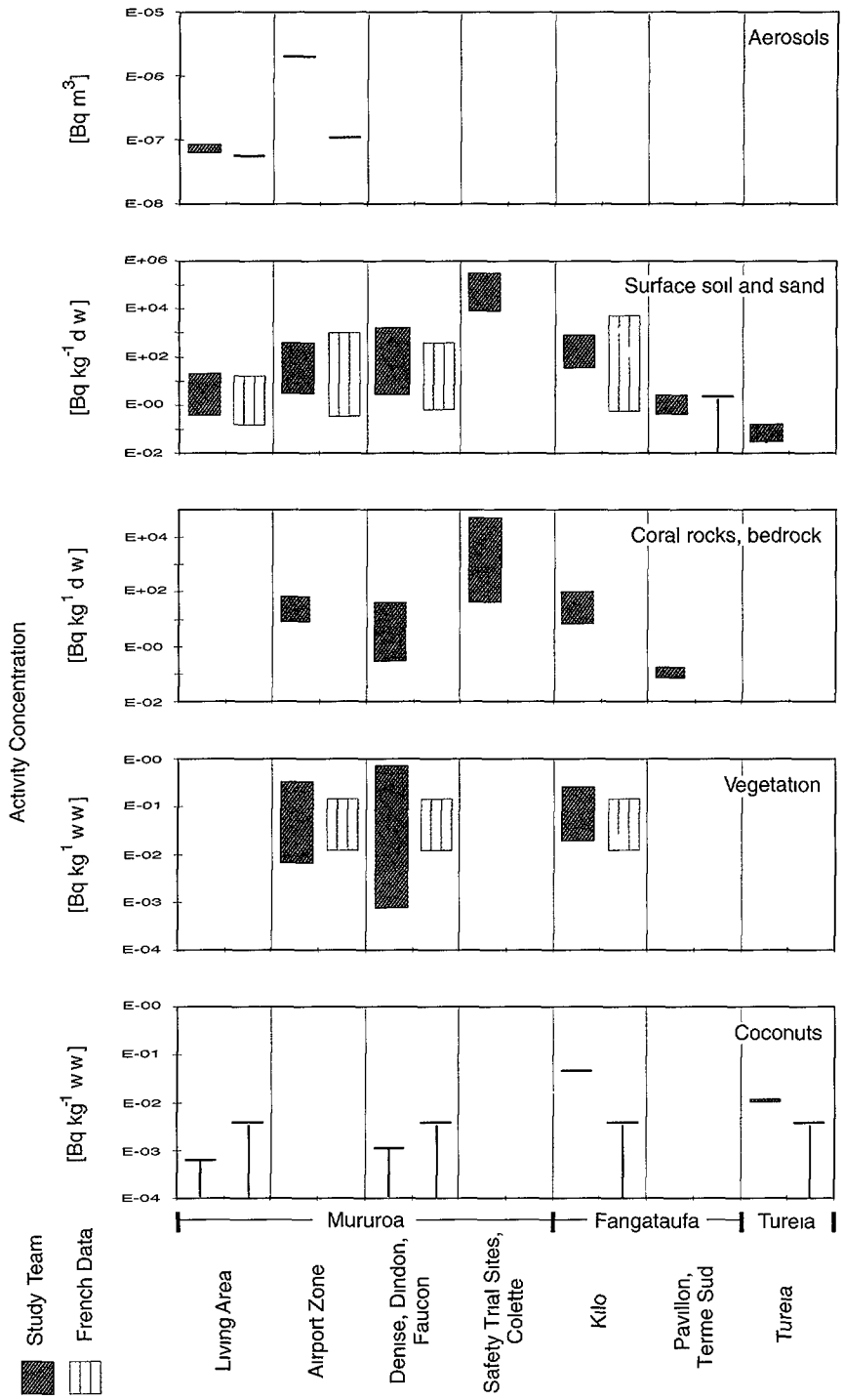


FIG 21 Comparison of activity concentrations of $^{239+240}Pu$ measured during the 1996 sampling campaign with data provided by the French Liaison Office (right hand value of each pair).

observed by the Study team and the SMSRB were completely overlapping and hence in satisfactory agreement In some cases, differences were observed. Because of the quality assurance measures applied, such differences have to be considered as significant. Differences can be attributed to the nature of the spot samples taken during the Study, the known small scale heterogeneity of the radionuclide distribution in the physical environment and the biological variability in the accumulation of radionuclides.

The French data used for comparisons are taken from the following sources.

— Aerosol data from Bourlat et al. (1994);

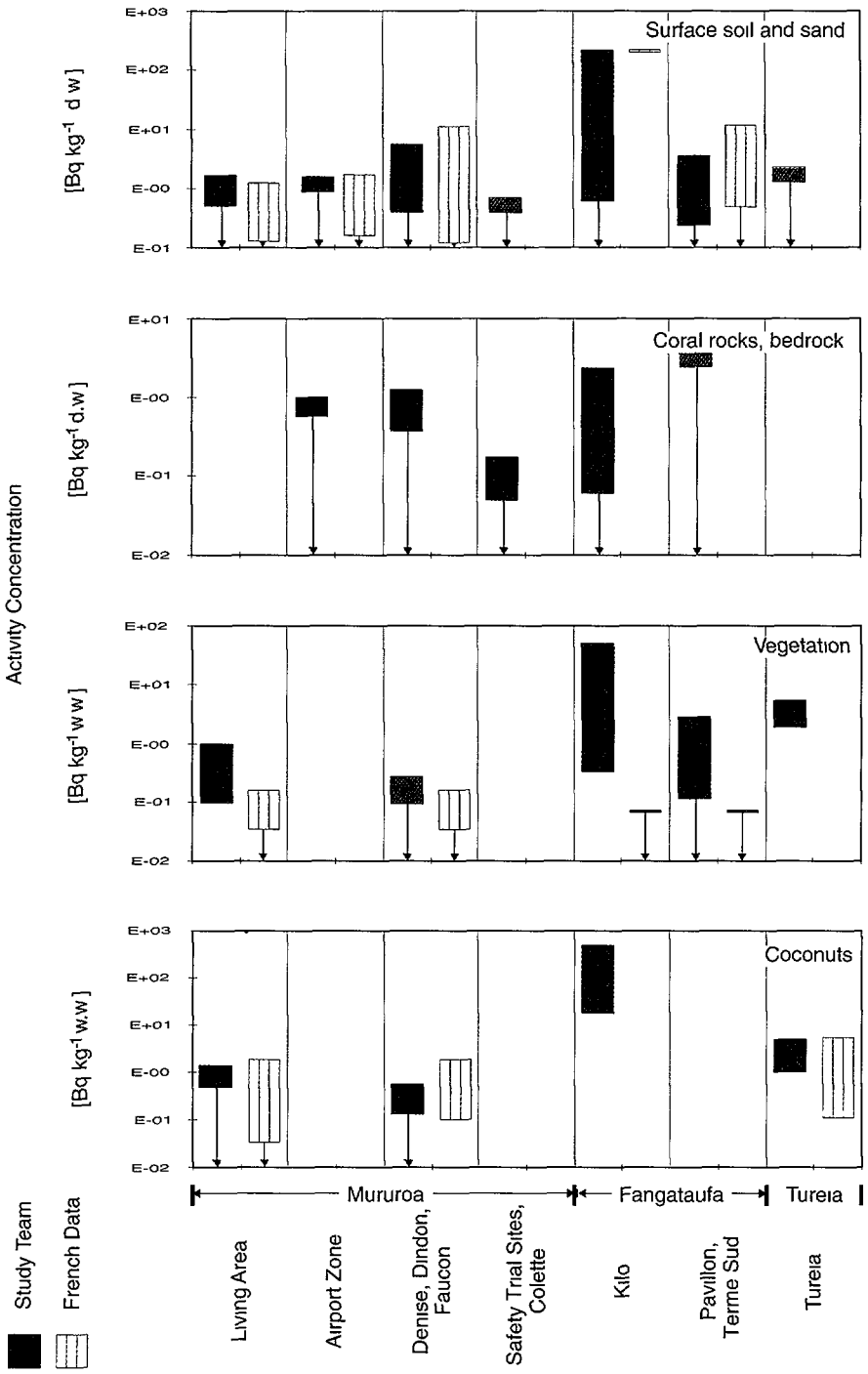


FIG. 22 Comparison of activity concentrations of ^{137}Cs measured during the 1996 sampling campaign with data provided by the French Liaison Office (right hand value of each pair).

— Topsoil data from French Liaison Office Document No. 2;
— Environmental data from French Liaison Office Document No. 3.

No attempt was made to harmonize the lower limits of detection (LLDs) between the different laboratories involved, because they are dependent on the individual methods and instruments used, as well as the sample counting times.

Living area on Mururoa (Anémone, Martine, Léa)

The measured concentration of $^{239+240}Pu$ in aerosols from the living area averaged 75 nBq/m^3, which, given the likely influence of differences in weather conditions

and human activities during the sampling periods, is in satisfactory agreement with the French value of 56 nBq/m^3.

In situ gamma measurements in this area did not show any gamma emitting nuclides above the detection limit.

The concentrations of ^{137}Cs measured in the living area topsoil, loose corals and sands were all less than 1.6 Bq/kg. This is in agreement with the French results, which range from below the detection limit up to 1.72 Bq/kg The activity concentrations for $^{239+240}$Pu ranged from 0.37 to 18.4 Bq/kg and show a large degree of overlap with the French results.

The $^{239+240}$Pu and ^{241}Am activity concentrations obtained by the Study team from soil profiles displayed a homogeneous distribution down to 22 cm, a clear indication of disturbed soil. The values were low, of the order of a few becquerels per kilogram (dry weight), and were consistent with the generally low activity concentrations in the living area It appeared that ^{238}Pu followed a different pattern and was detectable only in the 12–22 cm depth interval; the reason for this is not understood.

Concentrations of ^{137}Cs in vegetation and fruit samples collected in the living area generally agreed with the corresponding French measurements. Coconut flesh samples yielded values below the LLD of 0.0006 Bq/kg (wet weight) for alpha emitting nuclides and around 0.7 Bq/kg for ^{137}Cs.

Airport zone (Kathie, Jeanne, Irène, Camélia)

Aerosol activity concentrations of 2 μBq/m^3 for plutonium isotopes, sampled at the western end of the airfield (Irène), were higher than the value of 0.11 μBq/m^3 reported in the French data for the eastern end close to the living area (Kathie).

The Study team's measurements in the airport zone clearly showed higher topsoil activity concentrations for $^{239+240}$Pu than in the living area, ranging from 3 to 350 Bq/kg. The values were in agreement with the French data, and are consistent with the fact that some debris from the Colette area was used for the construction of the airstrip. In addition, loose coral rocks collected by the Study team in the Kathie area (between the living area and the airport) showed levels of plutonium up to three times higher than the topsoil samples from the same area

The ^{137}Cs activity concentration levels measured in this zone were below 0.5 Bq/kg, in agreement with the French data and similar to the levels in the living area.

The Study team's soil profiles in the airport zone showed a constant concentration of the alpha emitting isotopes ^{238}Pu, $^{239+240}$Pu and ^{241}Am down to 22 cm, indicating a disturbed soil. No core samples could be taken at deeper levels because of the presence of coral rock debris and water The results from in situ gamma spectrometric measurements indicated ^{241}Am concentrations between 400 and 1500 Bq/m^2, and overlapped the ranges obtained from the soil profiles.

Concentrations in vegetation samples from this zone completely overlapped the French results and were in the range 0.01–0.32 Bq/kg (wet weight) for $^{239+240}$Pu. The ironwood tree leaves were in the upper part of the range (above 0.18 Bq/kg), whereas the leaves of *A argentea* and low vegetation consistently showed values below 0.07 Bq/kg. The ^{137}Cs activity concentration was more uniform and ranged from 0 03 to 0.15 Bq/kg. No coconut samples were collected in the airport zone.

North zone (Denise) and west zone (Dindon, Faucon)

More topsoil samples (23 in total) were taken from Faucon than from other areas because it was expected to have been affected most by fallout from the barge tests. Most of the $^{239+240}$Pu concentrations measured by the Study team, ranging from 0 6 to 360 Bq/kg, were in agreement with the French results. However, significantly higher values, between 1200 and 1600 Bq/kg, were found in three Study team samples. The activity concentrations of ^{238}Pu, $^{239+240}$Pu and ^{241}Am were clearly correlated.

The distribution patterns for ^{90}Sr and ^{137}Cs were completely different from one another and from the patterns for actinides. The activity concentrations of ^{90}Sr in the north and west zones, ranging between 0.6 and 23 Bq/kg, were the highest found on Mururoa. The Study team's results for ^{137}Cs were below 3.3 Bq/kg, and well within the range of the French data obtained a few years before. The maximum ^{137}Cs value observed by the Study team was a factor of 3 lower than the maximum reported by the French Liaison Office.

The soil activity profile in the Faucon area showed the distribution expected from an undisturbed area. The core had a fairly low level of activity and the depth profile was similar to profiles reported by the French authorities. The data showed that about 90% of the activity was located within the top 22 cm. The soil activity profile taken by the Study team at Denise, however, showed a constant $^{239+240}$Pu concentration down to 24 cm depth, whereas ^{241}Am displayed a regular undisturbed profile. In all cores from this area, ^{238}Pu and ^{241}Am levels were close to or below the detection limit

In situ gamma spectrometric measurements showed almost no ^{241}Am in the Faucon area but relatively high levels, ranging from 2 to 14 kBq/kg, in the Denise area,

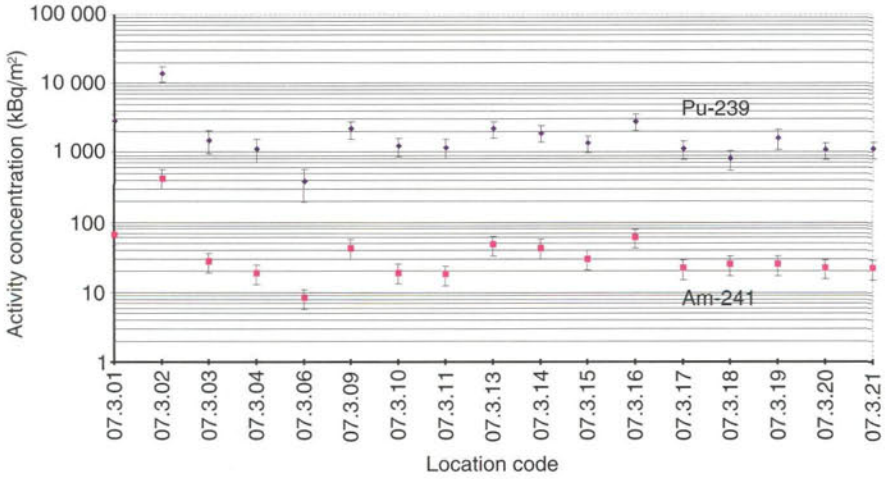


FIG. 23. In situ gamma spectrometry measurements on the Colette motu of Mururoa.

which is much closer to Colette and the sites of the safety trials.

Activity concentrations of $^{239+240}$Pu found by the Study team in vegetation from the Faucon area ranged from 0.8 to 19 mBq/kg (wet weight). The ironwood tree leaves displayed values in the upper part of the range, the other plants typically giving values a factor of 10 lower. The ironwood tree results in the Study were, however, lower than the French values, which ranged from 60 to 140 mBq/kg. The Study team's results for vegetation from the Denise area were in the same concentration range as for Faucon, and in this case were in agreement with the French data. Once again, the ironwood tree leaves showed a concentration 10 times higher than in other plants, indicating the ability of their needle shaped leaves to concentrate radionuclides.

Alpha emitting nuclide concentrations in coconut samples from this area were below the LLD of 1 mBq/kg. The ^{137}Cs concentration was similar to the very low levels observed in the living area: about 0.28 Bq/kg for Denise and 0.13 Bq/kg for the Dindon area. These data were within the range of the French results.

Safety trial sites (Colette, Ariel, Vesta)

The only residual radionuclides of interest in the area of the safety trial sites were ^{239}Pu and ^{241}Am. Two of the safety trials conducted in the Colette area are reported to have released some fission energy (Table III in Section 3), but they did not appear to have left behind any detectable quantity of long lived fission products. The results obtained by the Study team for the Colette area were based on collected coral rocks and sand, coral bedrock depth profiles and in situ gamma spectrometry. The profiles indicated that virtually all (over 99%) of the activity was within 1 cm of the surface. On this basis, activity concentrations were calculated for ^{239}Pu and ^{241}Am from the in situ gamma spectrometric data, assuming an exponential depth distribution within the coral bedrock and a relaxation thickness for self-absorption of 0.3 g/cm^2 (considering the great unevenness of the surface of the Colette motu, with many cracks and partial coverage by coral debris and sand, it was thought unrealistic to use a smooth surface model of zero absorption for the calculations).

The ^{241}Am and ^{239}Pu inventories, calculated by the Study team from the 59.5 and 129 keV gamma emissions, respectively, are shown in Fig. 23. The data were clustered between 1 and 3 MBq/m^2 for ^{239}Pu and between 20 and 70 kBq/m^2 for ^{241}Am. The ^{239}Pu/^{241}Am activity ratios were clustered around two values, 45 and 60, probably reflecting the different ages and degrees of purity of the plutonium used in the various safety trials. Figure 24 shows the results of the in situ gamma spectrometry measurements superimposed on the SMSRB's activity map of the same location. The LLD for ^{239}Pu with this technique was 0.8 MBq/m^2. It appears that the ^{239}Pu activities measured by the Study team using gamma spectrometry in 1996 were approximately two to six times higher than the values measured by the French scientists in 1987. Moreover, it appeared that the French cleanup criterion — 1 MBq/m^2, averaged over 20 m × 20 m areas — was only partly met.

The difference between the values reported by the SMSRB and the Study team can be explained by considering the different measurement techniques used. The SMSRB's values were based on the measurement of

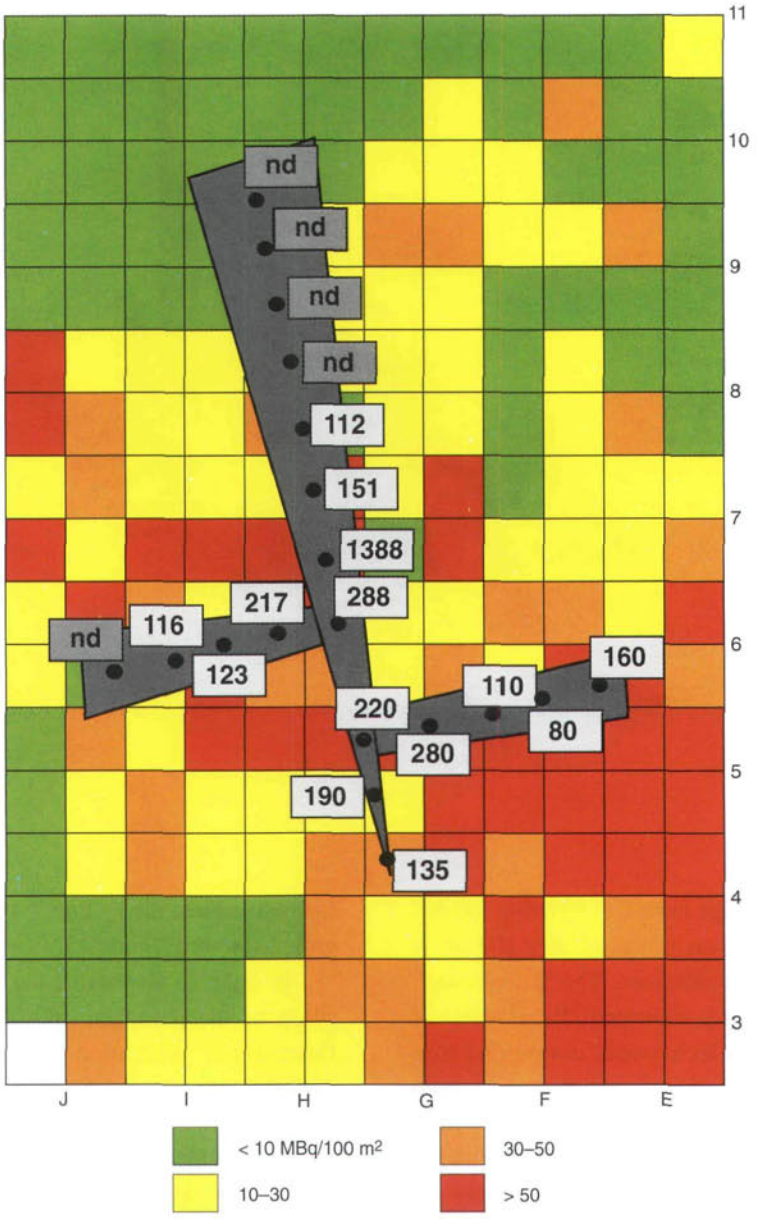


FIG. 24. Comparison of ^{239}Pu activity levels on the Colette motu of Mururoa as determined from in situ gamma spectrometry performed by the Study team and the French data (cf. Fig. 20). (nd: below LLD.)

^{241}Am using sodium iodide detectors, which are sensitive to changes in temperature and require a threshold setting to eliminate low energy background radiation. Furthermore, a single value for the ^{239}Pu/^{241}Am ratio was used by the SMSRB to calculate the ^{239}Pu activity, whereas the Study team found this ratio to vary from place to place, clustering around two different values. In the technique used by the Study team, the gamma radiation from ^{239}Pu was measured directly with germanium detectors. Therefore, the higher results obtained by the Study team are considered to be more representative of the current situation.

The levels of surface activity (Bq/m^2) determined by in situ gamma spectrometry were consistent with the activity concentrations of ^{239}Pu and ^{241}Am in core samples determined by radiochemical analysis in the laboratory.

The non-uniform nature of the distribution of the residual activity in the Colette area, with the presence of hot spots and particulate contamination, is essentially different from the residual activity reported for the other locations. Figure 25 shows the results of the Study team's search for hot spots — areas with ^{241}Am activity exceeding 50 Bq/20 cm^2 — on the 10 m × 10 m area in the middle of the motu chosen for examination (Fig. 20). The data indicate that the hot spots were very unevenly distributed. On the basis of ^{241}Am measurements and an assumed ^{239}Pu/^{241}Am ratio of 50, hot spot activities for

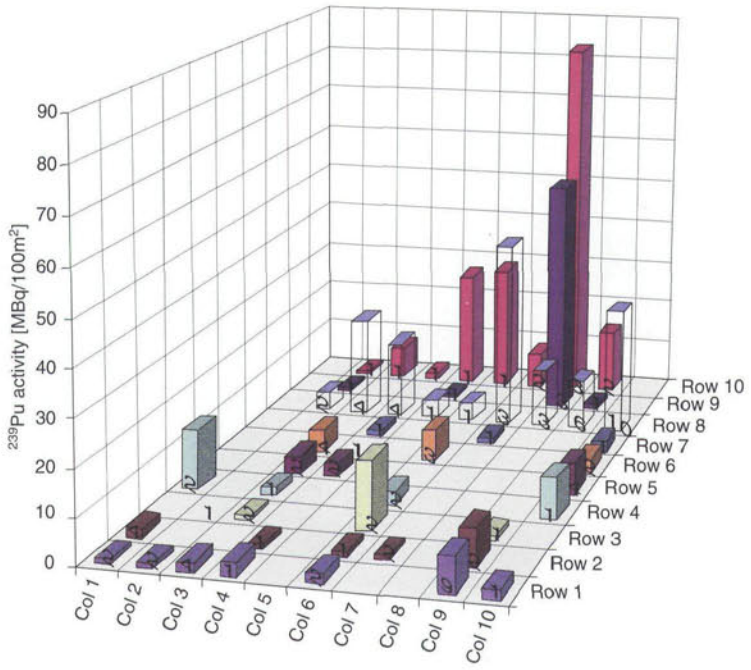


FIG. 25. Activity concentration of ^{239}Pu and number of hot spots in each square metre of a 10 m × 10 m square on the Colette motu of Mururoa.

^{239}Pu were calculated to range from 1 to 83 MBq/100 m^2. When all hot spot activity was averaged over 100 m^2, a value of 5 MBq/100 m^2 was obtained. The 'background' activity measured in this area indicated ^{241}Am levels of the order of 22 kBq/m^2, which would correspond to a ^{239}Pu activity of 110 MBq/100 m^2. The French cleanup criterion of 100 MBq/100 m^2 was therefore virtually achieved in this area. It also appears that the detected hot spots account for less than 5% of the overall activity per unit area of ^{239}Pu. The frequency distribution of hot spots found by the Study team shows 50% with activity below 30 Bq/cm^2, 75% below 60 Bq/cm^2, 90% below 120 Bq/cm^2 and 95% below 180 Bq/cm^2; a few spots with up to 400 Bq/cm^2 were identified.

Two active particles were identified in situ and collected on the Colette motu during the sampling. A search for further active particles in the sand and coral rock samples collected in the area was carried out later at the Seibersdorf laboratory. Thin layers of the samples of fine coral debris were scanned, and 14 particles with a ^{239}Pu activity exceeding 3500 Bq were identified and isolated from the debris. In samples consisting of loose coral pieces, active particles were sought on the surface of the rocks and, when found, removed by crushing the rock. Four particles were collected in this manner. All 20 particles, including the two identified and isolated on Mururoa, were analysed by gamma spectrometry; the ^{239}Pu activities ranged from 5 kBq to 1 MBq and, except for two values, the ^{239}Pu/^{241}Am ratios clustered in two groups, around 20 and 45.

In order to investigate the morphology and composition of the particles, optical microscopy and X ray fluorescence were used. Only preliminary results are available because the Study team was reluctant to use destructive techniques on the very limited number of particles, which were assumed to be quite heterogeneous. The optical imaging showed that the particle dimensions ranged from 200 to 500 μm and therefore would not represent an inhalation hazard. The analytical results showed that calcium, chlorine and iron were present, as would be expected from the calcium carbonate in the coral debris, the salt of the sea water and the iron associated with structural materials used in the test devices. Other metals such as manganese, nickel, chromium, cobalt and titanium were also identified, and might reflect the composition of the containers used for the fissile material in the trials. In addition to the plutonium and americium indicated by the radiometric data, uranium and neptunium were also identified by X ray fluorescence, at concentration levels (by weight) about 10–100 times lower than the plutonium. They probably result from impurities in the plutonium used for the tests. Microscopic quantitative analyses showed large variations in the abundance of different elements between the particles, and even within a single particle.

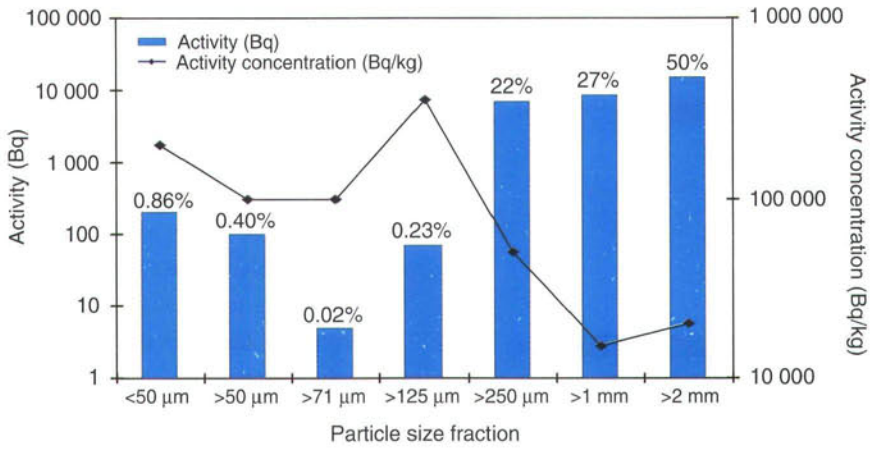


FIG. 26. Activity levels and concentrations in fine coral debris from the Colette motu, Mururoa, as a function of particle size.

To obtain information on the activity distribution as a function of particle size, about 1 kg of fine coral debris collected on the Colette motu was sieved into seven different fractions, ranging from 2 mm down to less than 50 μm. The various fractions were measured by gamma spectrometry and the results are shown in Fig. 26. The main conclusion was that about 99% of the activity was associated with particles larger than 250 μm. The highest activity concentrations were found, as expected, in the fractions with the smaller diameters, but the fraction smaller than 50 μm, which might contain particle sizes of concern for inhalation or incorporation in wounds, represents only about 1% of the total activity.

External dose rates at safety trial site, Colette

The measurements by high resolution gamma spectrometry on the Colette motu permit an estimate of the photon radiation field. The effective dose rate that an adult would experience on Colette can be calculated from the measured radionuclide concentrations (^{239}Pu, ^{241}Am) by assuming a given distribution within the coral rock and using appropriate conversion factors. The effects of the elemental composition of the soil, the depth profile of the activity and the angular distribution of the photon fluence must also be taken into account. The details of the calculations, the conversion factors used and the source of the data are provided in the Technical Report, Vol. 1. The average areal activity concentrations were calculated to be 2.3 MBq/m^2 for ^{239}Pu and 57 kBq/m^2 for ^{241}Am. The corresponding annual effective doses to a hypothetical adult spending 100% of his/her time outdoors on Colette would be, respectively, 77 and 34 μSv, giving a total dose rate of 111 μSv/a. If an ideal surface distribution were assumed, rather than an exponential depth distribution, this total dose rate would increase to 620 μSv/a. The standard deviation on these values is about 50%.

Fangataufa (Kilo–Empereur, Pavillon, Terme sud)

Kilo–Empereur is the area of Fangataufa believed to have been most affected by the September 1966 barge test. According to the French data, a 3.5 km strip on the lagoon side of the rim between north Frégate and Empereur shows elevated levels of plutonium in soil ranging from 100 to 5000 Bq/kg, but quite unevenly distributed. The maximum concentrations reported in the French monitoring data were about ten times higher than those measured by the Study team. The French data are corroborated by the soil and bedrock profiles, which show the typical distribution expected from an undisturbed area. In situ gamma spectroscopy measurements by the Study team showed ^{241}Am concentrations in the range 1–2 kBq/m^2, which is consistent with the soil profile values.

The Kilo–Empereur area also displayed the highest concentrations of ^{90}Sr and ^{137}Cs in soil. The French reports gave the highest ^{137}Cs soil concentration in this area as about 200 Bq/kg (measured in 1995), while the Study data ranged up to 13 Bq/kg. The Study survey identified relatively high surface deposition of ^{60}Co, ^{137}Cs and ^{155}Eu in this area, as measured by in situ gamma spectrometry; the values for ^{137}Cs ranged from 1 to 6 kBq/m^2.

Other areas on Fangataufa, such as Pavillon and Terme sud, showed values of the order of a few becquerels per kilogram for the plutonium isotopes and ^{137}Cs, in general agreement with the French results.

The $^{239+240}$Pu activity concentrations for vegetation in the Kilo area ranged between 20 and 250 mBq/kg (wet weight), in agreement with the French results. The

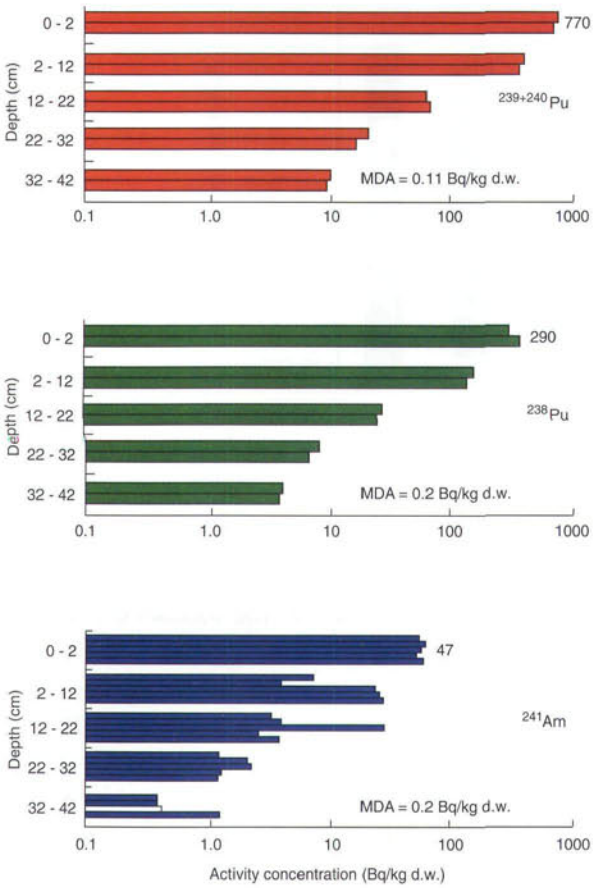


FIG. 27. Activity concentrations of $^{239+240}Pu$, ^{238}Pu and ^{241}Am as a function of depth in soil from the Kilo area of Fangataufa. (MDA: minimum detectable activity.)

activity concentrations of $^{239+240}Pu$, ^{238}Pu and ^{241}Am are illustrated as a function of depth in soil in Fig. 27. The ^{137}Cs levels ranged from the detection limit (0.07 Bq/kg) to 27 Bq/kg. Concentrations of $^{239+240}Pu$, ^{238}Pu and ^{241}Am in coconut flesh were measured at 47, 16 and 3 mBq/kg, respectively. The ^{137}Cs values ranged between 167 and 189 Bq/kg, and concentrations of ^{90}Sr were about 0.45 Bq/kg. These values were the highest measured in the campaign for coconut flesh. In coconut water, ^{137}Cs was measured during the Study at a level of 18 Bq/kg, which is the highest value observed for any coconut water sample. This value is still a factor of 3 lower than the natural activity concentration of ^{40}K (50–80 Bq/kg) observed in all coconut water samples.

Tureia (Fakamaru)

All samples from the inhabited atoll of Tureia were collected in Fakamaru, the only village on the atoll. Trace amounts of $^{239+240}Pu$, between the LLD of 30 mBq/kg and 150 mBq/kg, were measured in the upper layers of one soil core. The concentration of ^{90}Sr was also found to be close to the LLD of 0.6 Bq/kg. In the 12–22 cm depth interval, 90–220 mBq/kg ^{137}Cs was detected.

The gamma spectrometric investigation of low vegetation samples showed only ^{137}Cs, with levels between 3.15 and 3.53 Bq/kg. In *A. argentea* leaves, ^{137}Cs was detected in the range 1.89–2.12 Bq/kg. Traces of ^{60}Co and ^{125}Sb close to the LLD were also found.

Coconuts were sampled in the area from which the soil core was taken. In coconut flesh, traces of $^{239+240}Pu$ were found (around 11 mBq/kg) and levels of ^{241}Am ranged from 1 to 15 mBq/kg. Gamma spectrometry identified only ^{137}Cs, with values between 4.2 and 4.7 Bq/kg, which is in satisfactory agreement with the French value of 5.2 Bq/kg. Only one value above the LLD was found for ^{90}Sr; this was 0.06 Bq/kg, about a factor of 10 below the value for the Kilo area on Fangataufa.

The traces of alpha emitters in coconut flesh should be seen in perspective. The activity concentration of $^{239+240}Pu$ was higher than in the Mururoa samples, but considerably lower than at Kilo on Fangataufa. The values for ^{241}Am in the Tureia samples were lower than the LLD for the samples from Mururoa.

The concentration of ^{137}Cs in coconut flesh is higher for Tureia than for Mururoa, but two orders of magnitude lower than at Kilo on Fangataufa. Throughout French Polynesia, the values reported in French monitoring data range from 0.07 Bq/kg (Gambier Islands) to 11 Bq/kg (Tubuai in the Austral Islands) (French Liaison Office Document No. 3, Vol. 2).

In coconut water, small amounts of ^{60}Co were detected (0.24–0.36 Bq/L) along with around 1.0 Bq/L of ^{137}Cs. These values were higher than the reported French data, which showed an upper limit of 10 mBq/L for ^{60}Co (below the LLD for samples collected from Mururoa and Fangataufa) and ^{137}Cs concentrations ranging from 0.11 to 0.32 Bq/L. As with the coconut flesh, the ^{137}Cs activity concentration measured by the Study team in coconut water was slightly higher than on Mururoa, but much lower than at Kilo on Fangataufa. French monitoring data for the region range from an LLD of 0.013 (Mururoa) to 0.356 Bq/kg (Tubuai).

4.3.1.7. Conclusions of terrestrial monitoring programme

In general, the activity concentrations measured by the Study team were consistent with the French data made available to the Study. In particular, the data for plutonium in surface soil, sand and vegetation samples were completely overlapping at all locations. In many cases, however, French data were not available for comparison.

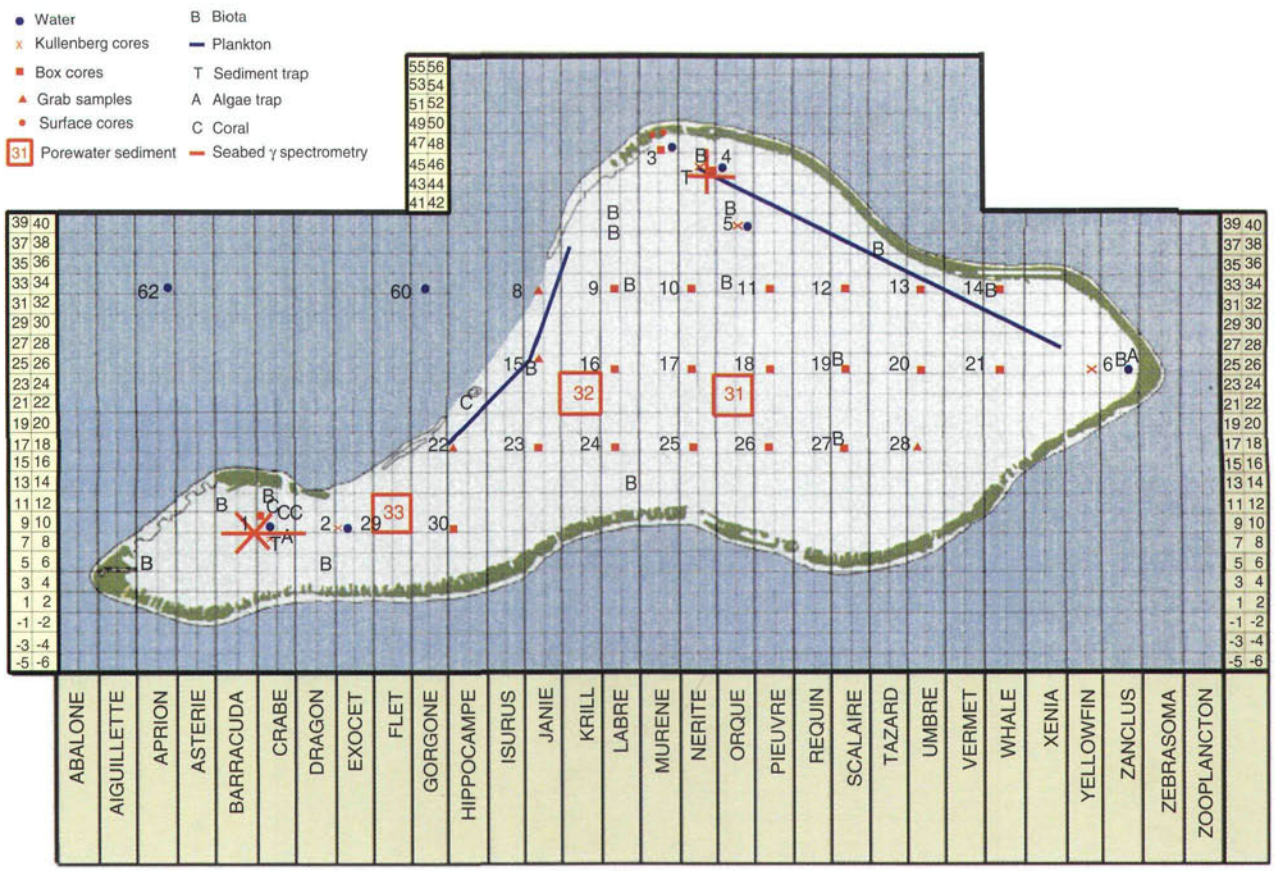


FIG. 28. Aquatic sampling points at Mururoa

On Mururoa, aerosol activity concentrations for plutonium isotopes at the western end (Irène) of the airport zone were considerably higher than the value reported by the French authorities for the eastern end at Kathie; this difference may simply be attributable to the difference in location.

Differences in $^{239+240}$Pu concentrations were also observed in coconut samples from Fangataufa and Tureia, where the Study team found concentrations which exceeded the highest values in the French data by a factor of up to 10. The quality assurance measures described above support the credibility of the individual measurements by the Study team, but the small number of samples and measurements cannot provide the basis for an interpretation of the observed differences, and any attempts in this direction would be purely speculative.

Ranges of ^{137}Cs concentrations found by the Study team in surface soils and sands and in coconuts partly overlapped the ranges quoted in the French reports, but the French data included consistently higher values than those measured in the Study. For the vegetation samples, the French results appeared consistently lower than those obtained by the Study team.

On the Colette motu, the surface ^{239}Pu activity measured by the Study team in limited areas was about three times higher than the average for the Colette motu reported by the SMSRB. The difference can be attributed to the measurement technique used by the SMSRB, which would lead to an underestimation of the ^{239}Pu activity. The major factors leading to this underestimate are the use of the indirect method — measuring ^{239}Pu via ^{241}Am — which necessitates the setting of a detector threshold because of the low resolution of the sodium iodide gamma probe, possible temperature effects on the detector and the assumption of a single average value for the ^{239}Pu/^{241}Am ratio.

Particles containing up to 1 MBq of plutonium were found on Colette and in samples of sand and coral rock collected from the motu. The particles were of very heterogeneous composition on the microscopic scale. The smaller particles (less than 15 μm diameter), which would be the most likely to be inhaled by humans, might contain up to several hundred becquerels.

From the few samples taken at Tureia, it may be concluded that levels of anthropogenic activity in the environment are very low. Concentrations of ^{137}Cs in

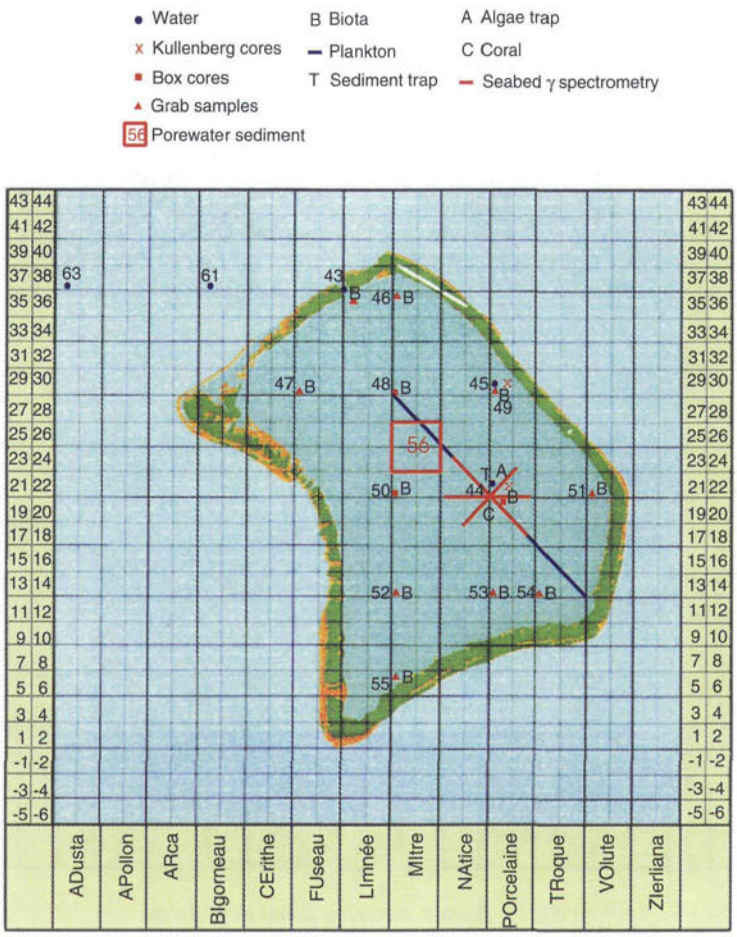


FIG. 29. Aquatic sampling points at Fangataufa.

both coconut flesh and water were within the range of values observed throughout the islands of French Polynesia. Traces of ^{60}Co and ^{125}Sb (close to the detection limit) found in some samples suggested that local fallout from the French atmospheric testing had made a small contribution to these levels, but the majority would have come from global fallout.

The IAC accepts that, considering the generally reasonable agreement between the French data and the Study results, the environmental monitoring data provided in the French Liaison Office documents (in particular Document No. 3) constitute a comprehensive and reliable account of the levels of artificial radioactive materials in the terrestrial environment of the atolls.

4.3.2. Aquatic environment

4.3.2.1. Introduction

This section presents a summary of the environmental measurement programme conducted by the Aquatic Working Group. The group's terms of reference included a review of the data provided by the French authorities on radionuclide distributions in the littoral (shoreline) and sublittoral (offshore) environments of the atolls. The objective was also to conduct sufficient new independent monitoring at and around the atolls to evaluate the existing French data and provide representative and high quality data for radiological assessment purposes. This work included measurements of the current radionuclide concentrations in the aquatic environment and estimation of concentration factors and distribution factors appropriate for the region. The variations in activity concentrations in the lagoons over the past few years are discussed and the likely sources of activity implied by the data are identified where possible.

4.3.2.2. Sampling and monitoring programme

The aquatic sampling campaign at Mururoa and Fangataufa took place from 1 to 27 July 1996. Its aim was to collect relevant and comparable samples of water, biota and sediment from the lagoons of the atolls and from the surrounding ocean. The results obtained,

TABLE XIII. SUMMARY OF AQUATIC SAMPLES

Area	Matrix	Number and type of samples collected
Ocean	Water	15 large volume (600 L) samples
	Biota:	
	Fish and shrimps	13 samples
	Plankton	2 samples
Mururoa lagoon	Water	12 samples (210 L)
	Biota	
	Fish and shellfish	17 samples
	Plankton	3 samples
	Algae	2 samples
	Sediment	5 Kullenberg cores
		25 box and grab cores (×3)
		2 surface sediments (×3)
		3 sediments for porewater extraction (×3)
		2 sediment gamma maps at sites 1 and 4
	Sediment traps	2 samples
	Coral	2 samples
Fangataufa lagoon	Water	6 samples (210 L)
	Biota:	
	Fish, crustacea and molluscs	12 samples
	Plankton	2 samples
	Algae	1 sample
	Sediment	2 Kullenberg cores
		13 box and grab cores (×3)
		1 sediment for porewater extraction (×3)
		1 sediment gamma map at site 44
		1 AQCS[a] sample (200 kg)
	Sediment trap	1 sample
	Coral	1 sample

[a] AQCS Analytical Quality Control Services (IAEA)

combined with earlier IAEA intercomparison data (IAEA 1995), were used to evaluate the far more comprehensive data from the monitoring programme instituted by the French Government.

The locations of the sampling sites and the types of samples collected at Mururoa and Fangataufa are illustrated in Figs 28 and 29, respectively, and a summary of the aquatic sampling plan is given in Table XIII. In general, more samples were collected than had been planned. However, no suitable sediment was found during the operation of the box corer on the submarine slope of Mururoa Atoll; to compensate, six water samples (instead of three) were collected at site 63 (about 10 km west of Fangataufa pass) to obtain an improved resolution for the radionuclide depth distribution profiles.

As in the terrestrial programme, all samples were collected in triplicate: one set for the Study team, one for the French team and one for the IAEA archives. The 33 water samples were pretreated in a laboratory at Mururoa to reduce the volume by about a factor of 20. All biota samples collected in the open ocean and in Mururoa lagoon were freeze-dried after dissection. The samples from Fangataufa were transported in ice boxes owing to the limited time available for freeze-drying at the Mururoa laboratory. All sediment cores were split into

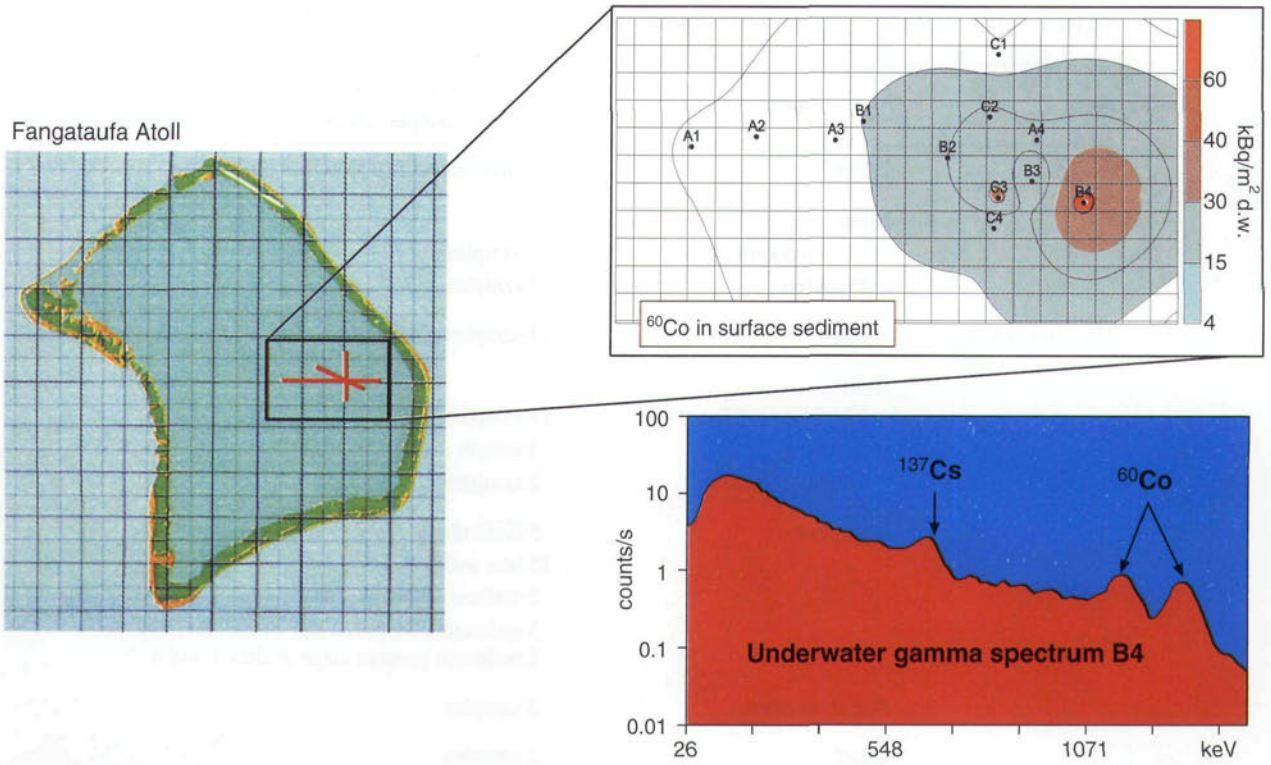


FIG. 30. Underwater gamma spectrometry of Fangataufa lagoon sediment (the grid squares of the isoline map are 100 m × 100 m).

slices to be further treated in the marine network laboratories. Grab samples of sediment were analysed as bulk samples.

Underwater gamma spectrometry of lagoon sediments

Underwater gamma spectrometry was used to locate the areas of the Mururoa and Fangataufa lagoons with the highest levels of residual activity in bottom sediments. The roughness of the lagoon bottoms did not allow towing of benthic devices, so the measurements were carried out on a network of discrete points covering the areas of highest residual activity identified by the SMSRB. The gamma spectrometry results were used to guide subsequent sample collection. This proved to be an efficient way to identify the areas of highest contamination on-site, which would otherwise have required a time consuming sequence of sampling, sample preparation and counting. The areas sampled were in the vicinity of Dindon and Denise in Mururoa lagoon and Frégate in Fangataufa lagoon (Figs 28 and 29). All of these locations were subject to direct contamination from the atmospheric barge tests (Section 4.2).

The most reliable parameters for immediate evaluation using this technique were the total (full energy range) count rate and the count rates from ^{60}Co and ^{137}Cs. An example of a recorded spectrum is given in Fig. 30 for illustration. Because there was significant variation from site to site in the depth distribution of radionuclides in sediment, an in situ efficiency calibration of the detector was not feasible. It was also not possible to evaluate radionuclide inventories in sediment from recorded spectra alone. For the purpose of the survey, however, only relative determinations were required.

The distribution of ^{60}Co and ^{137}Cs in lagoon sediments would not necessarily be expected to be the same as that for plutonium because of the different origins and geochemistries of these radionuclides. However, previous French investigations (French Liaison Office Document No. 1) demonstrated a correlation between these distribution patterns. Following the underwater gamma spectrometry survey, samples were taken from the sites identified as having local concentration maxima. Calibration and correlation analyses were carried out later to calculate ^{60}Co and ^{137}Cs inventories from in situ measurements and to estimate ^{60}Co and $^{239+240}$Pu inventories in lagoon sediments. A more detailed description of the sampling and monitoring programme is given in the Technical Report, Vol. 2.

4.3.2.3. Results of survey

The total number of samples requiring analysis was over three hundred. In order to limit the analysis period the analyses were performed by a network of marine

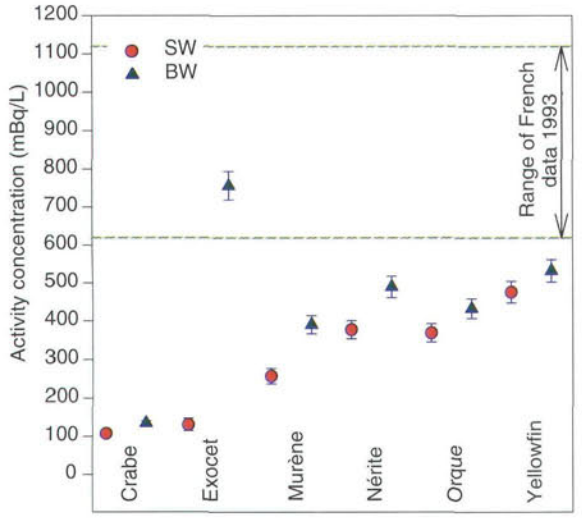


FIG. 31. Concentration of tritium (HTO) in surface water (SW) and bottom water (BW) of Mururoa Atoll.

laboratories. Nine national laboratories with proven technical competence and geographically representative of IAEA Member States, together with the MEL in Monaco, were chosen by Task Group A to carry out the complex analyses of samples; the participating laboratories are listed at the end of this report. The results obtained by the marine network laboratories are described in full in the Technical Report, Vol. 2, together with the techniques used for the analysis of water, biota and sediment.

Mururoa lagoon: Water

A study of the tritium concentrations measured by the Study team in the waters of Mururoa lagoon showed that concentrations in water close to the lagoon bottom were higher than in surface water, generally by 10–50% (Fig. 31). In the Exocet area, there was a difference of a factor of 6. Higher bottom concentrations were also confirmed by the higher tritium content (0.7–2.2 Bq/L) in pore water extracted from sediment close to the test shafts Orque, Krill and Flet (sites 31, 32 and 33 in Fig. 28). The spatial distribution of the surface ^{3}H concentration in the lagoon showed that the west side of the lagoon (west of Flet) is more influenced by ocean water than the east side, where the ^{3}H concentration is higher by a factor of 4. This is consistent with the known water circulation pattern in the lagoon (Section 8.3). The average tritium concentration measured in the lagoon was 360 ± 50 mBq/L, about a factor of 3 higher than in the open ocean. The fact that, on average, the values in 1996 were much lower than those reported for previous years (~1000 mBq/L) (French Liaison Office Document No. 3) may reflect an insignificant input (to date) from the most recent test series, a decreasing source term from the earlier underground tests (including the cessation of test shaft drilling), and/or possibly the fact that sampling took place after storm conditions.

The ^{90}Sr concentrations found in the lagoon were higher, by a factor of about 2, than those found in ocean surface water. At some sites, the concentrations at the bottom were clearly higher than those at the surface, but the difference was not as significant as for ^{3}H. The distribution of ^{137}Cs concentrations in surface and bottom waters was generally found to be homogeneous, i.e. showing no significant difference in concentration between sites and between water horizons, and the concentrations compared well with those found in the surrounding ocean surface water. The $^{137}Cs/^{90}Sr$ activity ratios in surface and bottom waters were generally lower than those found in ocean surface water, the latter being close to the value expected from global fallout (about 1.6). This finding may indicate an input of ^{90}Sr from the atoll bed.

The distributions of plutonium isotopes in filtered water and particulates were studied at four sites within the atoll lagoon. The $^{239+240}Pu$ particulate fraction ranged between 0.7 and 4.3% in surface water and between 1.0 and 3.3% in bottom water. The concentrations in filtered water were in the ranges 0.03–0.37 and 0.30–0.48 mBq/L for surface and bottom waters, respectively, i.e. there was more than a tenfold difference in surface water concentrations between sites, whereas the bottom concentrations showed only a moderate variation. Both surface and bottom water concentrations were between one and two orders of magnitude higher than ocean surface water concentrations. The $^{238}Pu/^{239+240}Pu$ activity ratios were 0.21 and 0.19 for surface and bottom waters, respectively, slightly higher than the value of 0.16 for ocean surface water. These results clearly indicate leaching of plutonium isotopes from the lagoon sediments of Mururoa Atoll.

For ^{241}Am, the ratios of activity in particulate form to that in solution were 1.2–3.1 and 0.9–2.7 in surface and bottom waters, respectively (i.e. the americium is predominantly in particulate form). Although the particulate americium concentrations were comparable with, or at least of the same order of magnitude as, the particulate $^{239+240}Pu$ concentrations, the total (soluble plus particulate) americium in the water column constitutes only 1–8% of the total $^{239+240}Pu$ in the water column.

Mururoa lagoon: Sediments

A comparison of radionuclide concentrations (^{60}Co, ^{137}Cs, ^{155}Eu, ^{238}Pu, $^{239+240}Pu$ and ^{241}Am) in box core

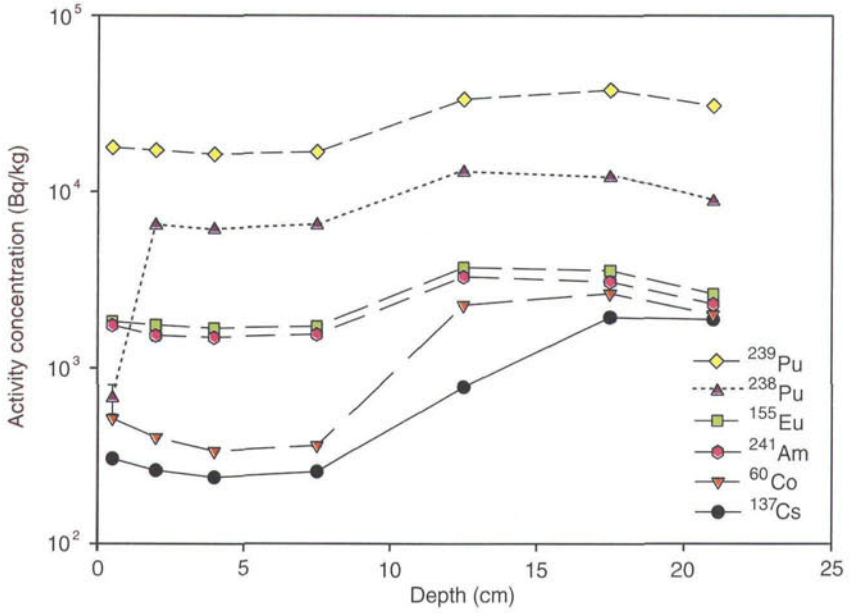


FIG. 32. Radionuclide concentrations in sediment from Mururoa Atoll, site 1 (Crabe).

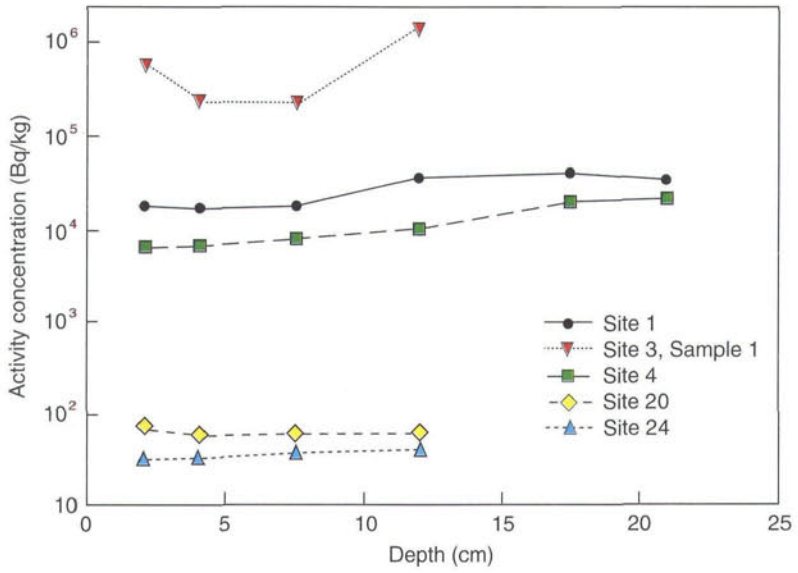


FIG. 33. Concentrations of $^{239+240}$Pu in some Mururoa lagoon surface sediments.

sediments taken from sampling site 1 in the Dindon area is shown in Fig. 32. As in other sediment samples taken throughout Mururoa lagoon, the dominant activity was due to $^{239+240}$Pu. Figure 33 shows that the highest $^{239+240}$Pu levels were measured in the Colette sandbank sediments (site 3). Deep core samples from site 1 (the 'zero point' immediately beneath the Sirius barge test) showed that the highest $^{239+240}$Pu levels extend down to 2 m (Fig. 34). Surface concentrations (top 10 cm) of $^{239+240}$Pu ranged from 30 to 170 Bq/kg, excluding those sites close to the coral rim (Denise and Françoise) and site 1 near the Dindon coral rim. In all cases, plutonium was well mixed at depth.

Profiles of $^{239+240}$Pu concentration with depth (from the surface to the deepest part of each sediment core) showed that the cores rarely included all of the plutonium, or even the peak concentrations. For most of the sampled sites, the sediment sample extended to a depth of less than 15 cm, and therefore the inventories (presented in Table XV, Section 4.3.2.4) are likely to be underestimates of the total inventories; in only one case (site 24) did the $^{239+240}$Pu profile show values decreasing

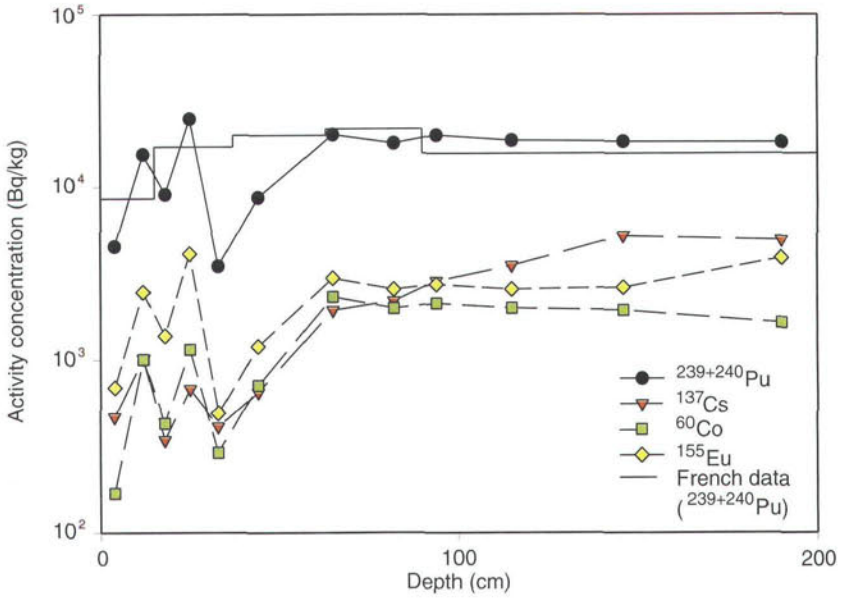


FIG. 34. Radionuclide profiles in deep core samples of Mururoa lagoon sediment at site 1 (Crabe).

with depth. The total $^{239+240}$Pu inventories showed values ranging from 4 to 70 kBq/m^2 in the central part of the lagoon, the highest values being near the Colette, Denise and Dindon hot spots (500–120 000 kBq/m^2).

Measurements of ^{210}Pb in sediment cores were carried out to estimate sedimentation rates. Both ^{210}Pb and ^{226}Ra were measured by alpha and gamma spectrometry on sections of selected sediment cores from Mururoa and Fangataufa lagoons. As expected, the ^{210}Pb profiles showed intense mixing of surface sediments, and the sedimentation rate estimated for depths below 10 cm was 2 mm/a (for site 12).

Mururoa lagoon: Active particles in Colette sediments

The search for particles with high plutonium activity was confined to the sediment samples collected from the Colette sandbank, adjacent to the safety trials area. Full details of this analysis are given in the Technical Report, Vol. 2.

Overall, on the basis of the sampling performed in the Study, it may be concluded that the sediments on the Colette sandbank contain up to 10^4 active particles per kilogram, with activities in the range 10–2000 Bq and grain sizes less than about 0.5 mm.

Mururoa lagoon: Biota

Generally, the radionuclide levels observed in biota were very low, especially those of ^{90}Sr, for which most values were below the detection limits (less than 0.08 Bq/kg). Concentrations of ^{60}Co in fish flesh were below 0.1 Bq/kg. Concentrations of ^{60}Co of 50 and 60 mBq/kg were observed for two shark samples (two species), but another sample (of a third shark species) showed a higher level (400 mBq/kg). The highest ^{60}Co levels, between 0.8 and 1.2 Bq/kg, were observed in trochus, a gastropod that feeds on seaweed and is usually attached to coral clusters in the lagoon. Concentrations of ^{137}Cs were below 0.3 Bq/kg, except in shark samples, where the range was 0.7–5 Bq/kg (the highest value being in the sample with the highest ^{60}Co concentration). Concentrations of $^{239+240}$Pu were lowest in red fish fillet (3 mBq/kg) and in shark samples (5–12 mBq/kg), and highest in one sample of black surgeon fish (0.6 Bq/kg) collected in the highly contaminated Denise area. In trochus samples, $^{239+240}$Pu levels were between 1.1 and 1.7 Bq/kg. Levels of ^{241}Am followed the same pattern as $^{239+240}$Pu levels, having the highest values in trochus (20–50 mBq/kg). Ratios of ^{238}Pu/$^{239+240}$Pu varied between 0.03 and 0.4, thus confirming a local origin for the plutonium in biota.

Microalgae collected on a plastic panel at Zanclus 25 (site 6) showed higher radionuclide concentrations (0.3 Bq/kg ^{60}Co, 2.9 Bq/kg $^{239+240}$Pu and 0.13 Bq/kg ^{241}Am). Higher radionuclide levels were also observed in plankton samples. For example, in plankton taken from the northern part of the lagoon, the observed radionuclide concentrations were 0.4 Bq/kg ^{60}Co, 0.8 Bq/kg ^{155}Eu, 5.6 Bq/kg ^{238}Pu, 52 Bq/kg $^{239+240}$Pu and 2 Bq/kg ^{241}Am. However, much lower plutonium levels (by about a factor of 20) were observed in the

plankton sample taken close to the pass (500–1000 μm fraction), where a marked influence from the open ocean water would be expected

These trends in concentration reflect the known variation in the capacities of different marine organisms to concentrate radionuclides (e.g. for plutonium, around five orders of magnitude between different organisms), with plankton typically having the highest concentration factors and bottom dwelling fish the lowest (Baxter et al. 1995).

Fangataufa lagoon· Water

The tritium concentrations in surface and bottom waters were measured at three sampling sites in Fangataufa lagoon, and similar results were obtained for each point. However, significantly higher tritium levels (4 7 and 0.65 Bq/L, respectively) were measured in pore waters extracted from sediment collected at site 56 and Mitre 29 (Fig 29) The levels of tritium in pore waters and the mean tritium concentration in the lagoon (180 mBq/L, higher by about a factor of 2 than in the surrounding ocean) suggest that, as in Mururoa lagoon, there is a continuing source of tritium.

Concentrations of ^{90}Sr and ^{137}Cs in surface waters showed very similar values at three different sites in Fangataufa lagoon. The concentrations in bottom waters showed a larger variation, while for site 44 both ^{90}Sr and ^{137}Cs concentrations appeared to be higher than in surface waters. However, the statistical uncertainty in these results was large In general, the concentrations of ^{90}Sr were significantly higher (by a factor of 1 7–3) than found in ocean surface waters For ^{137}Cs, the surface water concentrations were similar to those in the ocean whereas, for the bottom waters, the concentrations in the lagoon were higher by a factor of 1.1–2 As a consequence, the $^{137}Cs/^{90}Sr$ activity ratios in surface and bottom waters were generally lower than those found in ocean surface water. Again, therefore, there is some evidence for a ^{90}Sr source contributing to the levels in the lagoon at Fangataufa.

The distribution of plutonium isotope concentrations in filtered water and in particulate form was studied at three sites within the lagoon. The particulate fraction of $^{239+240}Pu$ was between 5 and 17% in surface water and between 5 and 19% in bottom water, i e. significantly higher than in Mururoa lagoon The concentrations in filtered water showed moderate variations, both between surface and bottom waters and between sites (giving a range of 0.4–0 6 mBq/L), and were generally somewhat higher than the concentrations found in Mururoa lagoon. The levels were about two orders of magnitude higher than those in ocean surface water. The $^{238}Pu/^{239+240}Pu$ activity ratios in filtered water showed very little variation between sites or between water sampling depths (range 0.39–0.41). The variation between sites was larger for particulate plutonium (range 0.25–0 38), although the statistical uncertainty was greater than for the filtered water measurements. In general, the activity ratios were significantly higher than those in ocean surface water. As at Mururoa, then, the results imply a mobilization of plutonium from the sediment in Fangataufa lagoon.

Concentrations of ^{241}Am in filtered water showed moderate variation between sites and water depths (1.6–3.4 μBq/L), while the ^{241}Am in particulates consistently showed higher concentrations in bottom water. The ratio between ^{241}Am in particulate form and in filtrate ranged between 1 3 and 2 7 and between 3.5 and 7 8 for surface and bottom waters, respectively, i.e. the ^{241}Am is predominantly in particulate form. The particulate ^{241}Am concentrations were about 10–20% of the particulate $^{239+240}Pu$ concentrations, whereas the total concentration of ^{241}Am in water was only 0.3–0 8% that of $^{239+240}Pu$, the latter percentages being significantly lower than found in Mururoa lagoon.

Fangataufa lagoon: Sediments

The highest plutonium concentrations in lagoon sediment at Fangataufa were measured at site 44, immediately beneath the barge test. A core penetrating to a depth of up to 1 m showed $^{239+240}Pu$ concentrations of 10^3–10^4 Bq/kg, with the highest value being observed in deeper layers. Surface concentrations (top 10 cm of sediment) in other areas of the lagoon ranged from 14 to 3100 Bq/kg. The total $^{239+240}Pu$ inventories (from the surface to the deepest part of each sediment core) in areas excluding the site 44 area immediately beneath the barge test ranged from 0 5 to 85 kBq/m^2 The highest value, found at site 44, was 850 kBq/m^2. As for Mururoa, however, these values represent underestimates of the inventories of plutonium. The sedimentation rate estimated for depths below 10 cm was 1 mm/a (site 50)

Fangataufa lagoon. Biota

Generally, the radionuclide concentrations found in Fangataufa lagoon fish were comparable with those from Mururoa lagoon; for example, the ^{137}Cs concentrations found in shark flesh were about 0.75 Bq/kg. Pearl oysters (a species not found in Mururoa lagoon) showed the highest concentrations of ^{60}Co (~9 Bq/kg) and $^{239+240}Pu$ (2.6 and 3.4 Bq/kg). One trochus sample contained 5.3 Bq/kg ^{60}Co and 4.5 Bq/kg $^{239+240}Pu$, values about a factor of 4 higher than in Mururoa lagoon.

Microalgae collected on a plastic panel in the centre of the lagoon yielded 1.2 Bq/kg ^{60}Co, 15 Bq/kg $^{239+240}$Pu and 1.5 Bq/kg ^{241}Am, values roughly six times higher than in Mururoa lagoon. In plankton samples (500–1000 μm fraction) taken in the centre of the lagoon, the observed $^{239+240}$Pu levels were 32 Bq/kg, i.e. about ten times higher than in Mururoa lagoon.

Ocean: Water

The tritium concentration profile in ocean water showed the expected decrease with increasing depth, from about 100 to 6 mBq/L. With the exception of surface water, the concentrations were similar between sites and showed a rapid decrease with water depth down to about 1000 m, becoming constant below that. The depth profile was consistent with observations elsewhere in the Pacific Ocean, indicating that the origin of ^{3}H was primarily global fallout. The water column inventory was estimated for site 63 by integrating an equation fitted to the depth profile data from the surface to 1000 m, and by linear interpolation between 1000 and 1950 m water depth. The resulting estimate of inventory was 60 kBq/m^2.

There were very small differences in ^{90}Sr concentrations between the sampling sites, and the profiles were typical of global fallout in the Pacific Ocean. The water column inventory was estimated for site 63, by the same method as for tritium, to be 0.6 kBq/m^2. This estimate is higher than estimated deposition densities from global fallout for latitudes 20–30° S (~0.3 kBq/m^2), indicating the presence of a local source.

Depth profiles of ^{137}Cs followed the same pattern as ^{90}Sr, and the differences in concentrations between sites were insignificant. The resulting estimate of the water column inventory for site 63 was 1.0 kBq/m^2 and the ^{137}Cs/^{90}Sr inventory ratio was 1.9. This ratio is slightly larger than the value of 1.6 expected from global fallout alone, and hence there is some evidence to suggest that some localized flow of radionuclides from the two atolls into the ocean may be occurring.

The $^{239+240}$Pu depth distributions at four sites (numbers 60–63) are shown in Fig. 35. The variability between sites was rather small, and the distributions were typical for the Pacific Ocean, i.e. a gradual concentration increase with depth, reaching a maximum at about 700–1000 m, after which the activities decline progressively. This is believed to be due to plutonium scavenging in the euphotic zone (the upper 100 m of the ocean, where photosynthesis can take place); the particles (and associated plutonium) then sink, and the plutonium becomes more soluble again at greater depths. The water column inventory was estimated for site 63 by integrating the best fit equation. However, an acceptable fit could only be obtained for the depth range 400–1000 m, so the inventory in the remainder of the column was estimated by linear interpolation. The inventory was estimated to be 10.4 Bq/m^2; this estimate compares well with the global fallout estimates of 12 Bq/m^2 for latitudes 20–30° S. Inventories for sites 60 and 61 were difficult to estimate from the sparse data, but if the concentration profiles follow the same shape as for site 63, the inventories should be similar or slightly higher. The depth distributions of the ^{238}Pu/$^{239+240}$Pu activity ratios showed significant variation between sites for surface water, ranging between 0.1 and 0.2. Despite the large statistical uncertainties, it appeared that for site 63 the activity ratios showed a variation with depth, indicating the possibility of there being more than one source of plutonium.

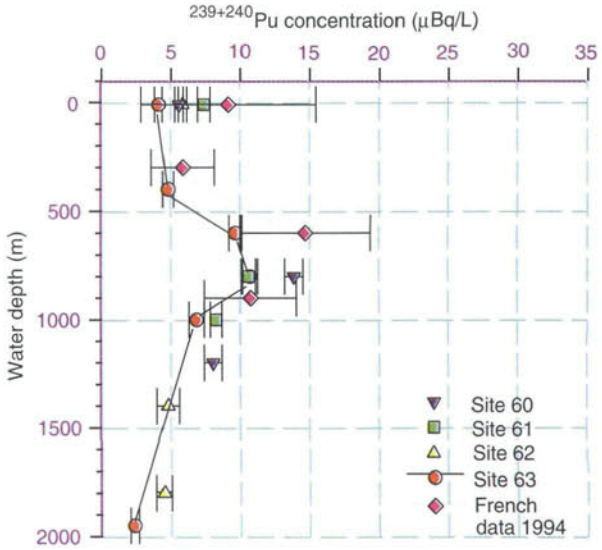


FIG. 35. Vertical concentration profiles of $^{239+240}$Pu in ocean water off Mururoa and Fangataufa.

The ^{241}Am depth distribution profile showed features similar to those of $^{239+240}$Pu.

Ocean: Biota

Fish in the open ocean, as expected, had much lower radionuclide concentrations than those in the lagoons. However, it is interesting to note that traces of ^{60}Co were found in fish and deep sea shrimps. Both ^{60}Co and ^{137}Cs were detected, at levels of 30–170 and 26–480 mBq/kg, respectively. Levels of $^{239+240}$Pu were between 0.3 and 100 mBq/kg, the highest concentrations being found in deep sea shrimps. Plankton samples (200–4000 μm fraction) collected about 2 km from the lagoon passes at both Mururoa and Fangataufa showed traces of ^{60}Co and ^{137}Cs and about 0.1 Bq/kg $^{239+240}$Pu.

4.3.2.4 Comparison with French data

Mururoa lagoon. Water

The tritium concentrations measured in 1996 in Mururoa lagoon water were significantly lower than those presented in French Liaison Office Document No. 3. These lower values are not inconsistent with the French observations, which, if weight is given to the Study's low 1996 value, could be interpreted as indicating a gradually declining concentration since 1990 (Fig. 36). Because the precision of the French measurements was much lower, they did not give any indication of tritium enrichment in bottom waters or of its spatial distribution in the lagoon

The tritium profiles observed in the lagoon by the Study team would nevertheless support the hypothesis of a continuous supply of tritiated water from the underlying sediment and rocks (probably the carbonate zone). This is also supported by the higher tritium contents found in pore waters extracted from the sediment. Although neither the sediment porewater sites nor the water sampling sites are coincident with tritium 'hot spots' in the carbonate zone presented in the French report (French Liaison Office Document No. 9), the higher tritium concentrations in porewater samples are probably due to tritium water migration from hot spot areas rather than to a contribution from localized shafts. The average tritium concentration in the lagoon (360 mBq/L, about a factor of 3 higher than in ocean water) can only reasonably be explained by a continuous supply of tritiated water from the underlying carbonate zone to the lagoon. The other possible sources of tritium, such as precipitation, can be excluded since the expected levels should not exceed 100 mBq/L.

The complete data set (French results for 1987–1995 plus Study results for 1996) shows (Fig 36) that the tritium concentration is either decreasing or is remaining

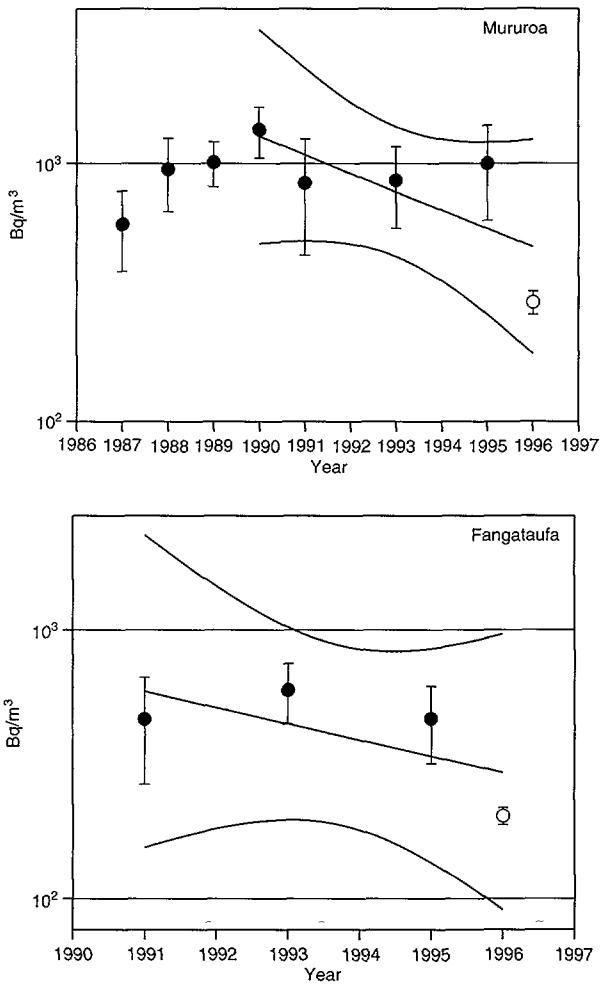


FIG. 36 Average ^{3}H concentrations in Mururoa and Fangataufa lagoon surface waters in recent years.

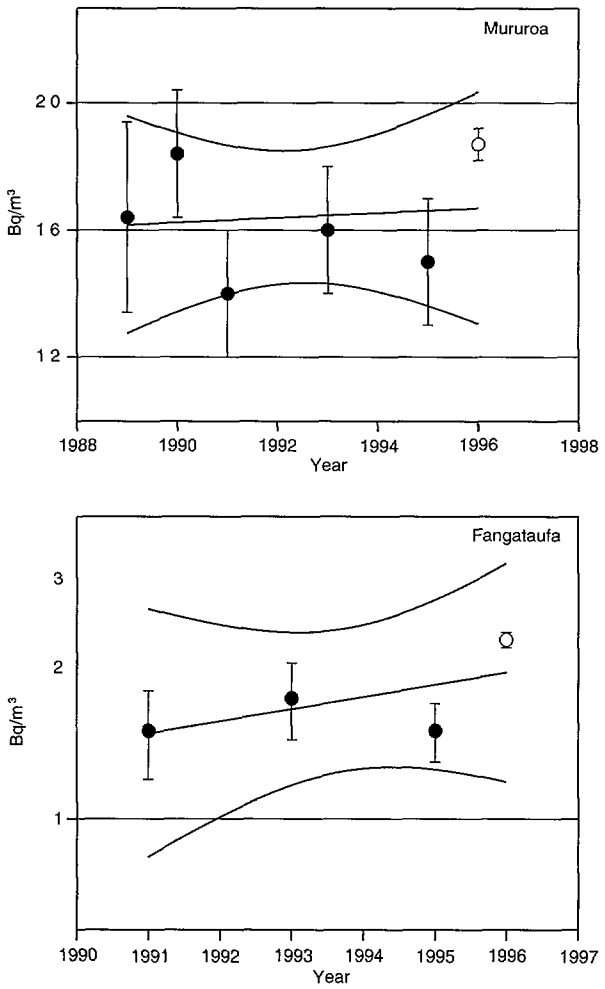


FIG 37 Average ^{90}Sr concentrations in Mururoa and Fangataufa lagoon surface waters in recent years

more or less constant (the result from 1996 may have been influenced by a large inflow of ocean water into the lagoon during a storm which occurred before sampling).

The ^{90}Sr and ^{137}Cs concentrations in surface water measured by the Study team compare very well with the patterns of concentrations reported by the French monitoring programme. On the basis of observations made by French scientists between 1989 and 1995, it is concluded that there has been no significant change in ^{90}Sr concentrations, probably reflecting a balance between mobilization from the underlying sediments and dilution by incoming ocean waters (Fig. 37). The average ^{137}Cs concentration measured in 1996 fits well with the trend in the French observations, which show a decrease with an effective half-life of approximately eight years between about 1982 and 1989 but approximately 15 years since then (Fig. 38).

The $^{239+240}Pu$ particulate concentrations measured in the Study were lower than, or lay towards the low end of, the 1993 data range provided by the French Liaison Office, but are higher than in 1995 (Fig. 39). Although there is substantial interannual variability (probably reflecting the suspended sediment load at the time of sampling), the Study data for 1996 fit well with the declining trend of recent years (effective half-life about nine years). The range of $^{239+240}Pu$ concentrations in filtered water in 1996 was slightly larger than the ranges of the French data for 1993 and 1995. The complete data set for the period 1985–1996 suggests an effective half-life of about seven years for the soluble phase (Fig. 40). The range of $^{238}Pu/^{239+240}Pu$ activity ratios found in the Study for water filtrate falls within the rather wide range of activity ratios in the French measurements. The combined plutonium data suggest export to the open ocean.

The estimated radionuclide inventories in Mururoa water are given in Table XIV The calculations were based on the mean surface and bottom water

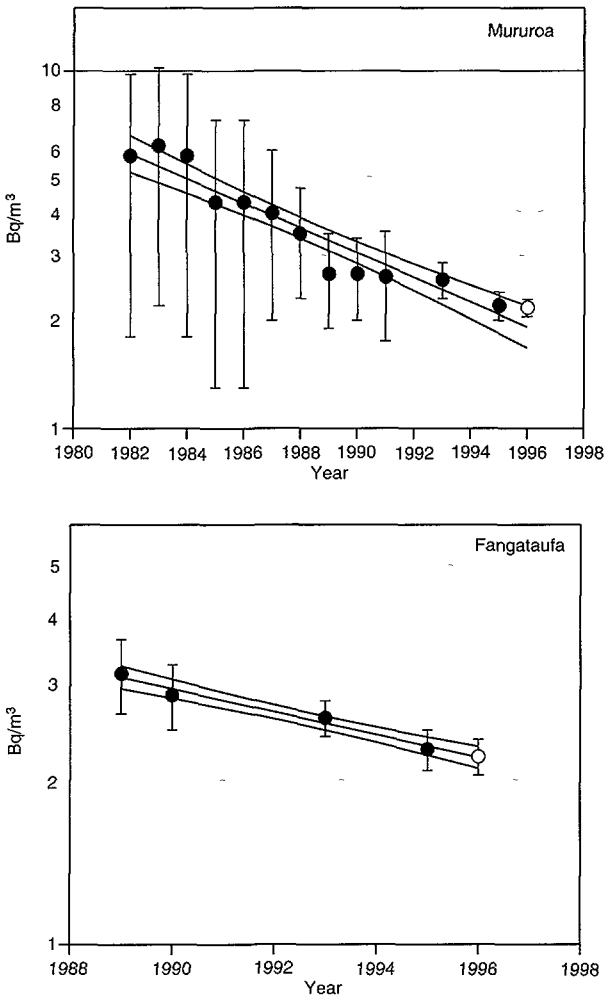


FIG. 38 Average ^{137}Cs concentrations in Mururoa and Fangataufa lagoon surface waters in recent years

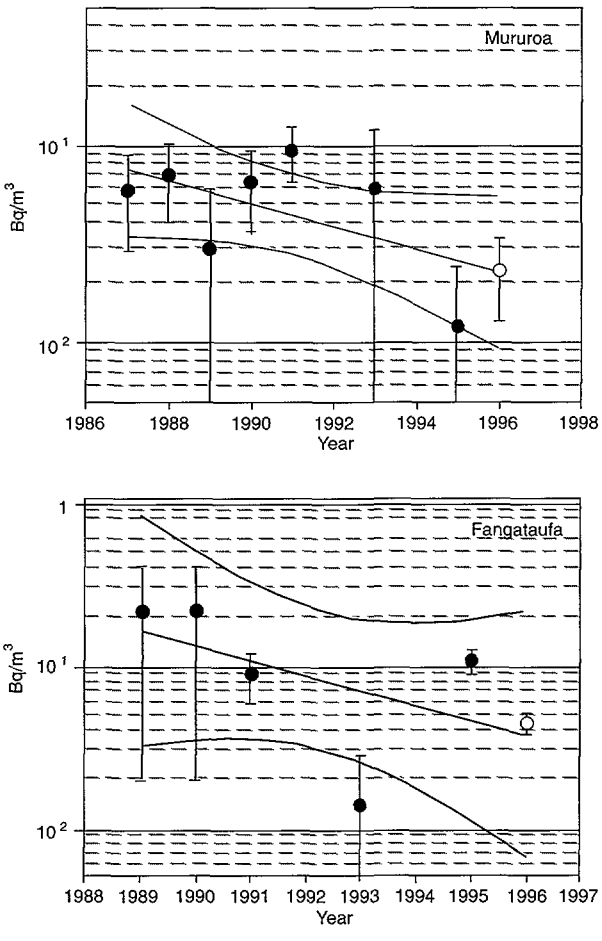


FIG. 39 Average $^{239+240}Pu$ (particulate phase) concentrations in Mururoa and Fangataufa lagoon surface waters in recent years

radionuclide concentrations found in the Study. Assuming an average turnover time of 0.25 years for the lagoon water (volume 4.7×10^9 m^3) and the relevant background concentrations for each radionuclide in oceanic waters, these inventories imply release rates from the lagoon of 5100 GBq/a ^{3}H, 18 GBq/a ^{90}Sr, 5 7 GBq/a ^{137}Cs and 6.4 GBq/a $^{238+239+240}$Pu

Mururoa lagoon. Sediments

The measured spatial distribution of $^{239+240}$Pu concentrations in the lagoon surface sediment (top 5 cm) is compared with French data in Fig. 41, showing that there was reasonable agreement between the Study team results and the French data. However, it must be borne in mind that these data do not represent inventories. The ^{155}Eu distribution in surface sediment was also in good agreement with French data (French Liaison Office Document No 1)

A comparison of the Study estimate of the $^{239+240}$Pu inventory in sediment with French data was carried out for the central part of the lagoon, where 17 box cores and four grab samples were collected (Fig. 28). The Colette, Denise and Dindon areas were excluded from this comparison because the number of cores collected by the Study team was insufficient to determine the inventory in these areas The $^{239+240}$Pu inventory thus calculated was about 2 TBq and is in reasonable agreement with the French value of 3 6 TBq (French Liaison Office Document No. 1)

Estimated radionuclide inventories in Mururoa sediments are listed in Table XV. As stated above, it was difficult to calculate the inventories for the Mururoa hot spots (Colette, Dindon and Denise) from the results of the Study because too few cores were taken. However, using the seabed gamma spectrometry data, and laboratory data on the corresponding ^{60}Co and $^{239+240}$Pu in sediment samples, a correlation analysis was carried out which enabled the $^{239+240}$Pu inventory at the Dindon hot spot to be estimated. The estimate thus obtained was about 8 TBq, which is in reasonable agreement with the French value of 4.9 TBq (French Liaison Office Document No. 1; see also Table X) The 1995 ^{60}Co inventory, which was estimated in a similar way, was

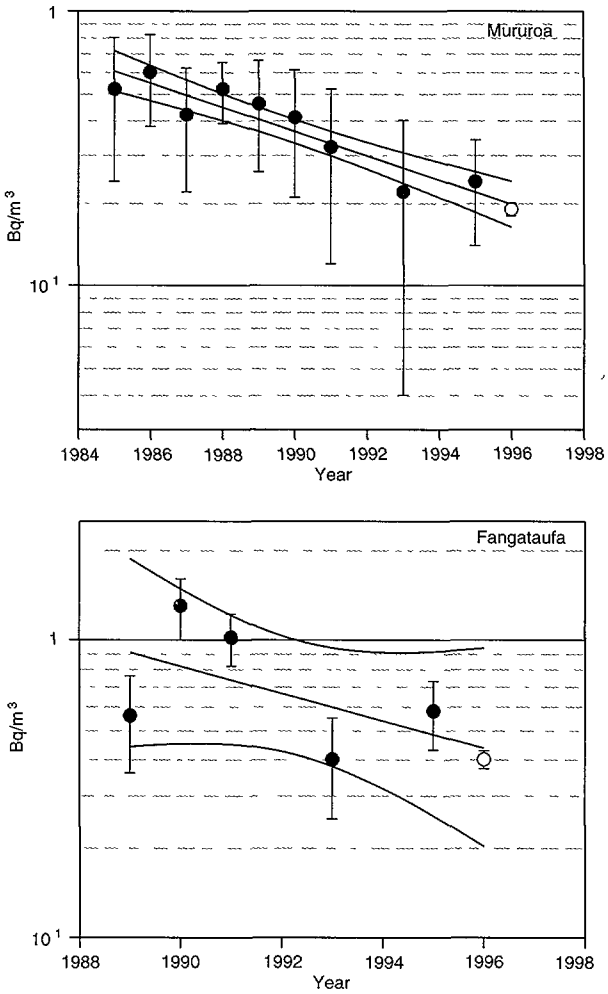


FIG 40 Average $^{239+240}$Pu (soluble phase) concentrations in Mururoa and Fangataufa lagoon surface waters in recent years

TABLE XIV. RADIONUCLIDE INVENTORIES IN MURUROA LAGOON WATERS

	Bq		Bq/m^2	
	Mean	Range	Mean	Range
^{3}H	$1\,74 \times 10^{12}$	$(1\,34–2\,15) \times 10^{12}$	12 000	9 900–15 900
^{90}Sr	$1\,02 \times 10^{10}$	$(0\,86–1\,52) \times 10^{10}$	70	63 7–113
^{137}Cs	$1\,02 \times 10^{10}$	$(0\,90–1\,18) \times 10^{10}$	70	66.7–87 5
^{238}Pu	$2\,61 \times 10^8$	$(1\,76–3\,26) \times 10^8$	2	1 3–2 4
$^{239+240}$Pu	1.42×10^9	$(0\,78–1\,76) \times 10^9$	10	5 8–13 0
^{241}Am	$2\,3 \times 10^7$	$(1\,7–2\,6) \times 10^7$	0 2	0 12–0 19

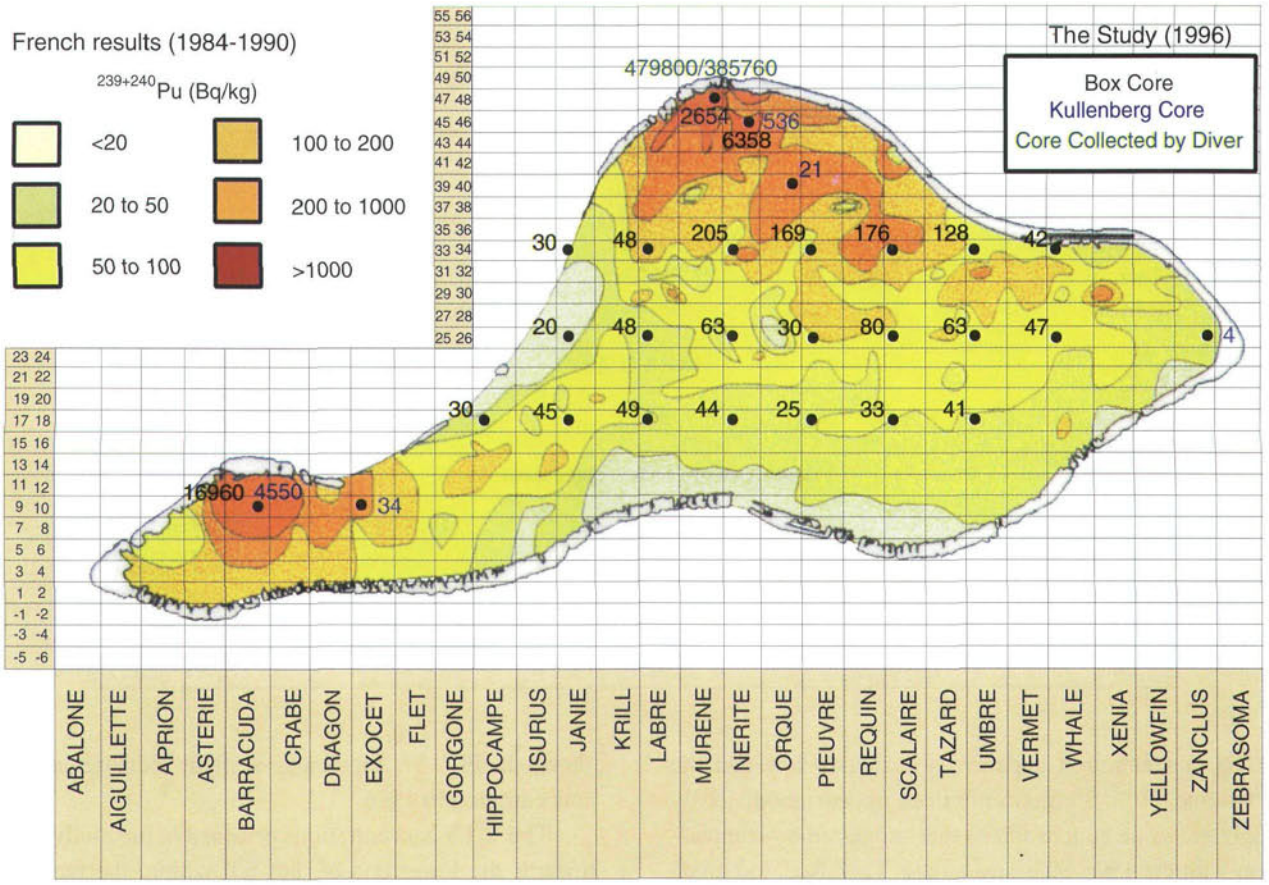


FIG. 41. Activity concentrations of $^{239+240}$Pu in Mururoa lagoon surface sediments. Point data are Study results (Bq/kg).

4×10^{11} Bq, which is also in agreement with the French value (4.7×10^{11} Bq).

Mururoa lagoon: Biota

An extensive data set of radionuclide measurements in biota was reported in the framework of an intercomparison exercise organized by the MEL in 1994–1995 (IAEA 1995). Although the sampling sites, as well as the species analysed, were different from those in this report, a rough comparison is still possible. A few results are also taken from a French data set for comparison (French Liaison Office Document No. 3).

Two representative sets of data for fish are compared in Table XVI, which shows that there was generally reasonably good agreement between the different data sets. The somewhat lower concentrations of ^{60}Co found in 1996 as compared with 1993 can be explained, at least in part, by radioactive decay. The ranges of values for ^{137}Cs and $^{239+240}$Pu overlapped or agreed to within a factor of 2 or 3. The major apparent exceptions were for shark, where larger differences were found between the Study team data and the French results. As noted above, the 1996 Study team data related to three different species, so the range of radionuclide concentrations observed probably reflected interspecies variability in behaviour and accumulation, in addition to the expected individual variability. It should also be noted that the French data for shark in Table XVI refer to a pelagic sample (species not given) and that the data look unusual in the overall context of the data given for pelagic fish in French Liaison Office Document No. 3. That is, the

TABLE XV. RADIONUCLIDE INVENTORIES (TBq) IN MURUROA SEDIMENTS

	Centre of lagoon		Total,
	Study data	French data[a]	French data[a]
^{60}Co	0.02	0.03	0.4
^{137}Cs	0.02	Negligible	0.8
^{155}Eu	0.07	0.08	0.6
^{238}Pu	0.3	0.6	3.3
$^{239+240}$Pu	1.8	3.6	18
^{241}Am	0.04	0.2	0.8

Note: Reference date 1 January 1997.

[a] Source: French Liaison Office Document No. 1.

TABLE XVI COMPARISON OF STUDY TEAM AND FRENCH DATA FOR FISH IN MURUROA LAGOON (Bq/kg wet weight)

Species	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
		The Study		
Black surgeon fish	<0 04–0 1	<0.06	0.15–0 20	0.041–0.586
Parrot fish	0 05–0 06	<0.08	0 24–0 30	0 009–0.015
Shark	0 05–0 39	<0 03	0 68–5 06	0.005–0 012
Red fish	0 05 ± 0 02	<0.03	0 18 ± 0 02	0 003
		IAEA (1995)		
Grouper	0 03–0 05	<0 03	0 26–0 35	0 001–0 004
		French Liaison Office Document No. 3		
Black surgeon fish	0.20–0 38	<0 14–0 85	<0 13–0 26	0 027–0 340
Parrot fish	0.31 ± 0 05	<0 13	0 27 ± 0.05	0 025 ± 0 009
Shark	0.32 ± 0 05		<0 07	5 18 ± 0.95
Goat fish	0 21 ± 0 05	<0 14	0 11 ± 0 04	0 01
Grouper	0 08 ± 0 03	<0 17	0 08 ± 0.03	0 061 ± 0.019

^{137}Cs concentration appears anomalously low and the ^{60}Co and $^{239+240}Pu$ concentrations appear anomalously high, the same conclusion as that suggested by comparison with the 1996 Study team data. Therefore, too much weight should not be given to these apparent differences.

Reasonably good agreement was obtained for shellfish (trochus), with the Study team reporting values less than the French limit of detection for ^{137}Cs and about a factor of 2 higher than the French values for ^{60}Co. The results of radionuclide analyses (^{60}Co, ^{137}Cs and $^{239+240}Pu$) of the microalgae and plankton samples collected in the lagoon were also within the ranges given in French Liaison Office Document No. 3.

Fangataufa lagoon. Water

The mean tritium concentration in Fangataufa lagoon obtained in the Study (180 Bq/m^3) was generally lower than, or at the lower limit of, the French data range For the period 1991–1995, the French monitoring survey did not observe any significant change in tritium concentration, but the data from the Study suggest a significant decrease since then (Fig 36). However, this decrease may reflect mixing of ocean water of low tritium concentration with lagoon water due to storm conditions before sampling (as at Mururoa). The increased concentrations in the sediment pore waters (3–20 times the concentrations in the overlying lagoon waters) indicate a local source of tritium.

The ^{90}Sr concentrations in surface water found in the Study were somewhat higher than, but overlapping with, the range of concentrations reported by the SMSRB As shown in Fig. 37, there was a slight increase in ^{90}Sr concentration in 1996.

The ^{137}Cs concentrations obtained in the Study were towards the lower end of, but fell within, the range of concentrations obtained by the French monitoring programme. The complete data set between 1989 and 1996 suggests a decrease in ^{137}Cs concentration in recent years, with an effective half-life of about 14 years (Fig 38). The $^{137}Cs/^{90}Sr$ activity ratios in surface waters reported in the Study were all below the range given in French Liaison Office Document No 3 but there were too few data to allow definitive conclusions on the significance of this finding.

The Study team data for $^{239+240}Pu$ concentrations were within the range of the French 1993 data set for the soluble fraction, and overlapped the French range for the particulate fraction. The average $^{239+240}Pu$ concentration in surface water (the soluble fraction) is decreasing with an effective half-life of about eight years (Fig 40). However, the particulate fraction showed larger fluctuations (Fig 39). The $^{238}Pu/^{239+240}Pu$ activity ratio (0.39 for both surface and bottom waters) was almost equal to that reported by the French monitoring programme (0.4) and higher than the ratio in ocean surface water (0.16).

Radionuclide inventories in Fangataufa lagoon water are given in Table XVII. Assuming an average turnover time of 0 082 years for the water volume of the lagoon (5.6×10^8 m^3) and the relevant background concentrations for each radionuclide in oceanic waters, these inventories imply release rates from the lagoon of 560 GBq/a ^3H, 8 6 GBq/a ^{90}Sr, 5 3 GBq/a ^{137}Cs and 4.6 GBq/a $^{238+239+240}Pu$

TABLE XVII. RADIONUCLIDE INVENTORIES IN FANGATAUFA LAGOON WATERS

	Bq		Bq/m^2	
	Mean	Range	Mean	Range
^{3}H	0.99×10^{11}	$(0.78–1.21) \times 10^{11}$	2800	2150–3350
^{90}Sr	1.40×10^{9}	$(1.25–1.45) \times 10^{9}$	39	34.7–40.3
^{137}Cs	1.50×10^{9}	$(1.19–1.72) \times 10^{9}$	42	33.1–47.8
^{238}Pu	1.10×10^{8}	$(0.90–1.37) \times 10^{8}$	3	2.5–3.8
$^{239+240}$Pu	2.83×10^{8}	$(2.32–3.49) \times 10^{8}$	8	6.4–9.7
^{241}Am	5.38×10^{6}	$(3.6–6.4) \times 10^{6}$	0.15	0.10–0.18

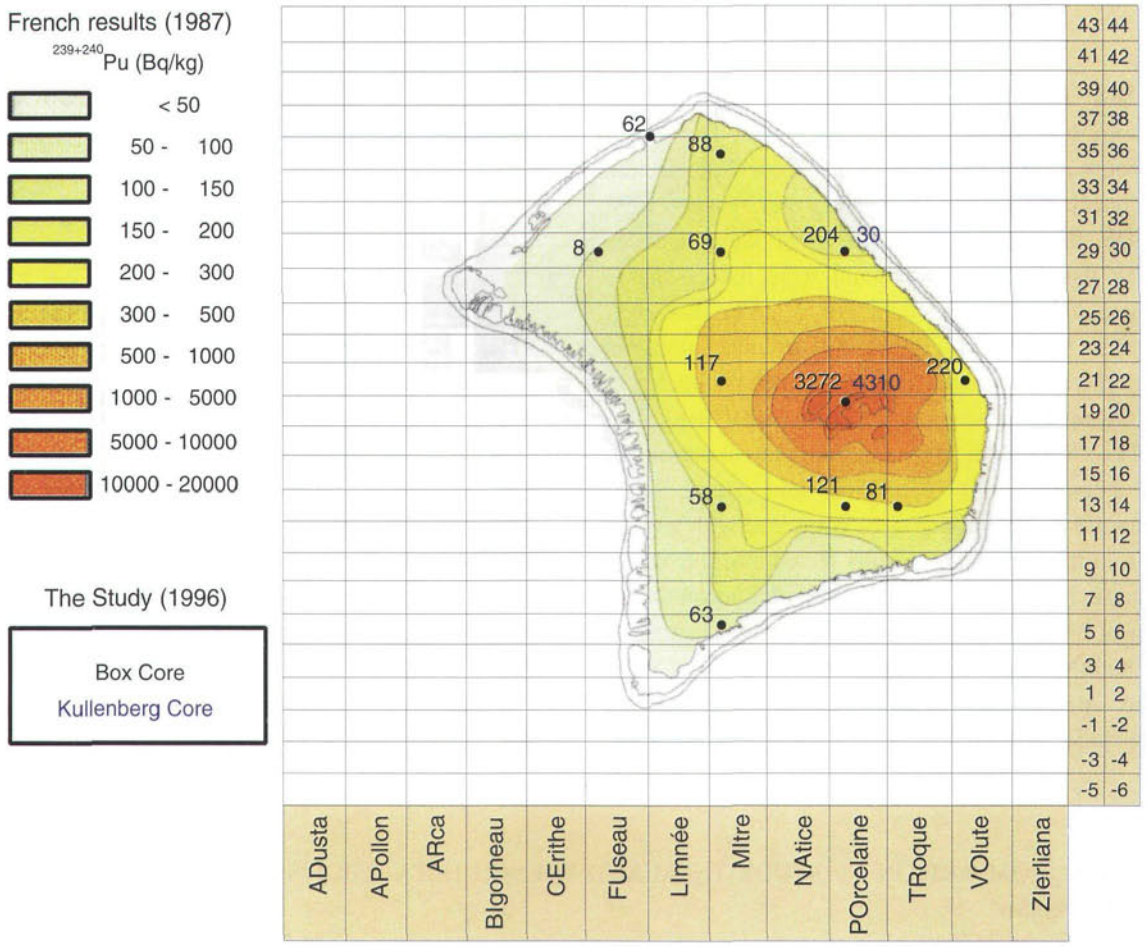


FIG. 42. Activity concentrations of $^{239+240}$Pu in Fangataufa lagoon surface sediments. Point data are Study results (Bq/kg).

Fangataufa lagoon: Sediments

The spatial distribution of $^{239+240}$Pu in the top 5 cm of lagoon sediment found by the Study team is shown in Fig. 42, and was in agreement with the French distribution map. This is also the case for ^{155}Eu (French Liaison Office Document No. 1). The estimated radionuclide inventories in Fangataufa lagoon sediments are listed in Table XVIII, where it can be seen that there was a reasonable degree of agreement between the results of the Study and the French data (French Liaison Office Document No. 1; see also Table XI).

Fangataufa lagoon: Biota

A comparison between data from the Study and French data (French Liaison Office Document No. 3) for fish samples collected in Fangataufa lagoon is given in

TABLE XVIII. TOTAL RADIONUCLIDE INVENTORIES (TBq) IN FANGATAUFA SEDIMENTS

	Study data	French data[a]
^{60}Co	0 1	0 03
^{137}Cs	0 05	0 2
^{155}Eu	0 3	0 4
^{238}Pu	2 3	2 9
$^{239+240}Pu$	5.5	7 4
^{241}Am	0.3	0 4

Note: Reference date 1 January 1997.

[a] Source. French Liaison Office Document No 1

Table XIX In all cases, the results for ^{90}Sr from the Study were less than the LLD in the French data. When due account is taken of the decay of ^{60}Co and the decline in the concentrations of ^{137}Cs in the water between 1993 and 1996, the lower concentrations of these nuclides found in fish by the Study team were in reasonable agreement with the French data. For $^{239+240}Pu$, however, there were substantial differences in concentrations between the two data sets, with the French results being higher by up to a factor of 800 (for parrot fish) The apparent concentration factor for plutonium in parrot fish varied between 140 (Mururoa) and about 6200 (Fangataufa) for the French data, compared with a value of 30 from the Study team results for both Mururoa and Fangataufa. French data for 1995 (French Liaison Office Document No 3, Vol. 2) yield concentration factors of 90 for both Mururoa and Fangataufa; the value of 6200 therefore appears anomalously high, and is also above the generally accepted range found in the literature (IAEA 1985) Thus too much weight should not be placed on the apparent discrepancy in Table XIX. The Study team data for the shellfish samples (trochus and pearl oyster) showed reasonable agreement with the French data (French Liaison Office Document No. 3, Vol. 1).

No French data were available on microalgae from Fangataufa lagoon. The plankton sample collected in 1996 showed concentrations of $^{239+240}Pu$ about ten times higher than those given in the 1994 French report (French Liaison Office Document No 3, Vol. 1) but similar to those for 1995 (French Liaison Office Document No. 3, Vol. 2). The discrepancy relative to the 1994 data is not unexpected when such limited data sets are compared, and could be due to differences between conditions in the lagoon during the two sampling periods

Ocean. Water

The tritium depth profiles obtained in the Study for shallow to intermediate water depths generally showed concentrations lower than the data obtained by the French programme in 1994. The French data for deeper water (600 and 900 m depth), taken at 12 nautical miles (22.2 km) from the atolls, were all below the detection limit, thus preventing a comparison.

In general, depth profiles of ^{90}Sr and ^{137}Cs compared very well with the French 1994 data, both in magnitude and in profile shape. The profiles of $^{137}Cs/^{90}Sr$ activity ratios were therefore also consistent

The $^{239+240}Pu$ depth profiles from the Study showed very similar shapes and magnitudes to the 1994 French

TABLE XIX COMPARISON OF STUDY TEAM AND FRENCH DATA FOR FISH IN FANGATAUFA LAGOON (Bq/kg wet weight)

Species	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
		The Study		
Parrot fish	0.12–0 36	<0 009	0 19–0.20	<0 005–0.013
Surgeon fish	0 35–0 61	0 020	0.14–0 24	0 010–0 031
Goat fish	0.62 ± 0 05	<0 013	0 29 ± 0.05	0 013 ± 0 002
Shark	0 19–0 44	<0.002	0 68–0.84	0 003–0 013
		French Liaison Office Document No. 3		
Parrot fish	1 17 ± 0 12	<0 15	0 27 ± 0 09	2 11 ± 0 04
Black surgeon fish	2 00 ± 0 18	<0 16	0 26 ± 0 05	0 08 ± 0 02
Goat fish	2 01 ± 0.18	<0.16	0 16 ± 0.04	0 07 ± 0 02
Grouper	0 37 ± 0.05	<0 18	0 12 ± 0 04	0 06 ± 0 02

data (Fig 35). However, the subsurface maximum observed at about 800 m water depth in the Study was not fully consistent with the French observations. In 1990, 1993 and 1994, a maximum concentration was observed at about 600 m using a high depth resolution procedure (French Liaison Office Document No. 3). Because the depth of the concentration maximum increases with time, and the Study estimate had an associated uncertainty of several hundred metres, the discrepancy is not significant The $^{238}Pu/^{239+240}Pu$ activity ratio profiles compared well but, owing to the large statistical uncertainties, possible differences would not be expected to be easily observable.

In the case of ^{241}Am, although the Study team's depth profiles and French data showed larger statistical uncertainties than for $^{239+240}Pu$, the agreement between the data sets is good.

Ocean: Biota

A comparison between Study team and French data on fish and deep sea shrimp samples collected in the open ocean is given in Table XX. The data presented show very low radionuclide concentrations and generally good agreement.

Several plankton samples were collected around Mururoa and Fangataufa Atolls Although the samples were collected at different sites and at different times, the agreement between Study team and French data was very good, except for $^{239+240}Pu$ at the passes, where the 1996 French values were higher by about an order of magnitude.

4.3.2.5. Radionuclide concentrations in lagoons: Discussion

A decreasing trend in ^{137}Cs and $^{239+240}Pu$ concentrations in lagoon water has been observed. This may be explained by a combination of processes including sediment leaching, deposition of fresh (non-radioactive) sediment in the lagoon (burial and/or mixing with the sediment containing radionuclides) and removal of contaminated sediment (especially during storms). This leads to an effective depletion of the inventory of the radionuclides available in the surface layers of sediment to support the concentrations in the overlying water. This trend, but not the individual processes, was suggested in French Liaison Office Document No. 3, Vol 1

Any ^{137}Cs and $^{239+240}Pu$ from underground sources may only appear in the lagoon water after intervals (migration times) of a few decades (^{137}Cs) or a few thousand years ($^{239+240}Pu$). Until then, the dominant ^{137}Cs and $^{239+240}Pu$ inventories are those in the lagoon sediments, and the time evolution of the concentrations of these radionuclides in water can be explained by the processes outlined above.

Tritium and ^{90}Sr concentrations in lagoon water have remained fairly constant over the past eight to nine years (Figs 36 and 37). Because lagoon water is exchanged with the surrounding ocean, this observation implies that there must be local sources of these radionuclides in the lagoon to maintain the concentrations. The enhanced concentrations of tritium measured in the sediment pore water cannot have been derived from the atmospheric tests, and there is insufficient ^{90}Sr adsorbed onto the sediments to explain the present concentration

TABLE XX. COMPARISON OF STUDY TEAM AND FRENCH DATA ON OCEAN BIOTA (Bq/kg wet weight)

Species	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
		The Study		
Tuna (skipjack)	<0 02	0.012 ± 0 003	0 23–0 34	0 001 7 ± 0.000 8
Tuna (yellowfin)	0 03–0 06	<0 02	0 43–0 48	0 000 9–0 005 4
Thazard (wahoo)	<0.03		0.29–0 38	0 000 3–0 015 0
Red fish	0 09 ± 0.05		0 11 ± 0 03	
Deep sea shrimps	0.07–0 17	0 020 ± 0.025	<0 03–0 04	0 012–0 106
		IAEA (1995)		
Grouper (Rangiroa Atoll)	<0 03	<0.03	0.24 ± 0 06	0 000 13 ± 0 000 05
		French Liaison Office Document No. 3		
Tuna (skipjack)	<0 1		0 14–0 28	<0 000 7
Tuna (yellowfin)	<0 04		0.1–0.3	<0 004
Deep sea shrimps	<0.06–0 72	<0 2	<0 04–0.09	<0 010–0 040

TABLE XXI. RECOMMENDED K_d VALUES

	Bottom sediment		Suspended sediment		IAEA (1985)	Recommended values from the Study	
	Mururoa[a]	Fangataufa[a]	Mururoa[a]	Fangataufa[a]		Bottom sediment	Suspended sediment
Sr	$(1–3) \times 10^2$	—[b]			$(0\ 1–5) \times 10^3$	2×10^2	
Cs	$(1–2) \times 10^3$	$(1–3) \times 10^2$			$(0\ 01–2) \times 10^4$	1×10^3	
Pu	$(0\ 3–1) \times 10^5$	$(0\ 8–5) \times 10^5$ 7×10^4 [c]	$(0\ 3–14) \times 10^5$	$(0\ 8–5) \times 10^5$	$(0\ 01–1) \times 10^6$	1×10^5	2×10^5
Am	$(4–20) \times 10^6$	$(0\ 4–5) \times 10^6$	$(2–13) \times 10^6$	$(1–8) \times 10^6$	$(0\ 1–20) \times 10^6$	2×10^6	5×10^6

[a] Estimated K_d ranges based on measured radionuclide concentrations in water and sediment.
[b] Data not provided.
[c] Based on porewater measurements

TABLE XXII RECOMMENDED CONCENTRATION FACTORS

	Mururoa (the Study)	Fangataufa (the Study)	Ocean (the Study)	Mururoa (IAEA 1995)	Atolls and ocean (French Liaison Office Document No 3)	IAEA (1985)[a]	Recommended value from the Study
Fish[b]							
Sr		3–8	10		20–40	0 3–10 (2)	2
Cs	70–140	50–110	60–260 120 (IAEA 1995)[c]	100–130	40–400	10–300 (100)	100
	Shark· 300–2 300	250–300					
Pu	1–60	7–70	50–300	0 6–2	20	0 5–100	40
	Surgeon fish 160–1 200		One tuna. 900			(40)	
Am	70–230		20–40			0 5–200	50
	Surgeon fish 900–10 000					(50)	
	Shark 150–400						

Molluscs[b]							
Sr		4		10		0 3–10 (1)	1
Cs	10–20	10–40		10–20	10–40	10–50 (30)	30
Pu	4 000–6 000	4 000–7 000		500–3 000	500–2 000	500–5 000 (3 000)	3 000
Am	10 000–25 000	One trochus 10 000 50 000–100 000		14 000		5 000–50 000 (20 000)	5 000+ 20 000
Crustacea							
Sr			10–30[d]			0 1–5 (2)	2
Cs		40[b]	10–30[d]	40[b]	50[d]	10–50 (30)	30
Pu			1 000–15 000[d]	300[b]	3 000–6 000[d]	100–1 000 (300)	300
Am			1 000–7 000[d]			100–1 000 (500)	500
Plankton							
Cs	7	15	15 14[e]		6–11	10–50 (30)	30
Pu	10 000–200 000	70 000	17 000 4 000[e]		400–7 000	500–5 000 (1 000)	1 000 50 000[f]
Am	1×10^6		5 000			500–5 000 (2 000)	2 000 100 000[f]

[a] IAEA recommended value in brackets [b] Flesh [c] Fish from Rangiroa Atoll [d] Whole sample [e] IAEA (1991). [f] Recommended value for lagoons

in the overlying water. In both cases, therefore, the presence of underground sources to maintain the current concentrations, and possibly increase them over time, should be considered. However, the observed levels could have been affected by the original drilling work and by the fact that some shafts were left open, which has been known to have resulted in higher concentrations in the past. With the closing of the shafts and the cessation of drilling activities, the dominant process leading to increasing levels of tritium and ^{90}Sr in lagoon water would become the transfer of tritium and ^{90}Sr through the carbonates.

4 3 2.6 *Distribution coefficients and concentration factors*

The distribution coefficient (K_d) for sediment and the concentration factor (CF) for biota are parameters used to quantify and compare the degree of uptake of elements by different types of material and organism K_d values are required for modelling the transport and dispersion of radionuclides. CFs are used to describe the accumulation of specific radionuclides by marine biota and are required for dose assessment studies.

Values of K_d and CF for those elements most frequently of interest were published by the IAEA (1985) However, they can be affected by environmental and biological variables such as water temperature and sediment geochemistry, and specific values for many areas of the ocean are not known There may be some doubt whether K_d and CF values derived for temperate latitudes can be applied to tropical regions and to specific geochemical conditions (e.g. Mururoa and Fangataufa sediments are composed almost entirely of calcium carbonate) Table XXI lists K_d values derived for the Study from measured radionuclide concentrations in water and bottom sediment (excluding the hot spots) from both Mururoa and Fangataufa lagoons. It is interesting to see that the results obtained are within the range of the published IAEA values (IAEA 1985). K_d values derived for plutonium and americium from suspended sediment are higher by about a factor of 2 than those derived from bottom sediment.

The situation is more complicated for CFs because of the wide variety of marine species that might be of interest The CFs compared in Table XXII, for strontium and caesium in fish, molluscs, crustacea and plankton, sampled in Mururoa and Fangataufa lagoons and in the open ocean, were within the ranges published by the IAEA (1985) For plutonium and americium, some samples gave higher values Therefore, the recommended CFs for plutonium and americium differ slightly from the published IAEA values

4.3 2.7. *Conclusions of aquatic monitoring programme*

On the basis of extensive sampling, seabed gamma spectrometry, laboratory analyses, data evaluation and comparison with French data, the following conclusions can be drawn:

(a) Generally, there was reasonably good agreement between the results obtained by the Study team and data from the French monitoring programme.
(b) A decline in radionuclide concentrations with time was observed at some sites compared with the earlier French data.
(c) The largest radionuclide inventories in Mururoa lagoon were those of $^{239+240}Pu$ (18 TBq) and ^{238}Pu (3.3 TBq) in bed sediment; ^{60}Co, ^{137}Cs, ^{155}Eu and ^{241}Am each contributed only about 0.4–0.7 TBq. For comparison, the inventory of the naturally occurring isotope ^{40}K in the lagoon water is 56 TBq.
(d) The plutonium isotopes in sediment also represented the largest radionuclide inventories in Fangataufa lagoon, with 7.4 TBq $^{239+240}Pu$ and 2.9 TBq ^{238}Pu; ^{60}Co, ^{137}Cs, ^{155}Eu and ^{241}Am each contributed between 0.2 and 0.4 TBq.
(e) There was evidence for underground releases of ^{3}H and possibly ^{90}Sr into the lagoons.
(f) The estimated radionuclide release rates from Mururoa lagoon into the open ocean are 5100 GBq/a ^{3}H, 18 GBq/a ^{90}Sr, 5.7 GBq/a ^{137}Cs and 6.4 GBq/a $^{238+239+240}Pu$.
(g) The estimated radionuclide release rates from Fangataufa lagoon into the open ocean are 560 GBq/a ^{3}H, 8.6 GBq/a ^{90}Sr, 5.3 GBq/a ^{137}Cs and 4.6 GBq/a $^{238+239+240}Pu$.
(h) Radionuclide concentrations in biota were low and consistent with data from the 1995 IAEA intercomparison exercise (IAEA 1995) and the French monitoring programme.
(i) Distribution coefficients derived from measured radionuclide concentrations in water and sediment from both Mururoa and Fangataufa lagoons (excluding hot spots) were within the range of IAEA recommended values (IAEA 1985).
(j) Concentration factors for caesium in plankton, fish and molluscs sampled in Mururoa and Fangataufa lagoons and in the open ocean were within the ranges published by the IAEA (1985), as was the case for plutonium in fish. For plutonium in plankton and molluscs, higher values (by up to a factor of 3) were derived from direct measurements in the Study

5. INVENTORY OF RESIDUAL RADIOACTIVE MATERIAL IN THE GEOSPHERE OF THE ATOLLS

5.1. INTRODUCTION

In this section, estimates are made of the inventory of radionuclides resulting from the underground nuclear tests and safety trials. The inventory is further broken down according to physical location Wherever possible, independent estimates are made and then compared with information provided by the French Liaison Office.

The section begins with a summary, drawn mainly from French sources (Bouchez and Lecomte 1996, French Liaison Office Document No 6), of the locations of the underground tests, the assembly and emplacement of nuclear devices, and the physical phenomena associated with an underground test. Figure 43 shows the methodology used in estimating the radionuclide inventory and other data required for the analysis of transport through the geosphere. In summary, the methodology is as follows.

(1) The yield of each nuclear test (in kt TNT equivalent) is estimated on the basis of seismic records from independent seismic stations, especially Rarotonga Observatory in the Cook Islands. The yields from individual tests are added together to give a total yield for both atolls as well as yields according to location (Mururoa or Fangataufa, under rim or lagoon) The estimates are compared with information from the French Liaison Office (Document No. 6).
(2) French data for the dimensions of a nuclear cavity and 'chimney' (Section 5.4) as a function of yield are compared with published data, mainly from US and Russian sources. This information is important in later assessments of geological pathways, structural stability and radionuclide transport (Section 6).
(3) From an estimate of total yield, the underground inventories of all radiologically significant radionuclides are calculated, on the basis of information provided by French scientists, from a knowledge of the nuclear reactions that occur (fission, fusion and activation). Once again, these estimates are compared with information from the French Liaison Office (Document No. 4).
(4) The 137 tests and 10 safety trials, together with buried waste from cleanup operations, are classified into seven categories to facilitate further assessment. Radionuclide inventories are determined for each of these categories and for generic nuclear tests ranging in size from 1 to 150 kt.
(5) Estimates are made of the partitioning of radionuclides (as percentages) between the various phases in the cavity–chimney (the 'lava' formed from the nuclear explosion, the rubble, water and gas).

The final output from these calculations is a database containing estimates of the radionuclide inventory in the various phases according to yield and broadly according to location This information becomes the input to geosphere transport calculations (Sections 6 4 and 6.5).

5.2 LOCATION OF UNDERGROUND TESTS

The French authorities did not provide the Study team with the exact location of each of the 137 underground tests or the 10 safety trials. They did, however, provide a plan view of each atoll (Figs 44 and 45) showing the test areas and the number of tests, maximum test yield and total test yield in each area

Underground testing at the CEP began in 1975 with two tests on the southern rim of Fangataufa Atoll That experience satisfied the French authorities that it would be possible to carry out future tests safely on the larger atoll of Mururoa, where all living quarters, laboratories and workshops were located. Between 1976 and 1987, all tests were carried out at Mururoa.

Until 1980, all test shafts were drilled on land but then, as available testing space became scarce, techniques were developed to permit drilling under the lagoon from a barge. The first test beneath a lagoon was carried out at Mururoa in 1981 From then on, testing under the lagoons became more common and these were the only test locations from 1987 onwards (except for one safety trial under the rim of Mururoa in 1989).

For safety reasons, the higher yield tests at Mururoa were carried out well away from the living quarters, in Area 4 (under the rim) and Area 7 (under the lagoon). From 1988 onwards, many of the larger tests (in the 40–150 kt range) were carried out beneath Fangataufa lagoon.

All nuclear tests were conducted in the volcanic rock at depths between about 500 and 1100 m. Of the ten safety trials, all were in Area 1 at Mururoa and seven were in the carbonate rocks at depths below 280 m

Three of the safety trials in the carbonate formations had a small nuclear yield (Section 5.9)

5 3. ASSEMBLY AND PLACEMENT OF NUCLEAR DEVICES

The nuclear devices tested at the CEP were housed within a cylindrical steel container 1.3 m in diameter, 10–25 m in length (depending on instrumentation needs) and weighing up to 70 t (Bouchez and Lecomte 1996). The components of the container, except for the nuclear device, were put together in an assembly hall on Mururoa. They were transported in the horizontal position by road or barge (in the case of tests under the lagoons) to the test site. The nuclear device was then fitted into the assembly and measurement cables were connected. The container was placed into the vertical position and lowered into the shaft using a steel cable and winch.

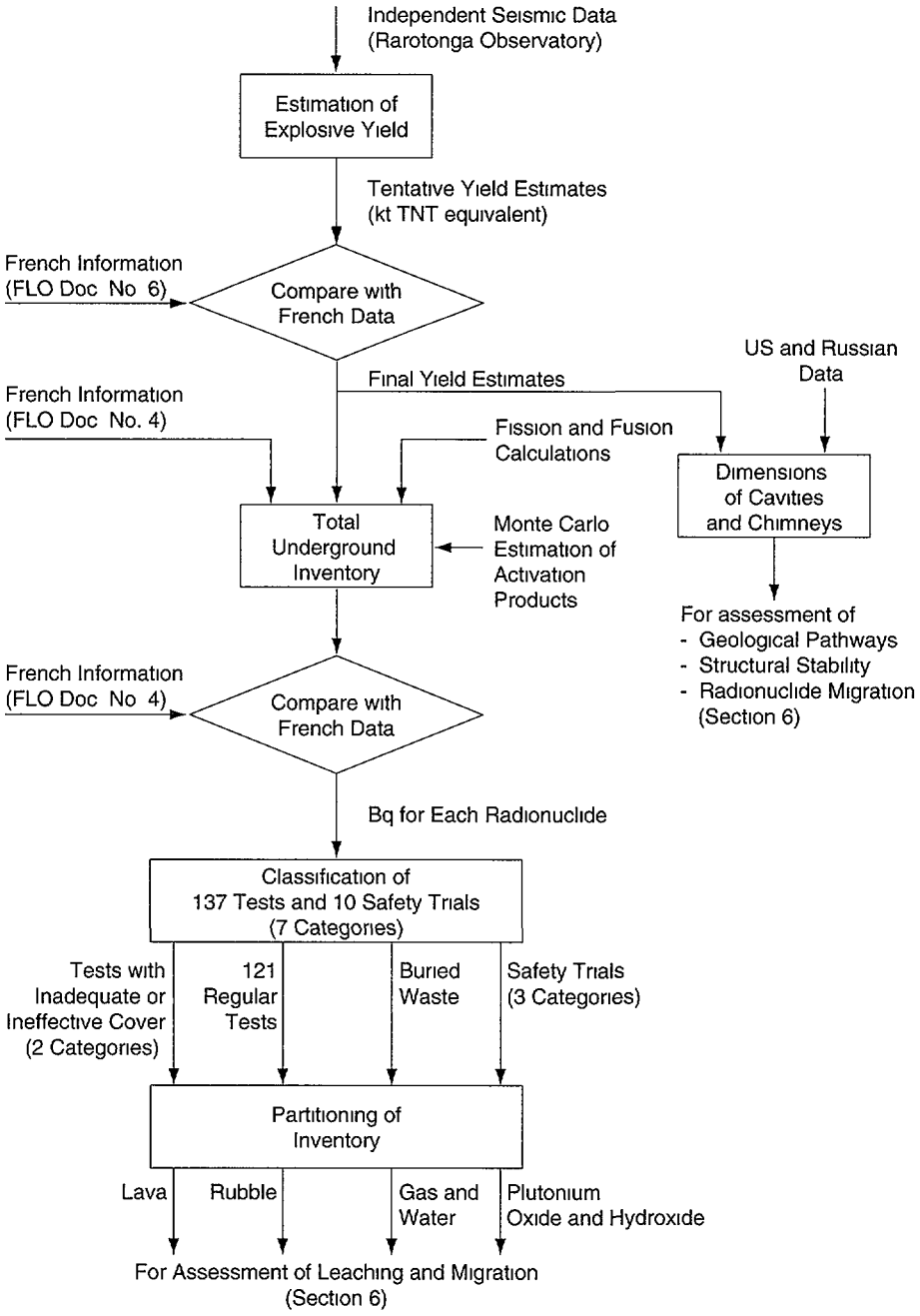


FIG 43 Methodology for estimation of inventory and partitioning of radionuclides (FLO French Liaison Office)

FIG. 44. Locations and yields of underground tests at Mururoa. (Adapted from French Liaison Office Document No. 6.)

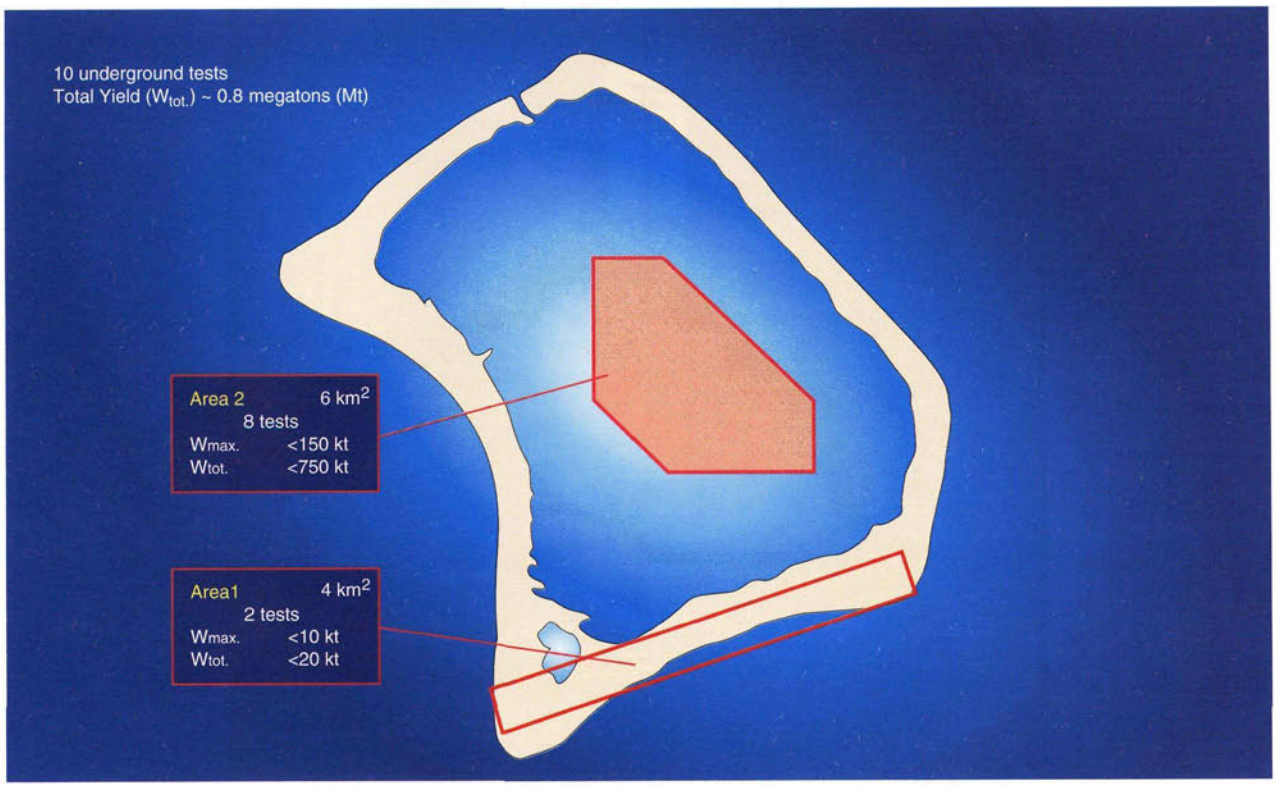


FIG. 45. Locations and yields of underground tests at Fangataufa. (Adapted from French Liaison Office Document No. 6.)

Drilling of the deep (500–1100 m), 1.52 m diameter vertical shafts, to ensure that the device would not jam as it was being lowered into position, was a major undertaking. In particular, specifications called for a maximum slant from the vertical of less than 1°. The carbonate zone is highly permeable so the shafts, whether on land or under the lagoons, are filled with water. The drill assembly comprised nine toothed wheels made of steel or tungsten carbide. The drill cuttings were conveyed to the surface by injecting air into the shafts and airlifting the debris to the surface. Drilling of the shafts under the lagoon required development of new techniques for drilling from a barge, including compensation for heaving caused by heavy swells.

The first hole drilled on the rim at Fangataufa was completely lined with a steel casing. This was found to be unnecessary and, in later tests, only the top few metres, which comprised unconsolidated sediments, were cased. Nevertheless, it was sometimes necessary to use cement to consolidate the rock when drilling through unstable zones.

After drilling of the shaft, the exact position for detonation (the zero point) was determined on the basis of a geological assessment. Major faults and geological discontinuities, which might favour leakage of radionuclides, were avoided as far as possible. Another criterion was complete confinement within the basaltic rock, with the size of the explosion and the thickness of

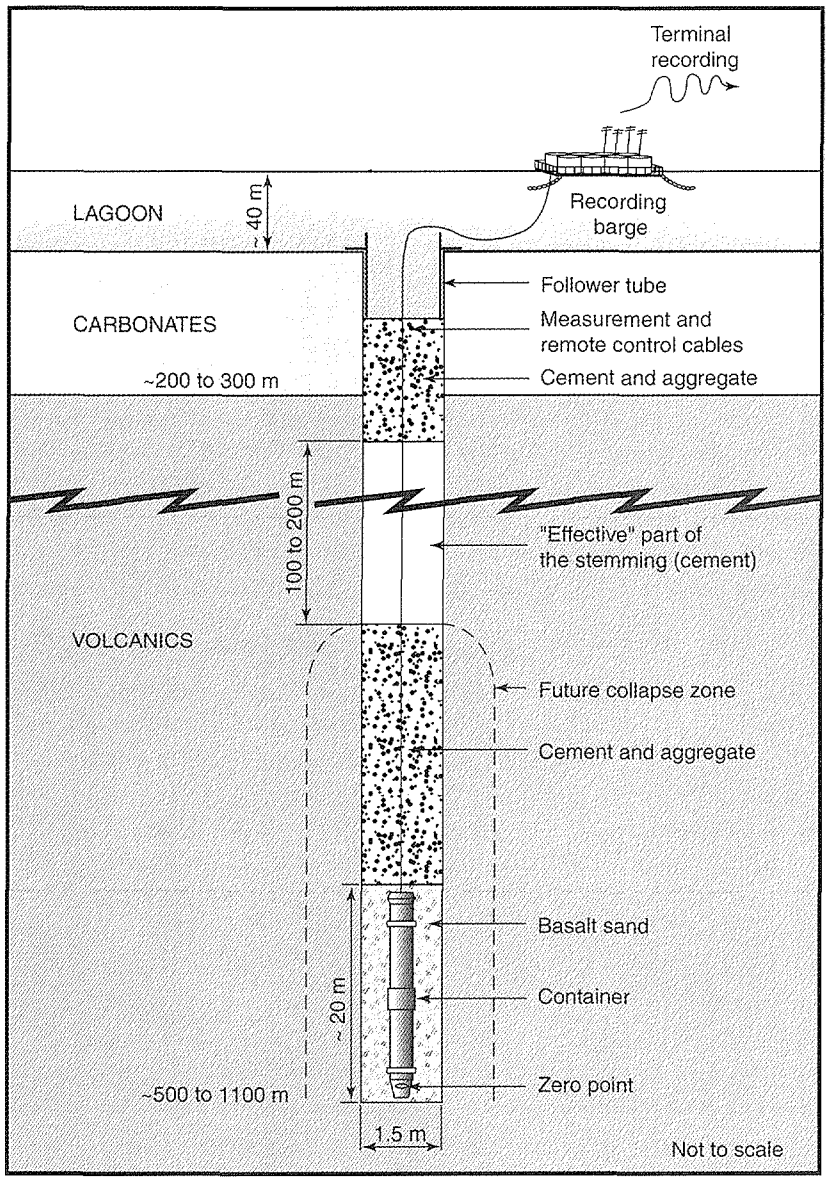
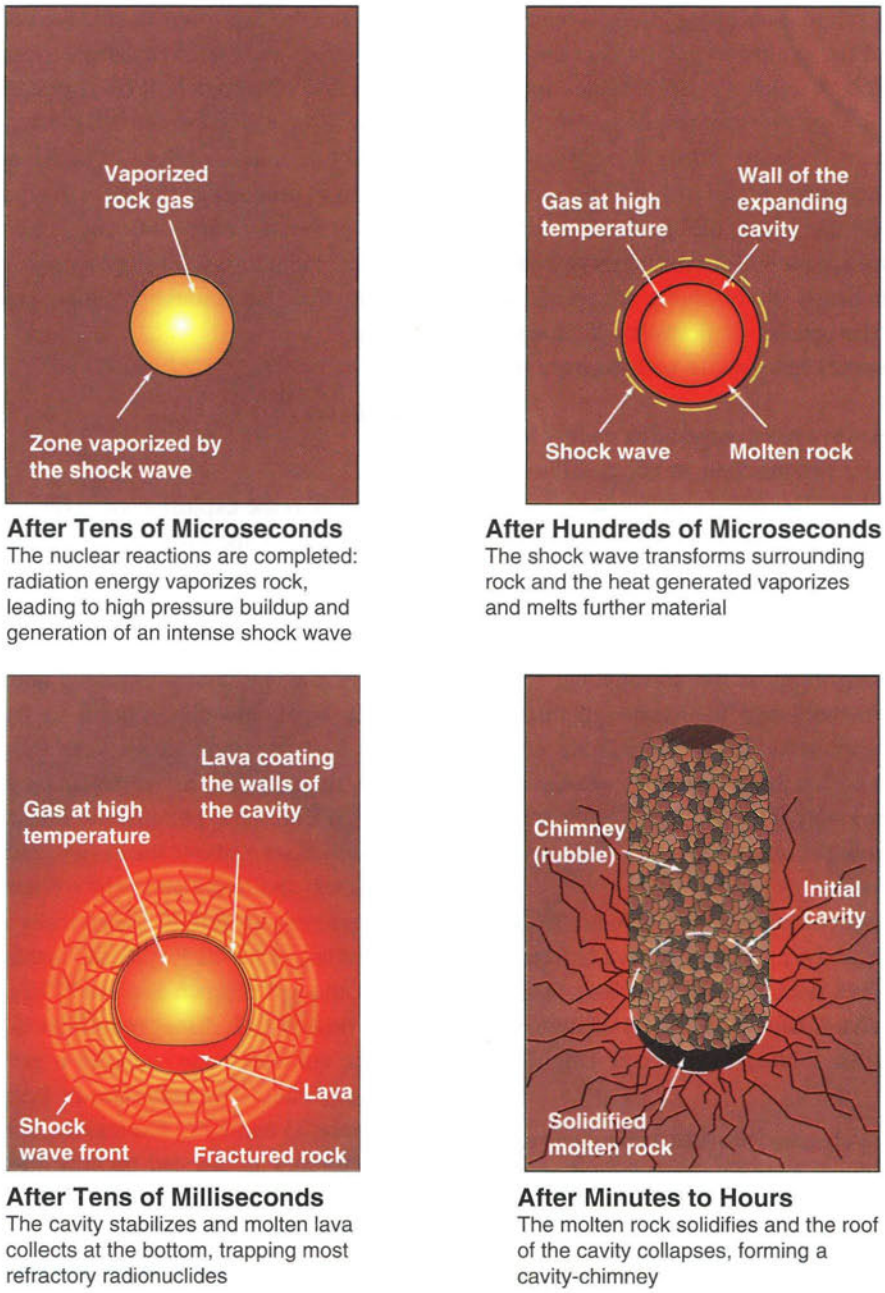


FIG. 46. Assembled nuclear device in place under Mururoa lagoon. (Adapted from Bouchez and Lecomte (1996).)

volcanic cover being taken into consideration. This criterion was not always met, as will be discussed in Section 5.9.

After lowering of the assembled device to the selected zero point, the annular space around the container was backfilled with basaltic sand. The shaft was then gradually filled with a mixture of cement and basalt aggregate to the top of the predicted collapse zone. Above this point, a homogeneous cement plug was used, typically 100–200 m in length. The cement slurry was required to meet precise specifications to ensure proper setting under water since this cement stemming plug is an important component of the containment barrier (Bouchez and Lecomte 1996). Above this point, further layers of cement or aggregates were added but these were not considered to be critical to the containment. Measurement and remote control cables between the container and the control centre were encased within the cement. Figure 46 shows an assembled device in place under Mururoa lagoon.



After Tens of Microseconds
The nuclear reactions are completed: radiation energy vaporizes rock, leading to high pressure buildup and generation of an intense shock wave

After Hundreds of Microseconds
The shock wave transforms surrounding rock and the heat generated vaporizes and melts further material

After Tens of Milliseconds
The cavity stabilizes and molten lava collects at the bottom, trapping most refractory radionuclides

After Minutes to Hours
The molten rock solidifies and the roof of the cavity collapses, forming a cavity-chimney

FIG. 47. Sequence of events following an underground nuclear explosion.

5.4. PHYSICAL PHENOMENA ASSOCIATED WITH AN UNDERGROUND NUCLEAR TEST

An underground nuclear explosion generates enormously high pressures and temperatures at the explosion source. Figure 47 depicts the sequence of events after the detonation.

In the first or *nuclear phase* of an explosion (not shown in Fig. 47), which lasts only about 1 μs, all the nuclear reactions take place. Virtually no movement of material occurs during the nuclear phase.

In the second or *hydrodynamic phase*, a pressure of several hundred kilobars is generated and the surrounding rock behaves as a fluid. This phase affects a region of a few metres around the explosion point where the rock is vaporized or melted. A shock wave propagates and the expansion of gases at high pressure results in the formation of a near spherical cavity whose dimensions are determined by the resistance of the surrounding rock.

In the third or *plastic phase*, the shock wave travels through the solid rock with sufficient energy to change its properties permanently by crushing, fracturing and cracking. During this phase, a network of fractures develops which becomes less intense with distance from the explosion point.

When the shock wave has dissipated its energy to the extent that permanent deformation is not possible, the *elastic phase* is reached. The wave now propagates elastically and becomes a seismic wave which can be detected over global distances.

In the final phase, the cavity reaches its maximum size when the pressure of the gases is no longer sufficient to cause further compaction of the surrounding rocks. The cavity begins to cool and the vaporized material condenses. A lava meniscus forms at the base of the cavity. The pressure within the cavity drops and the fractured rock above the cavity falls, creating a 'chimney' of rubble. The final collapse may not occur until several hours after the explosion

The interstitial spaces within the rubble are initially filled with gases but, as the pressure falls, water from the surrounding basalt rock begins to infiltrate back into the cavity–chimney[6]. Eventually, the cavity–chimney is filled with water at the lithostatic pressure. This filling process can take from several days to months, depending on the yield of the explosion (and hence the volume of the cavity–chimney formed)

The mass of material vaporized in a nuclear explosion is about 80 t per kt yield. The quantity of lava formed varies between 500 and 1000 t per kt yield, depending on the nature of the rock and its moisture content (French Liaison Office Document No. 4, Smith 1995).

5.4.1. Dimensions of cavity and chimney

The radius of the cavity depends on the energy (or yield) of the explosion and the type of rock A number of empirical and semiempirical expressions have been proposed (Butkovich 1967, Michaud 1968, Clossman 1969, Borg 1970, Derlich 1970, Choukin 1992, Smith et al. 1996). In most of these expressions, the volume of the cavity is proportional to the energy release, so that the cavity radius varies with the cube root of yield. The French authorities have proposed a simple empirical expression that summarizes their experience at the CEP site:

$$R_c = 100\left(\frac{W}{h}\right)^{1/3} \quad (1)$$

where W is the explosive yield (kt), h is the depth (m) of the test below the surface and R_c is the cavity radius (m). Allowing for differences in rock type, this expression is generally consistent with other data in the open literature (Technical Report, Vol 3).

Following cavity formation and the passage of the shock wave outwards from the cavity, there is a redistribution of the static stresses. As the gases in the cavity cool, the pressure inside the cavity falls well below the normal lithostatic pressure. Under these conditions, the weakened rock above the cavity collapses, resulting in a chimney and some secondary fracturing. The time of collapse can be detected seismically and varies from test to test but, at the CEP, typically occurs between 1 and 5 h after the test (French Liaison Office Document No. 7). The broken rock that accumulates in the cavity and then in the chimney zone occupies a greater volume than it did originally. The void ratio of fallen rock is generally between 25 and 30%. Eventually, upward propagation of the chimney is arrested because there is no longer any free volume into which new blocks can fall.

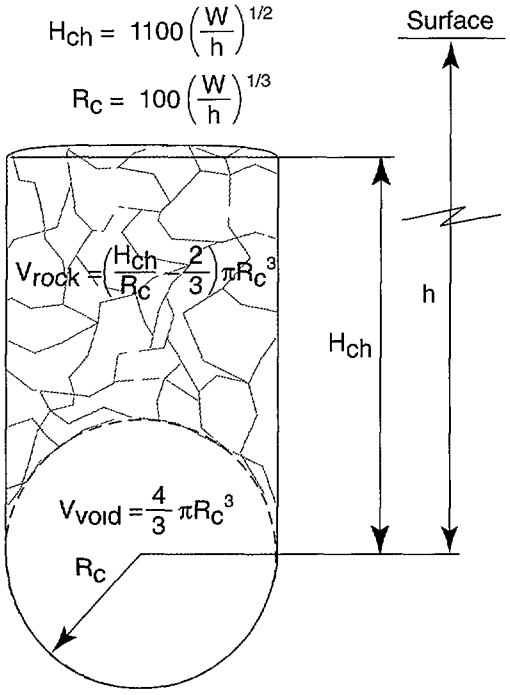
The height of the chimney zone is generally four to five times the cavity radius if the height is defined as the distance between the zero point and the top of the chimney The French Liaison Office (Document No. 6)

[6] The term (cavity–)'chimney' has been used extensively in the US literature to refer to the rubble cone formed after the collapse of the cavity formed by an underground nuclear test Although the term is misleading, as it evokes the idea of a duct leading to the free atmosphere rather than a closed cavity, it has become common jargon in the technical literature and has been used throughout the reports resulting from the Study

has given a formula for the height H_{ch} which fits this for yields below 10 kt·

$$H_{ch} = 1100\left(\frac{W}{h}\right)^{1/2} = 11\left(\frac{W}{h}\right)^{1/6} R_c \qquad (2)$$

This expression is empirical and there does not appear to be any theoretical reason for the square root dependence. At higher yields, this formula is quite conservative, with an H_{ch}/R_c ratio as high as 8, which has been described as the upper envelope of all chimney heights at the CEP. The relationship between cavity radius and chimney height is illustrated in Fig. 48 It should be noted that the chimney may not be as symmetric or as well defined as shown in the figure



TYPICAL DIMENSIONS

Yield, W (kt)	Depth, h (m)	Cavity radius, R_c (m)	Chimney height, H_{ch} (m)
5	500	22	110
5	1000	17	78
50	500	47	348
50	1000	37	246
150	1000	53	426

FIG 48 Dimensions of a nuclear cavity and chimney

The depth of burial was not provided for each test, with the result that Eqs (1) and (2) could not be used for transport modelling calculations. In the Study, the following simple expressions are used.

$$R_c = 10W^{1/3} \qquad (3)$$

$$H_c = 5R_c \qquad (4)$$

5.4.2. Venting and prompt injection

Very high pressures are generated during an underground nuclear explosion and, under some conditions, these can lead to the release of radioactive gases and vapours to the atmosphere and/or injection of gases and molten material into fractures of the rock beyond the immediate vicinity of the cavity. 'Venting' refers to the release of volatile radionuclides at the time of detonation. US data indicate that, of 500 underground tests carried out in Nevada, 32 (6.4%) resulted in off-site contamination due to venting (United Nations 1993). Trace amounts of short lived radionuclides have also been detected in Europe from underground testing by the former USSR. However, the radiation doses from venting have been very small compared with those from atmospheric testing (United Nations 1993).

Independent evidence for venting at the CEP is equivocal. Certainly, radionuclide releases from underground tests have not been detected at any of the fallout monitoring stations in the South Pacific On the other hand, a New Zealand, Australian and Papua New Guinea Scientific Mission to Mururoa Atoll (the 'Atkinson Mission') (New Zealand Ministry of Foreign Affairs 1984) concluded that venting had occurred on the basis of the detection of tritium in soil gas However, this evidence is open to other interpretations (Section 5.9). During the Cousteau Mission to the test site at Mururoa in June 1987, ^{131}I was detected (Cousteau 1988) This was attributed by the French authorities to leakage from a re-entry borehole drilled shortly after a test. The French Liaison Office has advised the Study team that minor releases have occurred via instrument cables embedded in the cement plug (Fig. 46), but there has been no major venting

The Study team is unable to reach any definitive independent conclusion as to whether venting occurred at the CEP, because any evidence would have disappeared a long time ago. In contrast to the US tests mentioned above, at the CEP the depth of testing and the saturation of the rocks with water would have ensured that any venting would be minimal. It is clear, however, that the radiological consequences of venting have been

insignificant; essentially the same conclusion was reached by the Atkinson Mission.

Prompt injection is caused by a similar mechanism to venting and involves the injection of volatile radionuclides, or indeed molten rock ('stringers'), into fractures beyond the cavity radius This phenomenon has been identified from post-test drilling at the Nevada Test Site and has resulted in transport of radionuclides, particularly isotopes of ruthenium, antimony and caesium, away from the test cavity (Nimz and Thompson 1992, Smith 1995)

Although no detailed explanation of the mechanism of prompt injection has been published, it is possible that fractures could open up, after passage of the shock wave, when the tangential stresses in the rock become tensile for short periods. It would appear probable that hot gases in the cavity could pass through the molten lava, opening up fractures in the rock and then entering these fractures. The hot gases could melt the fracture surfaces, creating a thin lava coating on these surfaces.

Prompt injection appears less likely at the CEP than at other test sites because of the porosity, the horizontally layered structure and the in situ stress state, which favour vertical fracture propagation. Any such injection would tend to be primarily into the region which becomes the chimney after collapse of the cavity ceiling. French scientists have reported that they have never detected any evidence of prompt injection in any of their post-test drilling exercises.

5.5. ESTIMATION OF YIELDS FROM SEISMIC RECORDS

An underground nuclear explosion results in a seismic signal similar to that produced by an earthquake. Figure 49 reproduces the seismic trace recorded at Rarotonga Observatory from two of the French tests. The seismic signal is related to the yield W by an equation of the form:

$$m_b = a \lg W + b \qquad (5)$$

where m_b is the seismic body wave magnitude and a and b are constants which depend on the site and other factors such as depth and rock density and composition. Ideally m_b is determined from a number of seismic stations distributed in sectors around the source.

In order to estimate independently the yield of the French tests, the Study team examined the seismic records from New Zealand and Australia and a list published by the Natural Resources Defense Council (NRDC) in Washington, D.C., USA. However, the NRDC list is derived from the other two records with minor modifications. In the end, it was decided to use the New Zealand data from Rarotonga Observatory, 2000 km west of Mururoa, as the most reliable for the purpose of the Study. For a few tests, where records from Rarotonga were unavailable, data from the Yellowknife seismic array in Canada were used.

The French authorities have made public the names, dates and times of all 147 underground tests, including the 10 safety trials, but only the 7 trials with no fission energy release are identified (Table V) (Bouchez and Lecomte 1996, Carlstan et al. 1996). The actual yields of individual tests were not revealed; instead, the tests were divided into three categories according to yield as follows: A (0–5 kt), B (5–20 kt) and C (20–150 kt).

Not all the French tests were detected by Rarotonga Observatory. The signals from 11 nuclear tests, all of category A, were too weak for measurement. These tests have been arbitrarily assigned a yield of 1 kt.

Estimation of yield from the seismic signal of a single explosion is subject to considerable error, especially for low yield tests. Typically, individual yields are accurate to within a factor of 2 below or above the true value. However, the estimate of total yield from a large number of tests can be expected to be far more reliable. Table XXIII shows the yields of all underground tests at the CEP as estimated by the Study and as categorized by the French authorities (see also Table V). The seven safety trials with no fission energy release are indicated in Table V but the three with some fission are not.

The yields estimated by the Study are outside of the French classification (A, B or C) for 34 tests, mostly those with a low yield where the measurement uncertainty is greatest However, the effect of these discrepancies on the total yield (which is dominated by the high yield tests) is small (Technical Report, Vol. 3).

Figure 50 shows the estimated annual yields according to atoll and location (rim or lagoon) based on the seismic data. Table XXIV gives the cumulative yield on the same basis This shows that the largest tests were carried out in Fangataufa lagoon. The average test size was about 80 kt at Fangataufa and about 20 kt at Mururoa.

Estimates of the total yield as calculated in the Study are compared with French estimates in Table XXV. In addition to calculation of the total yield from the summation of the best estimate for each test, a Monte Carlo simulation was carried out to determine the likely range of yields on the basis of uncertainties in the measurement of the variables in Eq. (3). The total yield provided by the French Liaison Office (Document No. 4) is within the range of the Study estimates and very close to the Study's best estimate.

5.6. ESTIMATION OF FISSION AND FUSION YIELDS

The basic physics of nuclear weapons is summarized in Annex IV and will not be repeated here except to note that the nuclear fuel may contain isotopes of plutonium, uranium, hydrogen and lithium and their decay products, specifically the following isotopes:

— Weapons grade plutonium	^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am
— Weapons grade uranium	^{235}U, ^{238}U, ^{234}U
— Tritium	^{3}H
— Depleted or natural uranium	^{238}U, ^{235}U
— Lithium deuteride	^{6}LiD, ^{7}LiD.

The primary device may be fuelled by either weapons grade plutonium (>93% ^{239}Pu) or weapons grade uranium (>90% ^{235}U). Most modern weapons use plutonium in the core (commonly known as the 'pit') of the primary device. Tritium is used for boosting a fission device and is both an intermediate product and the fuel in the thermonuclear stage, where it is produced by neutron reactions with lithium and deuterium in the lithium deuteride. High enriched uranium (HEU), as well as depleted uranium, can be present in both the primary and secondary stages but, since there are reasons to assume that plutonium cores were used in the French tests (see Section (A) below), it has been assumed that HEU was not used in the primary devices.

The quantities of radionuclides produced by a nuclear test depend on the design of the device and the fuel used. The French authorities did not provide information on the types of device used in their tests. They did, however, provide a tabulation of the total residual radionuclides from the test programme as of 1 May 1996

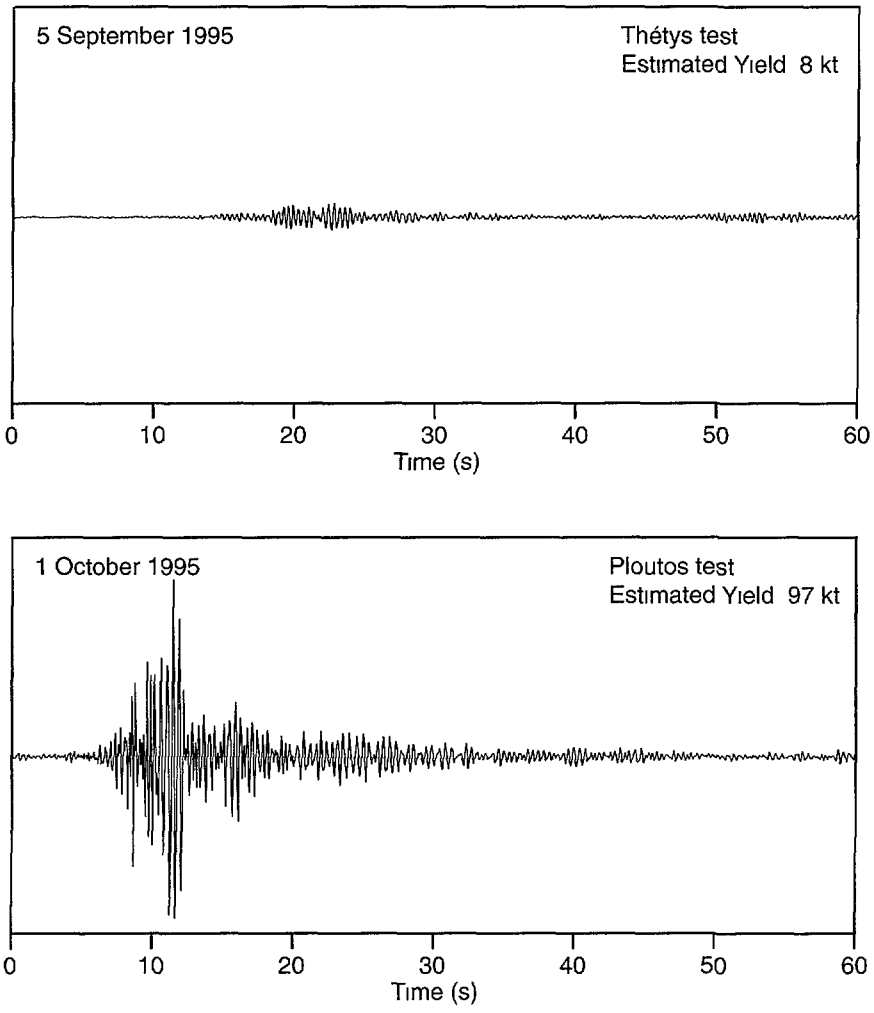


FIG 49. Relative seismic traces recorded at Rarotonga Observatory from two French tests (Data courtesy of W Smith, New Zealand Institute of Geological and Nuclear Sciences)

TABLE XXIII. YIELDS (*W*) OF FRENCH UNDERGROUND TESTS AND SAFETY TRIALS AT FANGATAUFA AND MURUROA AS ESTIMATED FROM SEISMIC MEASUREMENTS AT RAROTONGA OBSERVATORY

Year	Date	Name	Yield category[a]	m_b	*W* (kt)
		Fangataufa rim			
1975	5 Jun	Achille	A	5.33	23
	26 Nov.	Hector	B	5 23	17
		Total, Fangataufa rim		*2 tests*	*40 kt*
		Fangataufa lagoon			
1988	30 Nov	Cycnos	C	5.87	103
1989	10 Jun.	Cyzicos	C	5.75	74
	27 Nov.	Lycos	C	5.81	87
1990	26 Jun.	Cypsélos	C	5 86	100
	14 Nov.	Hyrtacos	C	5.92	118
1991	29 May	Périclyménos	C	5 88	106
1995	1 Oct	Ploutos	C	5.85	97
1996	27 Jan	Xouthos	C	5 58	46
		Total, Fangataufa lagoon		*8 tests*	*731 kt*
		Mururoa rim			
1976	3 Apr	Patrocle	A	4.20[b]	1
	11 Jul	Ménélas	B	5 09	12
	22 Jul.	Calypso	A		0[c]
	30 Oct	Ulysse A	A	4 20[b]	1
	5 Dec	Astyanax	A	4 20[b]	1
1977	19 Feb	Ulysse B	B	4 81	5
	19 Mar	Nestor	C	5 59	47
	2 Apr	Oedipe	A	4.20[b]	1
	28 Jun.	Andromaque	A		0[c]
	6 Jul.	Ajax	B	5.40	28
	12 Jul	Clytemnestre	A		0[c]
	12 Nov.	Oreste	A	5 20	16
	24 Nov	Enée	C	5 61	50
	17 Dec	Laocoon	A	5 09	12
1978	27 Feb	Polyphème	A	4 03	1
	22 Mar.	Pylade	A	5.09	12
	25 Mar.	Hécube	A	4 20[b]	1
	1 Jul.	Xanthos	A	4.20[b]	1
	19 Jul	Arès	B	4 40[d]	2
	26 Jul.	Idoménée	A	4.73	4
	2 Nov	Schédios	A	4 55	3
	14 Nov.	Aphrodite	A		0[c]
	30 Nov	Priam	C	5 70	64
	17 Dec	Etéocle	A	5 15	14
	19 Dec	Eumée	B	5 09	12
1979	1 Mar	Penthésilée	B	4.95	8
	9 Mar	Philoctète	B	5.15	14
	24 Mar	Agapénor	B	4.95	8
	4 Apr	Polydore	B	4 85	6
	18 Jun.	Pyrrhos	B	4 73	4
	29 Jun	Egisthe	C	5.40	28
	25 Jul	Tydée	C	5 90	112

TABLE XXIII. (cont.)

Year	Date	Name	Yield category[a]	m_b	W (kt)
		Mururoa rim (cont.)			
1979 (cont.)	28 Jul.	Palamède	A	5.15	14
	19 Nov	Chrysotémis	A	4 20[b]	1
	22 Nov	Atrée	A	4 73	4
1980	23 Feb	Thyeste	A	4 32	1
	3 Mar	Adraste	A	5 07	11
	23 Mar	Thésée	C	5.77	78
	1 Apr.	Boros	B	5 25	18
	4 Apr	Pélops	B	4 37	2
	16 Jun.	Euryple	C	5.37	26
	21 Jun	Ilus	B	5.01	9
	6 Jul	Chrysès	B	4.77	5
	9 Jul	Léda	A		0[c]
	19 Jul.	Asios	C	5 77	78
	25 Nov.	Laerte	A	4.47	2
	3 Dec	Diomède	C	5 62	51
1981	27 Feb.	Brotéas	A	4.95	8
	6 Mar	Tyro	A	4.40[d]	2
	28 Mar	Iphiclès	B	4.77	5
	8 Jul.	Lyncée	B	5.32	22
	11 Jul	Eryx	A	4 95	8
	18 Jul.	Théras	A	4.47	2
	3 Aug.	Agénor	C	5 21	16
	6 Nov	Léto	A	4 20[b]	1
	11 Nov	Proclès	B	4.55	3
	5 Dec.	Cilix	B	4.81	5
1982	20 Feb	Aérope	A	4.58	3
	24 Feb	Déiphobe	A	4 20[b]	1
	23 Mar.	Evénos	A	4 20[b]	1
	31 Mar	Aeson	A		0[c]
	27 Jun.	Laodice	A	4 37	2
	1 Jul.	Antilokos	C	5 28	20
	21 Jul.	Pitane	A	4.47	2
	27 Nov	Procris	A	4.20[b]	1
1983	25 Apr	Automédon	A	4.25	1
	18 Jun.	Burisis	A	4.58	3
	20 Jul.	Battos	B	5 04	10
	3 Dec	Linos	A	4.73	4
1984	8 May	Démophon	A	5 32	22
	12 Jun	Aristée	B	4 47	2
	27 Oct	Machaon	B	4 54	3
	1 Dec	Milétos	A	4.17	1
1985	30 Apr.	Cercyon	B	5.12	13
	3 Jun	Talaos	B	5 07	11
	24 Oct.	Héro	A	4 47	2
	24 Nov.	Zétès	B	4 81	5
1986	26 Apr	Hyllos	B	4 77	5
	6 May	Céto	A	4.75	5
	27 May	Sthénélos	B	4.67	4
	10 Nov.	Hésione	A	4 87	6

TABLE XXIII. (cont.)

Year	Date	Name	Yield category[a]	m_b	W (kt)
		Mururoa rim (cont.)			
1986 (cont)	6 Dec	Pénéléos	A	4.99	9
1989	25 Nov	Daunus	A		0[c]
		Total, Mururoa rim		*83 tests*	*976 kt*
		Mururoa lagoon			
1981	10 Apr	Clymène	B	4 95	8
	8 Dec.	Cadmos	B	5 17	15
1982	20 Mar.	Rhésos	B	5.23	17
	25 Jul	Laios	C	5 65	56
1983	19 Apr	Eurytos	C	5 53	40
	25 May	Cinyras	C	5 55	42
	28 Jun	Oxylos	B	5 46	33
	4 Aug.	Carnabon	C	4 95	8
	7 Dec.	Gygès	B	5 17	15
1984	12 May	Midas	C	5.65	56
	16 Jun	Echémos	C	5 47	34
	2 Nov.	Acaste	C	5.47	34
	6 Dec.	Memnon	C	5 63	53
1985	8 May	Nisos	C	5 82	90
	7 Jun	Erginos	B	4 77	5
	26 Oct	Codros	C	5 25	18
	26 Nov.	Mégarée	C	5.64	54
1986	30 May	Galatée	C	5.43	30
	12 Nov	Nauplios	B	5 34	24
	10 Dec	Circé	C	5 45	32
1987	5 May	Jocaste	B	4 77	5
	20 May	Lycomède	C	5 42	30
	6 Jun	Dirce	B	4.54	3
	21 Jun	Iphitos	C	5.17	15
	23 Oct.	Hélénos	C	5.62	51
	5 Nov	Pasiphae	B	5 25	18
	19 Nov.	Pélée	C	5.69	62
	29 Nov.	Danaé	B	4 65	3
1988	11 May	Nelée	C	5.28	20
	25 May	Niobé	C	5.79	82
	16 Jun	Antigone	A	4.77	5
	23 Jun	Déjanire	B	5 42	30
	25 Oct.	Acrisios	A	4 37	2
	5 Nov.	Thrasymèdes	C	5.59	47
	23 Nov	Phères	C	5 57	45
1989	11 May	Epéios	B	5.21	16
	20 May	Tecmessa	A	4 47	2
	3 Jun	Nyctée	C	5.28	20
	24 Oct.	Hypsipyle	C	5 34	24
	31 Oct	Erigone	B	5 28	20
	20 Nov.	Tros	B	5.40	28
1990	2 Jun	Télèphe	B	5 42	30

TABLE XXIII. (cont.)

Year	Date	Name	Yield category[a]	m_b	W (kt)
		Mururoa lagoon (cont.)			
1990 (cont.)	7 Jun.	Mégapenthès	B	4.65	4
	4 Jul.	Anticlée	B	5.25	18
	21 Nov.	Thoas	C	5.49	36
1991	7 May	Mélanippe	A	4.25	1
	18 May	Alcinoos	C	5.21	16
	14 Jun.	Pitthée	C	5.40	28
	5 Jul.	Coronis	A	3.80	1
	15 Jul.	Lycurgue	C	5.47	34
1995	5 Sep.	Thétys	B	4.93	8
	27 Oct.	Aepytos	C	5.52	39
	21 Nov.	Phégée	C	5.22	17
	27 Dec.	Thémisto	C	5.29	21
		Total, Mururoa lagoon		*54 tests*	*1445 kt*

[a] Yield classification as provided by the French authorities: A, <5 kt; B, 5–20 kt; C, 20–150 kt.

[b] None of these 11 (all category A) tests under the rim of Mururoa Atoll were detected at Rarotonga owing to the weak signals. They were assigned a magnitude of 4.20 corresponding to a yield of 1 kt.

[c] Safety trial without nuclear yield.

[d] These two tests were missed at Rarotonga owing to record changes. Data from the Yellowknife seismic array in Canada were used instead.

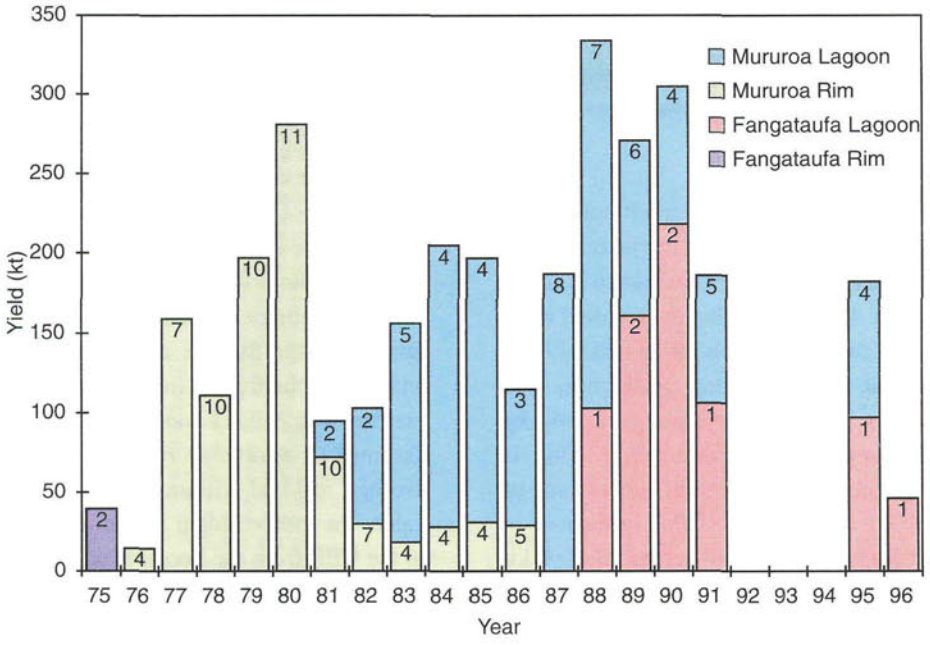


FIG. 50. Explosive yield, as estimated by the Study, and number of underground tests according to year and location. (The 140 tests include the 3 safety trials that led to some fission energy release.)

TABLE XXIV. NUMBER AND YIELD OF UNDERGROUND TESTS AND SAFETY TRIALS AT MURUROA AND FANGATAUFA

Location	Number	Total yield (kt)	Average yield (kt)
Mururoa rim	83[a]	976	13[b]
Mururoa lagoon	54	1445	27
Total, Mururoa	137[a]	2421	19[b]
Fangataufa rim	2	40	20
Fangataufa lagoon	8	731	91
Total, Fangataufa	10	771	77
Total, CEP	147[a]	3192	23[b]

[a] Includes 10 safety trials, 3 of which went critical

[b] Average yield is for nuclear tests only, i e. safety trials with no yield are excluded

TABLE XXV. COMPARISON OF ESTIMATES OF TOTAL YIELD (kt) BASED ON SEISMIC RECORDS WITH INFORMATION PROVIDED BY FRENCH AUTHORITIES

		The Study	
Location	French value	Best estimate	Range (95% confidence limits)
Mururoa	2400	2421	2390–3065
Fangataufa	800	771	641–1174
Total	3200	3192	3180–4058

(French Liaison Office Document No 4) Although these data were reasonably complete, no information was provided in written reports on uranium isotopes or some long lived activation products.

The approach taken in the Study has been to use information provided by the French scientists on residual levels of a few key radionuclides to estimate the fission and fusion yields attributable to the fuel components. The strategy is outlined below; more detailed information is provided in the Technical Report, Vol. 3.

(A) Energy yield due to fission of plutonium was estimated from the residual mass of plutonium

The information provided by the French authorities strongly suggests that most, if not all, of the underground test devices had a plutonium core. The French Liaison Office (Document No. 4) indicated that the residual mass of plutonium from all the underground tests was 517 kg After taking account of plutonium production and consumption reactions, it is estimated that about 546 kg of plutonium was present before detonation. This is equivalent to a pit of plutonium containing an average of 3.7 kg (3.4 kg ^{239}Pu and 0.3 kg ^{240}Pu), which is in reasonable agreement with reported values of 3–4 kg used in US and USSR devices.

Complete burnup of 1 kg of plutonium releases about 17 5 kt of energy. For the purposes of these calculations, the maximum burnup of plutonium was estimated to be 10%, which is equivalent to an average explosive yield of 6.5 kt per pit. (Burnups of plutonium of 20% or more are possible but require heavier containment, which is considered undesirable in modern weapons.) For low yield tests (<6.5 kt), it was assumed that all the yield came from plutonium fission When account is taken of these low yield tests, the average efficiency of plutonium utilization decreases to 7.8%. On this basis, the estimate of the total explosive yield due to fission of plutonium is 645 kt for Mururoa and 65 kt for Fangataufa.

(B) Energy yield due to fusion was estimated from residual levels of tritium

Tritium is consumed in thermonuclear reactions but, in practice, much is left over. Information in the literature (United Nations 1993, De Geer 1996) indicates that about 670 kg (or 240 EBq) of tritium remained from 273 Mt of fusion in worldwide atmospheric tests. This is equivalent to 2.46 g (or 0.88 PBq) of tritium remaining per kiloton of fusion.

As noted above, tritium may also be used as a booster in the primary device and is produced in ternary fission, although the latter source is negligible and was ignored in the Study's calculations On the basis of an analysis of the tritium inventory remaining from the low yield tests in Areas 1 and 2 of Mururoa Atoll (which were assumed to involve no fusion), it was estimated that the average residual tritium was 3.7 g per test. From this value, the total residual tritium (at the time of each test) in the CEP from the boosters was estimated to be 507 g.

The French Liaison Office (Document No. 6) gives the residual inventory of tritium initially deposited beneath the two atolls at the time of each test as 1412 g (or 505 PBq). After taking account of the residual tritium from the booster, the fusion yield is estimated to be

TABLE XXVI. BREAKDOWN OF ESTIMATED YIELDS (kt) FROM FUEL COMPONENTS

Location	^{239}Pu fission	^{235}U fission	^{238}U fission	Fusion	Total
Mururoa	650	1220	240	310	2420
Fangataufa	60	600	50	60	770
Total, CEP	710	1820	290	370	3190

(1412 – 507)/2 46 or 370 kt· 310 kt at Mururoa and 60 kt at Fangataufa

(C) Energy yield due to fast fission of ^{238}U was estimated from residual levels of ^{237}Np

Uranium-238 is often used in the secondary stage of a nuclear device, where it undergoes fission by high energy neutrons produced by the fusion process. In the flux of high energy neutrons, ^{237}Np is produced by a reaction in which one neutron is absorbed by the ^{238}U and two neutrons are ejected. The resulting radionuclide, ^{237}U (half-life 6.8 d), decays by beta emission to ^{237}Np.

Neptunium-237 is also produced by neutron capture in plutonium isotopes, leading to the production of ^{241}Pu (half-life 14 years), which decays to ^{241}Am (half-life 432 years) and then to ^{237}Np.

Using the inventory data provided in French Liaison Office Document No. 4, it is possible to calculate the ^{237}Np produced from each of these sources. The calculations show that, of the 9.6 kg ^{237}Np produced to date and that will be produced in the future, 6.6 kg arises from ^{238}U and 3.0 kg from decay of ^{241}Pu and ^{241}Am.

From published data, it is estimated that, for every atom of ^{238}U converted to ^{237}U, there are 2 5 atoms of ^{238}U (on average) that undergo fission induced by fast neutrons in the secondary stage of the nuclear device (De Geer et al. 1979, Hicks 1984, Technical Report, Vol 3). Using this factor, the explosive yield due to the fast fission of the ^{238}U is estimated to be about 290 kt.

(D) Energy yield due to fission of ^{235}U was estimated from the total energy yield after subtracting the energy yields due to other reactions

Weapons grade uranium (where the ^{235}U content is above 90 wt%) can be used in the secondary stage of a nuclear device. The energy derived from this source was calculated simply from the difference between the total yield as calculated from the seismic data and the sum of the estimated yields from other sources described above. This gave a yield of approximately 1820 kt from ^{235}U fission: 1220 kt at Mururoa and 600 kt at Fangataufa.

The breakdown of energy yields due to fusion and the fissioning of ^{239}Pu, ^{235}U and ^{238}U calculated from the above methodology is given in Table XXVI. It should be noted that fusion contributes only about 12% of the total energy yield. This relatively low percentage is not surprising in underground tests since there is little need to follow the thermonuclear process after successful compression has been proven. Higher fusion yields would necessitate an increase in the costs of underground testing and would lead to greater fracturing and potential damage to the atolls.

As noted in Annex IV, the distribution of fission product yields can be quite sensitive to the particular nucleus that undergoes fission (^{235}U, ^{238}U or ^{239}Pu) and the energy of the neutrons. This fact can be used as an important check to determine whether the inventory provided by the French Liaison Office (Document No. 4) is consistent with the mix of fission yields given in Table XXVI.

The best indicator for this purpose is the ^{137}Cs/^{90}Sr activity ratio. For fission of ^{235}U, ^{238}U and ^{239}Pu, with neutrons having a fission energy spectrum, this ratio is 1.09, 1.78 and 3 07, respectively This difference in the yield of ^{137}Cs and ^{90}Sr in the fission of ^{235}U and ^{239}Pu by fission spectrum neutrons is illustrated in Fig. 51. The ^{137}Cs/^{90}Sr ratio provided by the French Liaison Office was 1.44 for Mururoa and 1.19 for Fangataufa. These values are within 4% of the ratios that would be expected from the mix of energy yields due to fission estimated in the Study and given in Table XXVI.

5.7. MODES OF PRODUCTION OF RADIONUCLIDES FROM NUCLEAR TESTS

In order not to exclude any important radionuclide from consideration, a complete scan was undertaken of the current Evaluated Nuclear Structure Data File (ENSDF) maintained by Brookhaven National

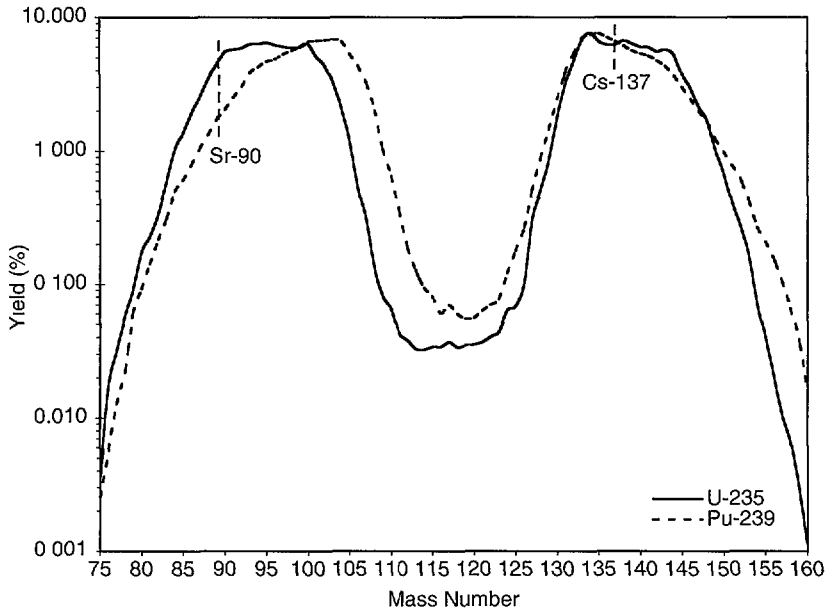


FIG 51 Yield curves for fission of ^{235}U and ^{239}Pu by fission spectrum neutrons

Laboratory. The ENSDF gives nuclear properties for more than 2000 radionuclides and 249 stable nuclides. For the purposes of the Study, only radionuclides with half-lives between 1 and 10^{10} years were considered. The rationale for the lower limit was that nuclides with a shorter half-life will not contribute to future doses because of the intrinsic time required for transport to the biosphere Indeed most of these short lived radionuclides have already decayed. The upper limit of 10^{10} years was chosen because extremely long half-lives imply low specific activities which would result in insignificant doses. This criterion reduced the number of radionuclides for future consideration to 124.

The next step was to determine which of these radionuclides might be present in the cavity–chimneys Five modes of production leading to the following radioactive materials were distinguished.

(1) Residual fuel materials
(2) Reaction products of fuel materials
(3) Fission products
(4) Activation products of non-fuel bomb materials
(5) Activation products of construction materials and rocks surrounding the explosion.

5.7.1. Residual fuel materials and reaction products (production modes 1 and 2)

As noted in Section 5.6, the residual fuel materials are tritium and isotopes of plutonium and uranium. In addition, other actinides are produced by neutron reactions, either directly or by decay. The residual quantities of most of these radionuclides were taken from the French data after confirmation that they were consistent with published data After consideration of possible reactions, two additional radionuclides (^{242}Pu and ^{236}U) were added to the basic list provided in the French reports.

The French Liaison Office did not include the quantity of residual uranium in its published list of radionuclides but did indicate in other communications that about 350 kg HEU was used in the tests. Naturally occurring uranium isotopes (^{234}U, ^{235}U and ^{238}U) were not considered further in this analysis because the amounts of these radionuclides produced in association with the explosions are very small compared with the quantities naturally occurring in the volcanic rocks; there is 50 t of naturally occurring uranium just in the basalt displaced from the test cavities (Technical Report, Vol. 3)

TABLE XXVII. RADIONUCLIDES PRODUCED BY UNDERGROUND NUCLEAR TESTING THAT SATISFY SELECTION CRITERIA

Radionuclide	Decay	Half-life (a)		Production mode
^{3}H	β^-	12.3	1, 2	Fuel residue and fuel product
^{14}C	β^-	5 730	4, 5	(n,p) in device and environment
^{36}Cl	β^-	301 000	4, 5	(n,γ) in device and environment
^{41}Ca	EC[a]	103 000	5	(n,γ) in environment
^{55}Fe	EC	2 7	4, 5	(n,γ), (n,2n) and (n,α) in device and (n,γ) in environment
^{59}Ni	EC	76 000	4	(n,γ) in device
^{60}Co	β^-	5 3	4	(n,p) in device
^{63}Ni	β^-	100 1	4	(n,γ) in device
^{79}Se	β^-	650 000	3	Fission product
^{85}Kr	β^-	10 8	3	Fission product
^{90}Sr	β^-	28 8	3	Fission product
^{93}Zr	β^-	1 530 000	3	Fission product
^{99}Tc	β^-	211 100	3	Fission product
^{106}Ru	β^-	1.0	3	Fission product
^{107}Pd	β^-	6 500 000	3	Fission product
$^{113}Cd^{m}$	β^-	14 1	3	Fission product
$^{121}Sn^{m}$	IT[b]	55	3	Fission product
^{126}Sn	β^-	~100 000	3	Fission product
^{125}Sb	β^-	2 8	3	Fission product
^{129}I	β^-	15 700 000	3	Fission product
^{134}Cs	β^-	2 1	3	Fission product
^{135}Cs	β^-	2 300 000	3	Fission product
^{137}Cs	β^-	30.1	3	Fission product
^{147}Pm	β^-	2.6	3	Fission product
^{151}Sm	β^-	90	3	Fission product
^{152}Eu	EC	13.5	5	(n,γ) in environment
^{154}Eu	β^-	8.6	3, 5	Fission product and (n,γ) in environment
^{155}Eu	β^-	4 8	3	Fission product
^{236}U	α	23 420 000	1, 2	Fuel residue and fuel product
^{237}Np	α	2 144 000	1, 2	Fuel residue and fuel product
^{238}Pu	α	87 7	2	Fuel product
^{239}Pu	α	24 110	1, 2	Fuel residue and fuel product
^{240}Pu	α	6 564	1, 2	Fuel residue and fuel product
^{241}Pu	β^-	14 4	1, 2	Fuel residue and fuel product
^{242}Pu	α	373 300	2	Fuel product
^{241}Am	α	432 2	1, 2	Fuel residue and fuel product

[a] EC: electron capture
[b] IT isomeric transition

5.7.2. Fission products (production mode 3)

Fission produces hundreds of short lived, neutron rich radionuclides that decay by beta emission to more long lived and finally stable nuclides. The fission yields of the various fission products depend on the energy of the initiating neutron and the target nucleus. In the Study, it was assumed that all fission of plutonium and ^{235}U was by neutrons with a fission energy spectrum, whereas fission of ^{238}U was due to a 50/50 mix of high energy (14 MeV) neutrons from fusion and the normal fission

neutron spectrum. Fission products with yields over 0 001% were considered in the Study Nineteen fission product radionuclides met this criterion.

5.7.3. Activation products (production modes 4 and 5)

The materials used in the French devices are not known exactly but would obviously include steel, aluminium, plastics, beryllium and high explosives. Six radionuclides (^{14}C, ^{36}Cl, ^{55}Fe, ^{59}Ni, ^{60}Co and ^{63}Ni) were selected for further consideration on the basis of possible neutron reactions in these structural materials.

The underground tests at the atolls were carried out in basalt. The pores within the basalt (about 10% by volume) are saturated with sea water. The only radionuclides produced in significant amounts by neutron reactions with materials surrounding the explosion (and meeting the half-life criterion) are ^{36}Cl, ^{41}Ca, ^{55}Fe, ^{152}Eu and ^{154}Eu.

5.8 RADIONUCLIDE INVENTORY

From a knowledge of the nuclear reactions and decay occurring in the fuel, construction materials and neighbouring rocks, the list of 124 radionuclides (determined solely from half-life considerations) was reduced to 36. Table XXVII lists these radionuclides and identifies their mode of production.

The radionuclide inventories were determined for each of the 137 underground nuclear tests and 10 safety trials carried out at the CEP The activity of each radionuclide was determined at the time of the test and then corrected for decay to a common date of 1 May 1996 for comparison with the information provided by the French Liaison Office.

As previously indicated, a core of 3.7 kg of plutonium (3.4 kg ^{239}Pu and 0.3 kg ^{240}Pu) was assumed in each device and it was further assumed that the amount of plutonium consumed equalled that produced so that the quantity of these isotopes remained unchanged. Fission product yields were determined from yield data in the open literature (England and Rider 1993) Monte Carlo simulations were used to determine the activation products These calculations depend on the exact geometry and composition of materials and hence are subject to considerable uncertainty.

The estimated total yield of 0 45 kt of energy released in the three safety trials that involved some fission would have consumed less than 30 g of plutonium, although some 1 TBq ^{90}Sr and 3 TBq ^{137}Cs would have been produced. The quantity of residual plutonium in each of the shafts housing the ten safety trials, including the three in which there was some fission energy release, was assumed to be 3.7 kg.

Table XXVIII compares the total inventory as estimated from the various calculations described above with the values provided by the French Liaison Office (Document No. 4) While it should be noted that the two compilations are not completely independent, in that residual fuel activities were based on the French information, the two sets of figures are generally in excellent agreement for the key fission products.

Nevertheless, some differences are apparent. The French estimate for ^{134}Cs is 25 times higher, but this could be explained by traces of stable caesium present in the actual devices but not assumed in the Monte Carlo simulations. It could also be due to the presence of natural caesium in the basaltic rock which was not considered in the Study because of the absence of data Two other estimates, for ^{106}Ru and ^{155}Eu, differ by more than a factor of 2 These differences are explained by simplifications used in the French calculations (Technical Report, Vol 3).

The inventory of radionuclides as determined in this manner was used in subsequent calculations in the Study, since it is generally consistent with, but more extensive than, the list provided by the French authorities

5.9 CLASSIFICATION OF TESTS FOR ASSESSMENT PURPOSES

The 137 tests and 10 safety trials undertaken at the two atolls, together with the two shafts used for burial of wastes, represent 149 discrete underground sources of radioactive material. It would be impractical to model radionuclide transport from each of these sources separately even if precise information were available on the location of each test or trial cavity To overcome this problem, it was decided to divide the 149 sources into seven categories as depicted in Fig. 52 and described in Table XXIX.

The majority of tests (121), with an estimated total yield of about 2900 kt, are in Category 1, where effective cover of volcanic rock exists above the chimney of each cavity To facilitate more detailed analysis of these 'regular tests', information was requested (and received) from the French Liaison Office on the yield of such tests and the thickness of volcanic cover. The information was supplied in ranges of yield (0–10, 10–40, 40–80 and >80 kt) and cover thickness (0–50, 50–100, 100–200 and >200 m) according to location (Mururoa rim, Mururoa lagoon, Fangataufa rim and Fangataufa lagoon). These data were converted to average yields and cover

TABLE XXVIII COMPARISON OF ESTIMATES OF RADIONUCLIDE INVENTORY (TBq) AT MURUROA AND FANGATAUFA ATOLLS WITH INFORMATION PROVIDED BY FRENCH AUTHORITIES (AS OF 1 MAY 1996)

Radionuclide	The Study			French total[a]
	Mururoa	Fangataufa	Total	
^{3}H	232 000	48 000	280 000	280 000
^{14}C	25	2.6	28	nd[b]
^{36}Cl	1 3	0 4	1 7	nd
^{41}Ca	1 0	0 3	1 3	nd
^{55}Fe	3 800	3 800	7 600	nd
^{59}Ni	2.9	0 9	3.8	nd
^{60}Co	1 600	1 000	2 600	2 500
^{63}Ni	340	110	450	nd
^{79}Se	0 008	0 003	0 011	nd
^{85}Kr	670	380	1 000	700
^{90}Sr	7 300	3 500	10 800	11 000
^{93}Zr	0 23	0 09	0.32	0 35
^{99}Tc	1 9	0.6	2 5	2 8
^{106}Ru	3 900	3 400	7 300	20 000
^{107}Pd	0 18	0 03	0 21	nd
$^{113}Cd^{m}$	2.7	0 6	3 3	nd
$^{121}Sn^{m}$	0 32	0 03	0 36	nd
^{126}Sn	0 14	0.03	0 18	nd
^{125}Sb	420	310	730	700
^{129}I	0 004 7	0.001 4	0 006 1	0 005
^{134}Cs	0 68	0.26	0 94	25
^{135}Cs	0 20	0 07	0 27	0 24
^{137}Cs	10 700	4 100	14 800	14 500
^{147}Pm	5 200	5 900	11 000	11 000
^{151}Sm	390	120	500	750
^{152}Eu	230	100	330	140
^{154}Eu	33	17	50	nd
^{155}Eu	330	140	470	1 200
^{236}U	0 12	0 02	0.14	nd
^{237}Np	0 22	0 03	0 25	0.25
^{238}Pu	185	15	200	200
^{239}Pu	1 030	70	1 100	1 100
^{240}Pu	280	20	300	300
^{241}Pu	6 200	620	6 800	6 800
^{242}Pu	0.008 4	0 000 85	0 009 2	nd
^{241}Am	350	30	380	380

[a] Source: French Liaison Office Document No 4.

[b] nd: data not provided

thicknesses. Table XXX gives the breakdown Radionuclide inventories were determined for generic tests of 1, 5, 10, 20, 25, 50, 60, 100 and 150 kt (Technical Report, Vol. 3).

Category 2 comprises three or four tests having yields above 20 kt (Lycos, Mégarée, Nestor and/or Enée) identified by the French authorities as having an inadequate cover of volcanic material (French Liaison Office Document No. 8) The ineffectiveness of the volcanic cover was inferred from measurements of tritium leakage into the carbonate rocks above the test location and from a re-examination of log records made during drilling of the test shafts. Nestor and Enée were carried out under the Mururoa rim in 1977 with 50–100 m of volcanic cover, Mégarée was a medium yield test carried out with 50–100 m of volcanic cover

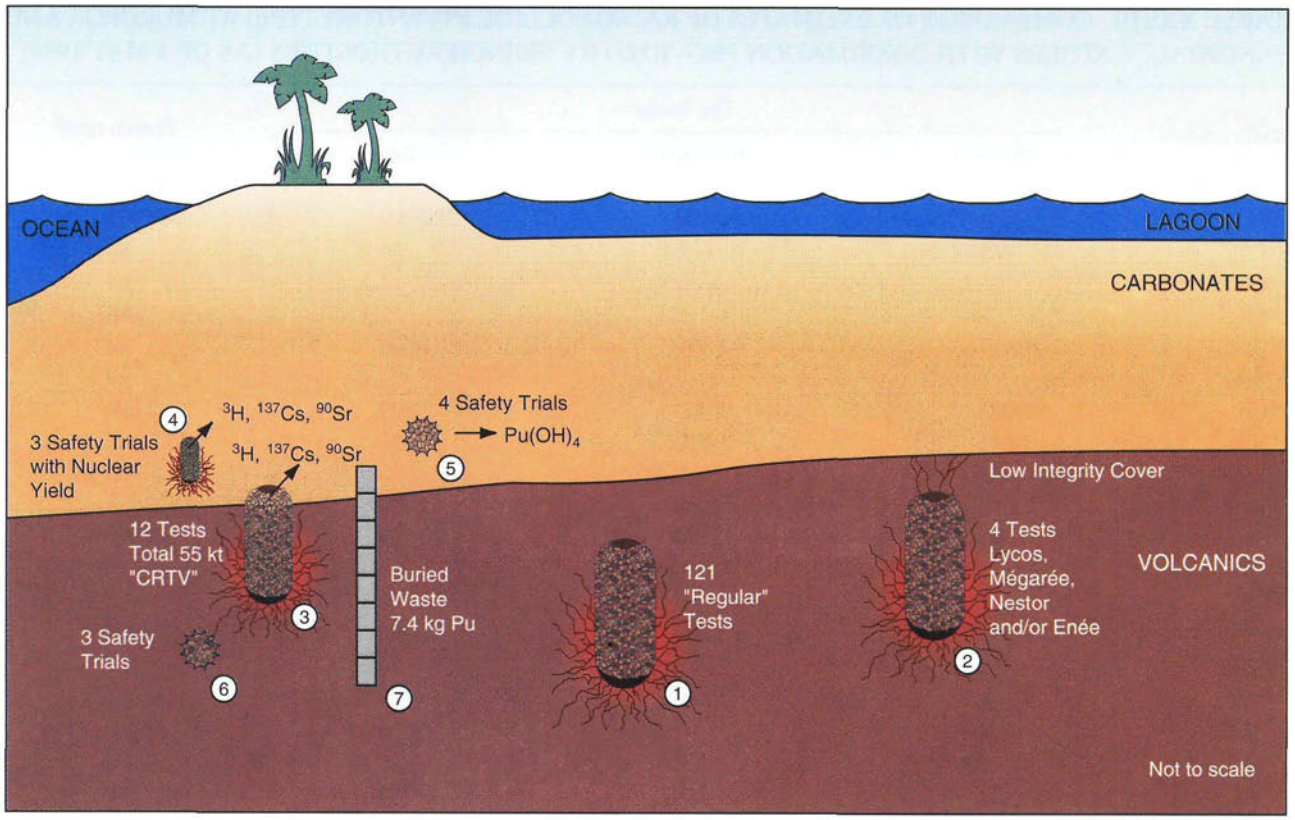


FIG. 52. The seven categories used in analysis of radionuclide transport through the geosphere. (CRTV: chimney reaching top of volcanics.)

under Mururoa lagoon in 1985, and Lycos was a high yield test carried out in 1989 under the lagoon at Fangataufa at a depth of 800 m and with 140 m of volcanic cover above the chimney. The detection of tritium from these 'leaky' tests suggests that a reasonable depth of volcanic cover is not a guarantee of total containment if the geological conditions are unfavourable. The estimated total yield from the four tests (based on seismic measurements) is about 240 kt (Technical Report, Vol. 3). It is possible that other, unidentified tests could have inadequate cover.

Category 3 comprises 12 low yield tests (average yield 5 kt) where the top of the chimney penetrated above the volcanic formation. Seven of these tests were under the north rim, four under the south rim and one under the south central rim of Mururoa (Areas 1, 2 and 3, respectively, in Fig. 44). These tests have been designated as CRTV ('chimney reaching top of volcanics') tests by the French Liaison Office and the same terminology will be used in this report.

Category 4 comprises the three safety trials that reached criticality and had a combined yield of 0.45 kt, producing about 1 TBq ^{90}Sr and 3 TBq ^{137}Cs (French Liaison Office Document No. 6). These values are consistent with fission of ^{239}Pu. Although the quantities of radionuclides produced from these trials were small, they are important because the trials took place in the carbonate zone. Residual plutonium associated with each trial was about 10 TBq, though it would have been confined largely to the lava produced by the fission energy release.

Categories 5 and 6 cover the safety trials without nuclear yield. For these it is assumed that about 10 TBq of plutonium (French Liaison Office Document No. 6) was the only residual radioactive material since it is not necessary to use either a tritium booster or a secondary stage in a safety trial.

Apart from the ten underground safety trials, five safety trials and other minor experiments involving plutonium were carried out above ground between 1966 and 1974. The safety trials led to surface contamination in the north zone of Mururoa rim. Cleanup operations were carried out to remove as much of this material as possible. The French authorities have estimated that 10 TBq was recovered from these operations. This plutonium, along with some 10 TBq of plutonium

TABLE XXIX. TEST CATEGORIES USED FOR MODELLING

Category 1	The majority of the nuclear tests (121 of the 137), i e. tests where a significant thickness of essentially undamaged volcanic cover exists above the test chimney ('regular tests')
Category 2	Three or four tests where tritium releases to the karst have been inferred even though the nominal depth of (low permeability) volcanic cover should have been sufficient ('tests with inadequate cover'). The French assessment suggests that, in these cases, the original volcanic cover was relatively weak, resulting in an annulus of damaged rock around the borehole This annulus acts as a high permeability conduit from the chimney to the base of the carbonates, allowing early release of tritium from the chimney
Category 3	Twelve low yield, relatively shallow CRTV ('chimney reaching top of volcanics') tests in which the chimney came into immediate contact with the base of the carbonates (karst).
Category 4	Three safety trials, conducted at a depth greater than 280 m in the carbonates, in which a (small) nuclear explosion (average yield 0 15 kt) resulted from each trial.
Category 5	The remaining four safety trials conducted at a depth greater than 280 m in the carbonates, where there was no nuclear yield Each of these tests contained about 3.7 kg of plutonium (about 10 TBq) The plutonium was originally present as a metal but would oxidize in water to form the hydroxide This category requires special consideration because the plutonium is present in a different form from that in the nuclear tests, where it partitions mainly into lava
Category 6	Three safety trials conducted at depth in the volcanics None of these tests resulted in a nuclear explosion. Approximately 3.7 kg of plutonium remains at depth from each of these tests. Because of the depth of burial, this category represents a lower potential hazard than Category 4.
Category 7	Plutonium waste produced by surface safety trials and laboratory experiments This was deposited in two shafts on the Mururoa rim just west of Area 1 in the volcanic rock at a depth of about 1200 m The total quantity of alpha activity was 10 TBq from the safety trial cleanup and 10 TBq from laboratory experiments, together equivalent to the plutonium from two safety trials. Because most of the plutonium was incorporated into cement and buried at depth in the volcanic zone, this waste represents a much lower potential hazard than the safety trials (Categories 4 and 5) carried out in the carbonate zone

waste arising from laboratory nuclear experiments (Section 4.2 2), 20 TBq in all, was deposited in two 1180 m deep shafts. This source term is designated as Category 7.

5.10. INITIAL DISTRIBUTION OF RADIONUCLIDES WITHIN CAVITY–CHIMNEYS

Radionuclides produced by a nuclear explosion may be present in a number of phases in the cavity–chimney. The partitioning of radionuclides between these phases, which largely depends on their chemical form and volatility, is very important because it affects their ability to escape from the cavity–chimney and ultimately to be transported through the geosphere. The four phases are lava, rubble, gas and solution:

— The lava, or glassy material, formed chiefly at the bottom of the cavity–chimney, contains most of the refractory (or non-volatile) elements, which include the actinides and lanthanides. Release of radionuclides from the lava is a slow process and is discussed in Section 6.4.1.1.
— The rubble is the crushed material that has collapsed into the cavity–chimney. Radionuclides are retained on the rubble largely by reversible adsorption processes
— The gas and solution phases contain gaseous, volatile and water soluble elements; examples include the noble gases and tritium.

The partitioning of radionuclides between the lava and rubble phases depends on the volatility of the chemical form of each element within the cavity–chimney during the cooling phase. There is a considerable amount of data, both published and unpublished, on the partitioning of radionuclides based on experimental measurements at other nuclear test sites. Some important radionuclides (^{137}Cs and ^{90}Sr) have noble gas and/or volatile precursors with half-lives

TABLE XXX YIELD AND DEPTH OF VOLCANIC COVER FOR 121 'REGULAR TESTS' AT THE CEP

Yield (kt)	Average (kt)	Number of tests with average cover of:				Total number of tests	Total yield (kt)
		25 m	75 m	150 m	250 m		
			Mururoa rim				
0–10	5	5	12	17	14	48	240
10–40	25	0	0	1	7	8	200
40–80	60	0	0	0	1	1	60
>80	100	0	0	1	1	2	200
Total		5	12	19	23	59	700
			Mururoa lagoon				
0–10	5	0	1	9	3	13	65
10–40	25	0	5	14	9	28	700
40–80	60	0	4	6	2	12	720
>80	100	0	0	0	0	0	0
Total		0	10	29	14	53	1485
			Fangataufa rim				
0–10	5	0	1	1	0	2	10
10–40	25	0	0	0	0	0	0
40–80	60	0	0	0	0	0	0
>80	100	0	0	0	0	0	0
Total		0	1	1	0	2	10
			Fangataufa lagoon				
0–10	5	0	0	0	0	0	0
10–40	25	0	0	0	0	0	0
40–80	60	0	0	0	0	0	0
>80	100	0	0	2	5	7	700
Total		0	0	2	5	7	700
			All tests				
0–10	5	5	14	27	17	63	315
10–40	25	0	5	15	16	36	900
40–80	60	0	4	6	3	13	780
>80	100	0	0	3	6	9	900
Total		5	23	51	42	121	2895

comparable with the timescale of the condensation and solidification processes: ^{137}I (half-life 24 s) and ^{137}Xe (half-life 3.8 min) in the case of ^{137}Cs; and ^{90}Kr (half-life 32 s) and ^{90}Rb (half-life 2.6 min) in the case of ^{90}Sr. The partitioning of these radionuclides between the lava and rubble will depend on the fractional decay of the precursors before the lava solidifies at about 1130°C. This depends on many factors, including the size of the test and the time of collapse of the cavity–chimney, which tends to quench the molten lava. Having regard for all these factors, the Study team estimated that about 40% of the ^{90}Sr would partition into the lava and the remaining 60% onto the rubble. For ^{137}Cs, the situation is more complex and the Study team estimated that the percentage entering the lava would vary from 25 to 40%, depending on the yield of the test, with the higher percentages appropriate to high yield tests (>40 kt)

The actinides and lanthanides are known to be incorporated predominantly in the lava On the basis of a survey of the information available to the Study, an appropriate value for the partitioning of plutonium into the lava would appear to be about 98%. The percentage of plutonium on the rubble is important because there it is more readily released into the cavity–chimney water.

TABLE XXXI. PARTITIONING (%) OF RADIONUCLIDES WITHIN TEST CAVITY–CHIMNEY

Radionuclide	Lava	Rubble	Gas	Water	Comments
^{3}H	0	0	2	98	Mostly present as tritiated water
^{14}C	0	10	80	10	Present as gas and in dissolved state
^{36}Cl	50	40	0	10	Intermediate volatility
^{41}Ca	70	30	0	0	Relatively non-volatile
^{55}Fe	95	5	0	0	Non-volatile
^{59}Ni, ^{63}Ni	95	5	0	0	Non-volatile
^{60}Co	90	10	0	0	Relatively non-volatile
^{79}Se	70	30	0	0	Volatile
^{85}Kr	0	10	80	10	Gas, all precursors are volatile
^{90}Sr	40	60	0	0	Relatively non-volatile but precursors are volatile
^{93}Zr	95	5	0	0	Refractory but precursor is of intermediate volatility
^{99}Tc	80	20	0	0	Volatile with intermediate and volatile precursors
^{106}Ru	70	30	0	0	Volatile with volatile precursors
^{107}Pd	70	30	0	0	Relatively volatile
$^{113}Cd^{m}$	70	30	0	0	Relatively volatile
$^{121}Sn^{m}$	60	40	0	0	Relatively volatile
^{126}Sn	70	30	0	0	Relatively volatile
^{125}Sb	70	30	0	0	Relatively volatile
^{129}I	50	40	0	10	Volatile and soluble
^{134}Cs	20	80	0	0	Intermediate volatility with no precursor
^{135}Cs	20	80	0	0	Intermediate volatility with volatile precursors
^{137}Cs	25/40[a]	75/60[a]	0	0	Intermediate volatility with volatile precursors
^{147}Pm	95	5	0	0	Refractory with no volatile precursor
^{151}Sm	95	5	0	0	Refractory with no volatile precursor
^{152}Eu, ^{154}Eu	95	5	0	0	Refractory
^{155}Eu	95	5	0	0	Refractory with no volatile precursor
^{236}U	90	10	0	0	Slightly volatile, depending on oxidation state
^{237}Np	95	5	0	0	Refractory when produced from ^{241}Am, slightly volatile when formed from ^{237}U
^{238}Pu, ^{240}Pu	98	2	0	0	Refractory
^{239}Pu	98	2	0	0	Refractory, one precursor is slightly volatile
^{241}Pu, ^{242}Pu	98	2	0	0	Refractory
^{241}Am	98	2	0	0	Refractory

[a] Value depends on yield of test. In the Study, it was assumed that the percentage of ^{137}Cs in the lava was 25% at Mururoa (where tests were generally of low yield) and 40% at Fangataufa (where tests were generally of high yield).

The validity of assumptions about the percentage of plutonium in the lava is assessed in Section 6.6.4.1 on the basis of measured concentrations of plutonium in cavity–chimney water.

Table XXXI summarizes the partitioning percentages for relevant radionuclides obtained from the information available to the Study, while Table XXXII, using the partitioning values given in Table XXXI, gives the total activity of all significant radionuclides in the CEP according to their location within the cavity–chimney These basic data provide the source term for the geosphere transport calculations.

Figure 53 shows the activity of residual radionuclides in the solidified lava as a function of time (neglecting any leaching). Because of the large amount of lava generated by all the nuclear explosions (about

TABLE XXXII. PARTITIONING OF TOTAL RADIOACTIVITY (TBq) AT THE CEP

Radionuclide	Lava	Rubble	Gas	Water	Total
^{3}H	0	0	6 000	274 000	280 000
^{14}C	0	3	22	3	28
^{36}Cl	0 9	0 7	0	0.1	1 7
^{41}Ca	0 9	0 4	0	0	1.3
^{55}Fe	7 200	400	0	0	7 600
^{59}Ni	3 6	0 2	0	0	3 8
^{60}Co	2 300	300	0	0	2 600
^{63}Ni	430	20	0	0	450
^{79}Se	0 008	0.003	0	0	0 011
^{85}Kr	0	100	800	100	1 000
^{90}Sr	4 300	6 500	0	0	10 800
^{93}Zr	0.30	0.02	0	0	0.32
^{99}Tc	2 0	0 5	0	0	2 5
^{106}Ru	5 100	2 200	0	0	7 300
^{107}Pd	0 15	0 06	0	0	0 21
$^{113}Cd^{m}$	2 3	1.0	0	0	3 3
$^{121}Sn^{m}$	0 22	0 14	0	0	0 36
^{126}Sn	0 13	0 05	0	0	0.18
^{125}Sb	510	220	0	0	730
^{129}I	0.003 1	0 002 4	0	0 000 6	0.006 1
^{134}Cs	0.19	0 75	0	0	0 94
^{135}Cs	0 06	0.21	0	0	0.27
^{137}Cs	4 300	10 500	0	0	14 800
^{147}Pm	10 500	500	0	0	11 000
^{151}Sm	480	20	0	0	500
^{152}Eu	310	20	0	0	330
^{154}Eu	47	3	0	0	50
^{155}Eu	450	20	0	0	470
^{236}U	0 12	0 02	0	0	0 14
^{237}Np	0 23	0 02	0	0	0 25
^{238}Pu	195	5	0	0	200
^{239}Pu	1 080	20	0	0	1 100
^{240}Pu	295	5	0	0	300
^{241}Pu	6 700	100	0	0	6 800
^{242}Pu	0 009 0	0 000 2	0	0	0 009 2
^{241}Am	370	10	0	0	380

2.5 million tonnes), the specific activity is not particularly high For example, the concentration of alpha emitters in the lava is comparable with that from a uranium deposit containing 0.7% uranium.

Although the inventories at the CEP are relatively small compared with some other sources (Section 5.11), this fact alone does not allow any general conclusion to be drawn about the relative radiation hazards. The nature of the confinement at the CEP is such that any releases of radionuclides will occur initially to the local environment in the lagoons or the nearby ocean. It is necessary, therefore, to assess release rates and exposure pathways to the most exposed groups living in that environment.

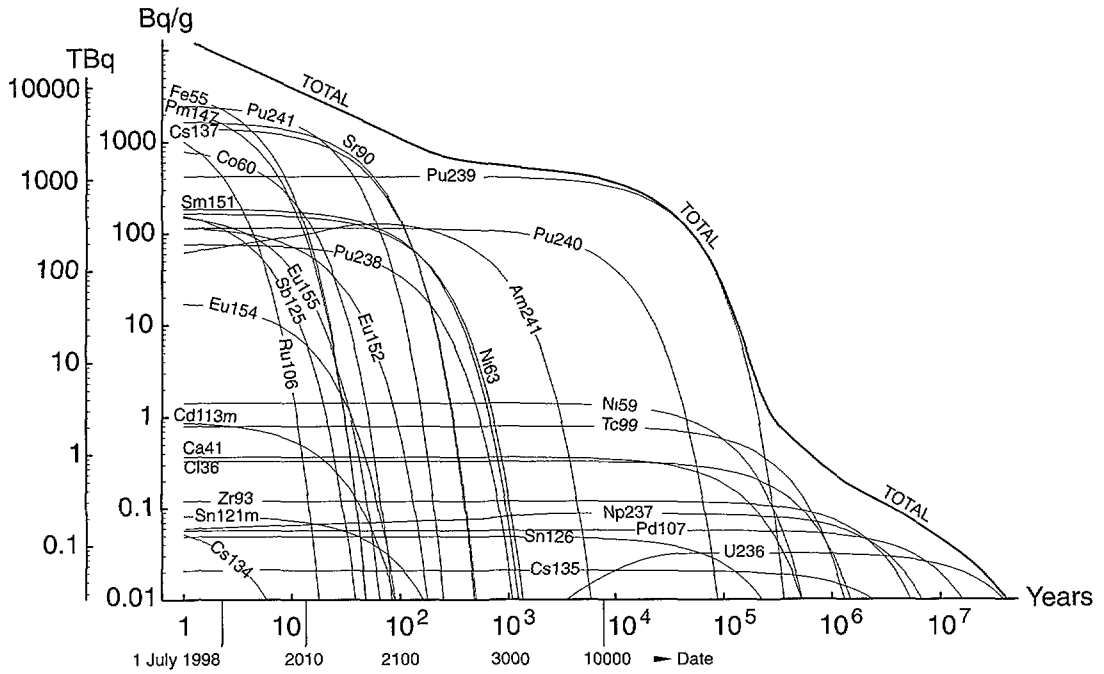


FIG 53. Total and specific activity of radionuclides in resolidified lava as a function of time (neglecting leaching).

5.11. UNDERGROUND INVENTORY IN PERSPECTIVE

In this section, the underground radionuclide inventory in the CEP is put into perspective by comparison with other sources. One obvious comparison is with other nuclear testing programmes. As of the commencement of the Study, the major nuclear powers had conducted 541 atmospheric tests with an estimated fission yield and total yield of 182 and 440 Mt, respectively (Annex I). Since the activity of each fission product radionuclide is approximately proportional to the fission yield, it is estimated that this atmospheric testing produced about 60 times the activity of ^{137}Cs, ^{90}Sr and other long lived fission products generated in the French underground testing programme. The inventory from atmospheric testing was distributed globally as fallout, 75% in the Northern Hemisphere and 25% in the Southern Hemisphere. The total tritium release from atmospheric testing was about 500 times that produced from underground nuclear testing at the CEP (United Nations 1993) Tritium is also produced naturally by interactions of cosmic rays with gases in the upper atmosphere; the steady state global inventory is estimated to be 960 PBq (Eisenbud and Gesell 1997), or more than three times the current inventory from the French underground tests. Similarly, the natural production rate of ^{14}C is about 1000 TBq/a (United Nations 1993) whereas the estimated underground inventory at the CEP is only 28 TBq.

In an atmospheric test, the radionuclides are widely dispersed whereas in an underground test they are essentially confined within the volcanic rocks, at least in the short term. The short lived radionuclides (e g. ^{131}I) in fallout from atmospheric testing can contribute significantly to radiation doses. Thus, the cessation of atmospheric testing was a crucial step in reducing the global radiation dose from nuclear weapon testing.

As of the commencement of the Study, throughout the world there had been some 1865 underground nuclear tests (including safety trials) with a total yield of about 90 Mt (51 Mt from fission and 39 Mt from fusion), 30 times that from French underground testing on Mururoa and Fangataufa Atolls. Between 1955 and 1992, the USA alone carried out over 900 underground tests at its Nevada Test Site, with a total residual activity of 4400 PBq. The underground inventory at the Nevada Test Site is, therefore, about 13 times the inventory at the CEP.

It is also instructive to compare the inventory in the CEP with that in a conceptual high level waste repository. The Kristallin project considered the hypothetical

disposal of 2700 flasks of vitrified high level waste in crystalline rocks in northern Switzerland (National Cooperative for the Storage of Radioactive Waste (Nagra) 1994a). Each flask was 1 m in diameter and 2 m long and contained about 400 kg of high level waste glass. The entire inventory of fission products at the CEP is equivalent in activity to that contained in three of these flasks. The total inventory of alpha emitting radionuclides at the CEP is roughly equivalent to the activity in about 100 such flasks of vitrified high level waste.

5.12 SUMMARY

The explosion of a nuclear device generates extremely high temperatures and pressures which vaporize and melt the rock in the immediate vicinity of the zero point. About 700 t of rock is melted per kiloton of explosive yield. Initially, a large spherical cavity is formed and, after some time, the rock above the cavity collapses to form a chimney with a height about five times the cavity radius A shock wave is generated and a network of fractures develops which becomes less intense with distance from the explosion point. At larger distances, the shock wave becomes a seismic wave which can be detected at great distances from the source.

Independent records from the Rarotonga seismic station in the Cook Islands have been used to estimate the explosive yields from individual underground nuclear tests conducted on Mururoa and Fangataufa Atolls. The total yields, calculated from the sum of the yields of individual tests, are estimated to be 2400 and 770 kt for Mururoa and Fangataufa Atolls, respectively, in good agreement with the values provided by the French Liaison Office.

The underground inventory of radionuclides has been calculated from the estimated yields by making some reasonable assumptions about the proportion of energy derived from fission of ^{239}Pu, ^{235}U and ^{238}U and fusion of hydrogen isotopes. Information provided by the French Liaison Office on the residual activities of fuel components was also used in these calculations. In general, the agreement between the estimates of the Study and the data provided by the French authorities is very good. Discrepancies in the activities of some less important radionuclides are apparent but these can be readily explained.

Following a nuclear explosion, radionuclides are distributed in the cavity–chimney between the gas and water phases and two solid phases: the lava formed from the molten volcanic rock and the rubble in the cavity–chimney. This distribution depends on the elemental properties of the residual radionuclides, especially the volatility at the temperature at which the molten volcanic rock solidifies. Estimates were made of the distribution of radionuclides between these phases. In general, the actinides and lanthanides will enter the lava while elements which are volatile, or have gaseous or volatile radioactive precursors (such as ^{137}Cs and ^{90}Sr), will be present in both the lava and the rubble.

The total underground inventory at the two atolls is small compared with that previously released in atmospheric tests and that present in wastes arising from the nuclear fuel cycle. The concentration of alpha emitting radionuclides in the lava is equivalent to that in a uranium deposit containing 0.7% uranium

For calculation purposes, the discrete source terms at the CEP have been grouped into seven categories one category for the 121 'regular tests', two categories where the activity was not fully contained within the volcanic rocks, three categories of safety trials, and one category of waste material buried in two shafts. The regular tests have been further subdivided according to yield and thickness of volcanic cover. For generic tests in each of these categories, the radionuclide inventory in each phase can be calculated. This is used as the input for determining the concentration of radionuclides in the water filling each representative cavity–chimney, which in turn becomes the source term for the radionuclide transport modelling calculations in Section 6

6. TRANSPORT OF RESIDUAL RADIOACTIVE MATERIAL THROUGH THE GEOSPHERE

6.1. INTRODUCTION

In Section 5, estimates were made of the inventory of radionuclides remaining from the French nuclear tests in the rocks beneath the atolls and their initial partitioning between the lava, rubble, gas and solution phases. This section is concerned with the transport of these radionuclides by water through the geosphere to the lagoons and directly to the ocean.

The assessment of radionuclide transport through the geosphere involves a number of sequential tasks (Fig. 54):

(1) First, it is necessary to understand the geology of the atolls and the geological pathways to the biosphere. These include natural fractures in the rocks, fractures caused by the nuclear explosions and any other artificial pathways (such as boreholes).
(2) Since groundwater flow is the mechanism for transport of radionuclides, hydrological modelling is undertaken to estimate the velocities of groundwater flow within the volcanic and carbonate rocks in the immediate vicinity of a cavity–chimney and at distances from it where the permeability is unchanged from pre-test conditions.
(3) The concentration (Bq/m^3) of each radionuclide in the saline water within the cavity–chimney is calculated on the basis of the leaching of the lava (which contains a major proportion of the radionuclides) and the sorption–desorption processes whereby radionuclides are exchanged between rock surfaces and groundwater.
(4) The transport of radionuclides through the geosphere is modelled from a knowledge of the cavity–chimney concentrations (as a function of time), the geometric characterization of water conducting features, nuclide transport mechanisms and groundwater velocities.
(5) Underground sampling from the cavity–chimneys of two tests and at a number of points in the carbonate rock is undertaken to compare the model predictions with actual measurements. Some adjustments to model parameters are made as a consequence of these direct measurements.
(6) The final output from this analysis is estimates of the release rates (Bq/a), as a function of time, of radionuclides from the geosphere to the marine environment.

6.2. GEOLOGICAL PATHWAYS

The evolution and geology of the atolls were described in Section 2. This section is concerned with the natural and artificial pathways whereby radionuclides can escape from the geosphere to the biosphere A detailed description of the geology and hydrology of the atolls is given by Guille et al. (1995) and in the Technical Report, Vol. 4.

6.2.1. Natural fractures and pathways

Volcanic rocks include a variety of structural units. At the start of the volcano building processes, the magma is discharged onto the ocean floor under the hydrostatic pressure of the water. At Mururoa and Fangataufa there are 4 km of overlying water. At this depth, gases in the lava remain in solution and the solidified rock tends to have a homogeneous structure. Cooling, as the lava flows, produces pervasive, more or less vertical fractures with a spacing that is roughly proportional to the thickness of the individual layers. As the volcano grows and the depth of water above the magma decreases, the lava becomes progressively more eruptive. The rock from this regime contains a myriad of gas pockets or vesicles As the volcano approaches the ocean surface, the eruptions become explosive as the magma, immediately chilled in the shallow water, breaks into small fragments, or breccia, and fine ash (<2 mm fragments), or hyaloclastic tuff. When the volcanic activity is above the ocean surface, the magma ejects directly into the air to form volcanic lavas and cinders, or scoria. Once the height of the volcano is several hundred metres above the ocean, lava flows become the predominant mode of magma discharge, spreading laterally down the steep sides of the volcano towards the ocean. Cooling of the magma under air or water produces contraction cracks perpendicular to the surface.

Superimposed on the solidified volcanic structure, later intrusive injections of magma tend to penetrate into existing fractures or layer interfaces, enlarging the apertures in the process, to form dykes (where the path is near vertical) or sills (where the path is near horizontal). Dykes, sills and related intrusive features can extend hundreds of metres or more and can be several metres in thickness

An important conclusion to be drawn from the physical evolution of the volcanic base of the atolls is that the

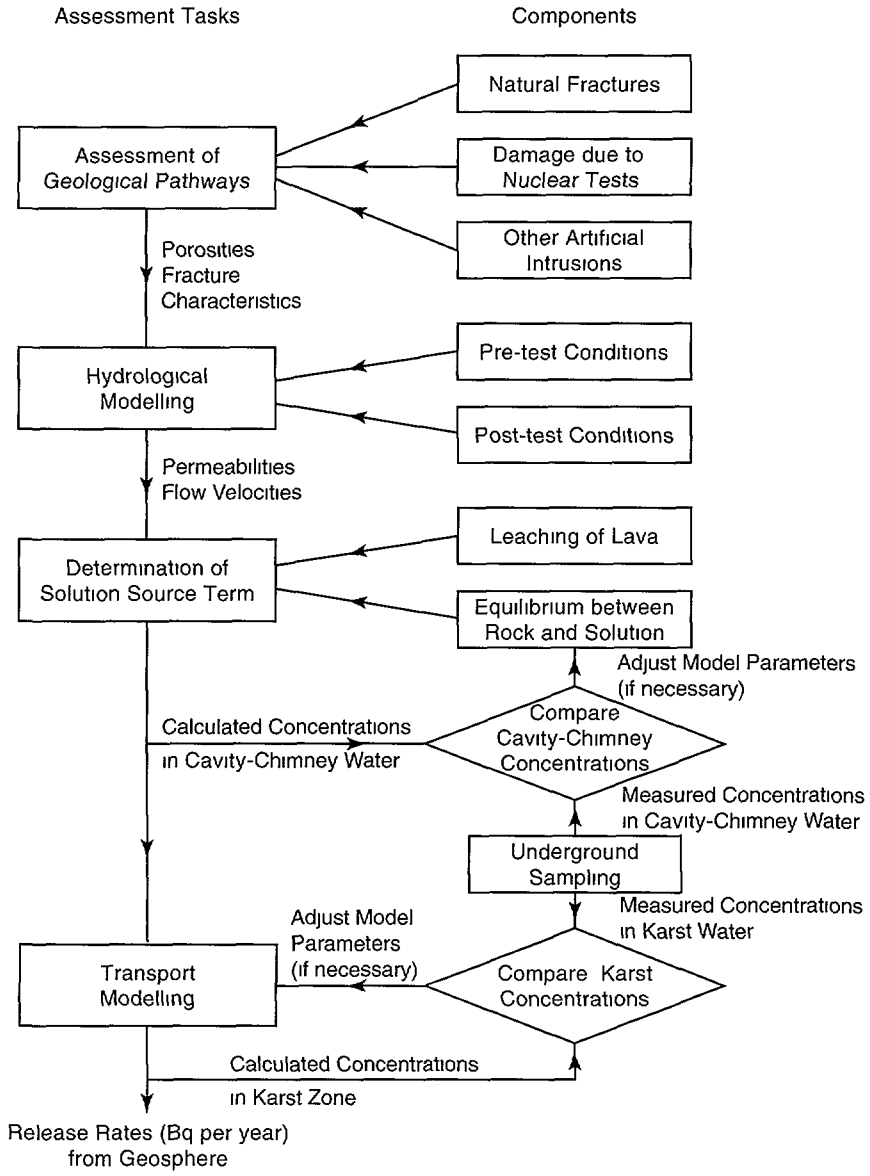


FIG 54 Tasks required for assessment of radionuclide transport through the geosphere

structure contains an extensive network of essentially linear fissures, i.e surfaces where resistance to fluid flow is significantly lower than in the intact rock. Conductive pathways have evolved from a variety of sources: large scale magmatic intrusions, the near horizontal flow surfaces (varying in thickness from fractions of a metre to tens of metres), cooling contraction fissures within (and generally perpendicular to) these layers, and more extensive fractures (dykes and sills) produced by magmatic injections that took place after cooling of the initial volcanic rock mass It is clear, therefore, that the properties of the volcanic base of the atolls are likely to be characterized by significant near vertical fracturing, near horizontal layering and large scale dykes and sills at Mururoa and Fangataufa. The thicknesses of layers of a given facies (e g. submarine volcanics) as measured at the two atolls vary up to 35 m but such thicknesses are rare The thickness is mainly less than 6 m and is most frequently 2–3 m.

The surfaces of initially large conduits in basalt become chemically altered by the flowing water and over a long time may become partly sealed by alteration products such as clays or, in other cases, calcite, etc. These alteration products typically have a high surface area and excellent retentive properties for some radionuclides, especially the actinide elements. They play an

important role in the retardation of radionuclide transport through the pores. In about three hundred deep boreholes drilled into Mururoa and Fangataufa Atolls for various purposes, no evidence has been found for the existence of lava tubes found in other Pacific islands, including Tahiti and Hawaii.

The physical properties of the volcanic rocks of Mururoa and Fangataufa vary considerably. Water content (by weight) ranges from a few per cent in the most recent lava flows to 30% for the highly altered submarine volcanics containing predominantly clay minerals. The water content of the subaerial volcanics is generally less than that of submarine volcanics. The saturated densities of volcanic rocks range from 1.85 to 3.15 kg/L, although most are in the range 2.3–2.5 kg/L. The average porosity is about 12.5% (Bouchez and Lecomte 1996).

As expected, the carbonate rocks are considerably more porous and permeable. The average saturated densities mostly fall within the range 2.15–2.45 kg/L. The porosities are typically 25–40%. Davies (1983) estimated the porosity of the transition zone as 20–40% on the south Mururoa rim and 10–20% under the lagoon.

The presence of sedimentary unconformities and karstification has been mentioned previously. These zones of high permeability are of particular importance to the hydrogeology of the carbonate zone and the migration of radionuclides. Karstic horizons have been observed on a number of levels in the limestone. In the upper 80–100 m of the carbonate cap, karstification is more pronounced under the rim than the lagoon; below 100 m it is common below the lagoon and rim of both atolls.

Important karstic horizons occur at depths of 90–100 m at the periphery of the atolls. Karstification in the limestone extends down to 150 m. Beneath both lagoons, karsts are present at the limestone–dolomite interface at 180–200 m and near the base of the dolomites at depths of 250–270 m. Beneath the rim, almost the entire sedimentary series is karstified. These surfaces correlate with sedimentary discontinuities across both atolls and are associated with changes in sea level. At the base of the carbonate series below 310–350 m, karstification is particularly extensive in the massive dolomites (Buigues 1997).

6.2.2. Damage due to nuclear tests

6.2.2.1. Fracture zones around a single test

Underground testing of nuclear explosives leaves residual radioactive material in underground cavities in conditions that have some similarities to the geological isolation of radioactive waste. However, in marked contrast to nuclear waste isolation, nuclear testing is inextricably linked to the release of large amounts of explosive energy, causing substantial damage to the rock mass in the vicinity of the explosion. The geological structure is changed and new potential pathways for radionuclide release to the biosphere may be introduced.

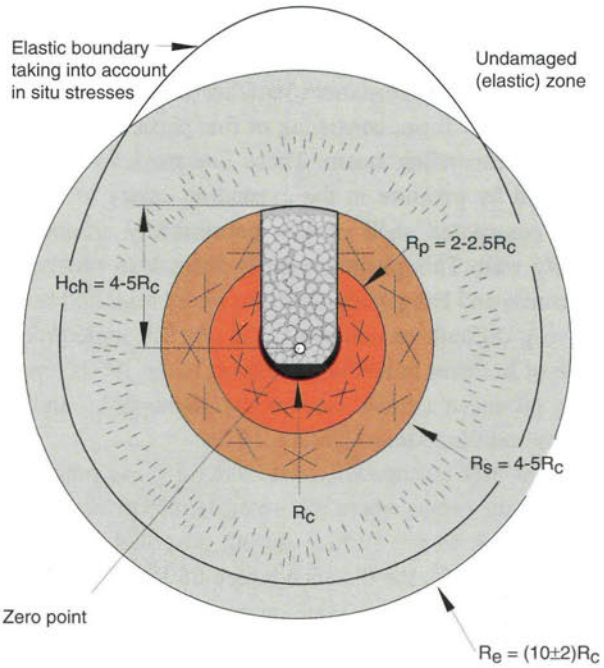


FIG. 55. Different zones of damage produced by a nuclear explosion in rock. Initially a cavity is formed with a radius R_c*; this is later filled with rubble when the ceiling of the cavity collapses. A thin crush zone of low permeability may form around the cavity, followed by a zone of shear failure up to 4–5*R_c*. Inside the shear zone is a zone of about 2.5*R_c *where an increase in rock permeability is apparent during post-shot drilling operations. Radial cracks are possible to an elastic limit of 10*R_c*.*

The physical phenomena associated with a nuclear explosion were described in Section 5.4. The explosion produces a spherical cavity and a fractured rock mass around the cavity. The following major zones have been identified (Fig. 55):

— Cavity within a radius R_c
— High permeability zone within a radius R_p
— Fracture zone with shear failure to radius R_s
— Crack zone between radii R_s and R_e
— Undamaged zone beyond radius R_e
— Chimney extending to a height H_{ch}.

The boundaries between these zones are, except for the cylindrical chimney, quite spherical although

non-uniform stress fields can cause some tendency towards an ovoid shape (Fig. 55).

In some circumstances, another zone — the crush zone — may form, consisting of fine particulates generated by expanding steam. These fine particles are later sintered by pressure in the expanding cavity to form a thin compacted shell of low permeability around the cavity wall. This phenomenon is difficult to observe at Mururoa and Fangataufa since the water saturated basalt is very difficult to compress. The French underground tests at In Ecker in the Sahara Desert in the 1960s reportedly produced a crush zone out to a radius of around 1.4 cavity radii in granite (Derlich 1970).

The high permeability zone is defined in a pragmatic way by the radius where the water used to pump drilling debris back to the surface during post-shot drilling is lost. This marks the distance where the rock permeability is significantly increased owing to the explosion and the drilling water is sucked into the cavity–chimney (probably via the walls of the chimney as the original cavity walls are covered with vitrified lava). This is found to occur on average at a radius of 2–2.5 times the cavity radius.

During the plastic phase a fracture zone is created with fractures due to shear failure. This zone normally extends out to a radius of four to five times the cavity radius. Outside that, the shear resistance of the rock is strong enough to stand the weakened shock and in the next zone, the crack zone, shear fractures tend to decrease in intensity, eventually giving way to some radial tensile cracks (not necessarily connected). This outer limit — the beginning of the elastic zone, beyond which the rock is essentially undamaged — can be defined as the surface where the magnitude of the tangential tensile stress in the wave radiating from the zero point falls below the sum of the tensile strength of the rock and the in situ compressive stress in the rock at that depth. At Mururoa and Fangataufa, the limit of the

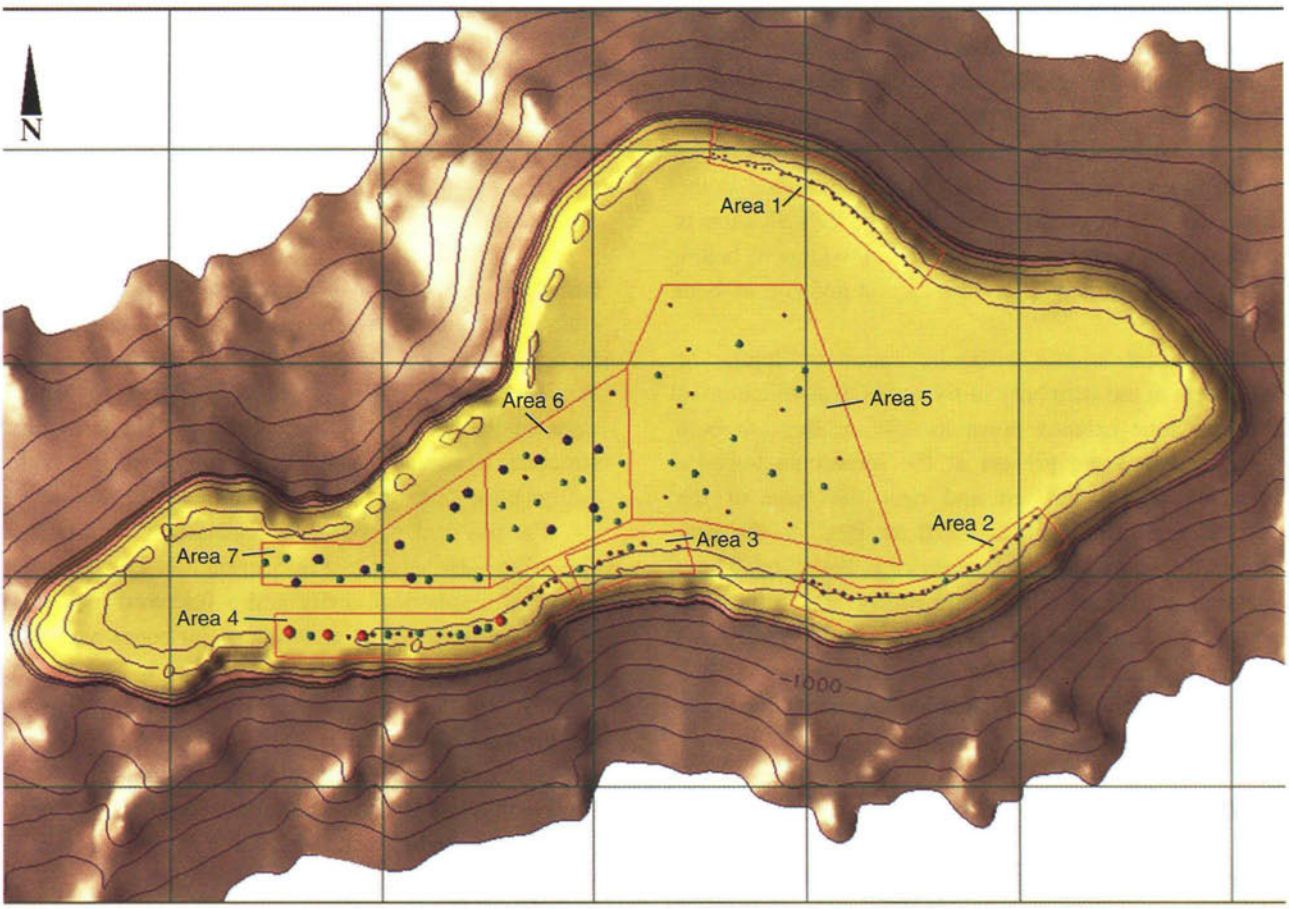


FIG. 56. Enhanced permeability zones from nuclear tests at Mururoa Atoll (purple, <10 kt; green, 10–40 kt; blue, 40–80 kt; red, >80 kt). The circles correspond to $5R_c$. The number of tests in each area is correct but the precise position and size of each test are not known.

TABLE XXXIII. VOLUMES OF DAMAGED ZONES AS PERCENTAGE OF ROCK VOLUME IN TEST AREAS

	Rock volume (m^3)	Percentage of rock volume within test area (500–1100 m below surface)			
		Cavities	Chimneys	High permeability zones	Fracture zones
		Mururoa			
Area 1	3.6×10^9	0.01	0.05	0.19	1 5
Area 2	4.2×10^9	0.03	0.11	0 41	3 2
Area 3	$1\ 8 \times 10^9$	0.04	0.17	0.64	5.0
Area 4	4.8×10^9	0 11	0 48	1.81	14.1
Area 5	$1\ 8 \times 10^{10}$	0.01	0 05	0.19	1.5
Area 6	$7\ 2 \times 10^9$	0.06	0 23	0.88	6.9
Area 7	$5\ 4 \times 10^9$	0.08	0 34	1 29	10 0
Overall	$4\ 5 \times 10^{10}$	0 04	0.17	0.65	5.1
		Fangataufa			
Area 1	2.4×10^9	0.01	0 03	0 10	0 7
Area 2	$3\ 6 \times 10^9$	0.15	0 64	2 41	18.9
Overall	$6\ 0 \times 10^9$	0.09	0.39	1.49	11 6

crack zone is at about 10 cavity radii; the crack density in this zone is fairly small and the cracks are also limited in length to just a few metres because of stratification of the rock. The maximum radius of fractured and cracked rocks is reported to be somewhat higher, about 14 ± 2 cavity radii, at the Nevada Test Site in the USA (Smith et al. 1996). For explosions in carbonate rocks at the Semipalatinsk Test Site in the former USSR, the maximum radius of the crack zone was around 10 cavity radii; for explosions in tunnels drifted into the granite rock massif at the same test site this radius could be up to 12.5 times the cavity radius (Kedrovskiy et al. 1970).

6.2 2.2. Possible overlap of fracture zones from adjacent tests

The above description of the mechanics of damage to the volcanic rock from a single test indicates a zone of high permeability out to $2.5R_c$, a fracture zone extending to $5R_c$ and some potential for damage out to the elastic limit of $10R_c$. Since limited area was available on the two atolls, it was necessary to carry out tests in relatively close proximity to each other Accordingly, it is necessary to consider the possibility of mechanical and hydrological interaction between adjacent tests.

As noted previously, the French Liaison Office did not provide the location of each test although it did provide information on the size of the test areas and the number of tests in each area (Figs 44 and 45). For example, in Area 4 at Mururoa there were 21 tests with a total yield of up to 750 kt over a 7 km section of the rim. This corresponds to an average horizontal spacing between tests of about 330 m.

Figure 56 depicts a horizontal cross-section of Mururoa Atoll showing likely areas of enhanced permeability (out to $5R_c$) from individual tests. This drawing is conceptual only since the spacing between tests of different yields is not known. Areas 4, 6 and 7 have the greatest intensities of relatively high yield tests.

Table XXXIII compares the total volumes of cavities, chimneys, high permeability zones and fracture zones as a percentage of the total rock volume within the respective test area (nominally a 600 m thick zone in the volcanics from 500 to 1100 m). In all areas, the chimney and high permeability zones are less than 0.7 and 3%, respectively, of the rock volume.

The French Liaison Office provided data on the distribution of distances between adjacent tests and these data are summarized in Fig 57. The data show that in no cases do the high permeability zones overlap. However, there is some overlap in the fracture zones in about 25% of tests. This suggests that there could be a degree of connectivity between some adjacent tests, although it is unlikely to change the hydrological pathways significantly. Also, for tests conducted under the rim where the separation may be relatively low, the hydraulic gradient, and hence flow, between adjacent cavity–chimneys will be very small.

The conclusion to be drawn from this analysis is that hydrological interaction between adjacent tests is likely to be minimal With respect to structural interaction in areas with closely spaced high yield tests, there is a

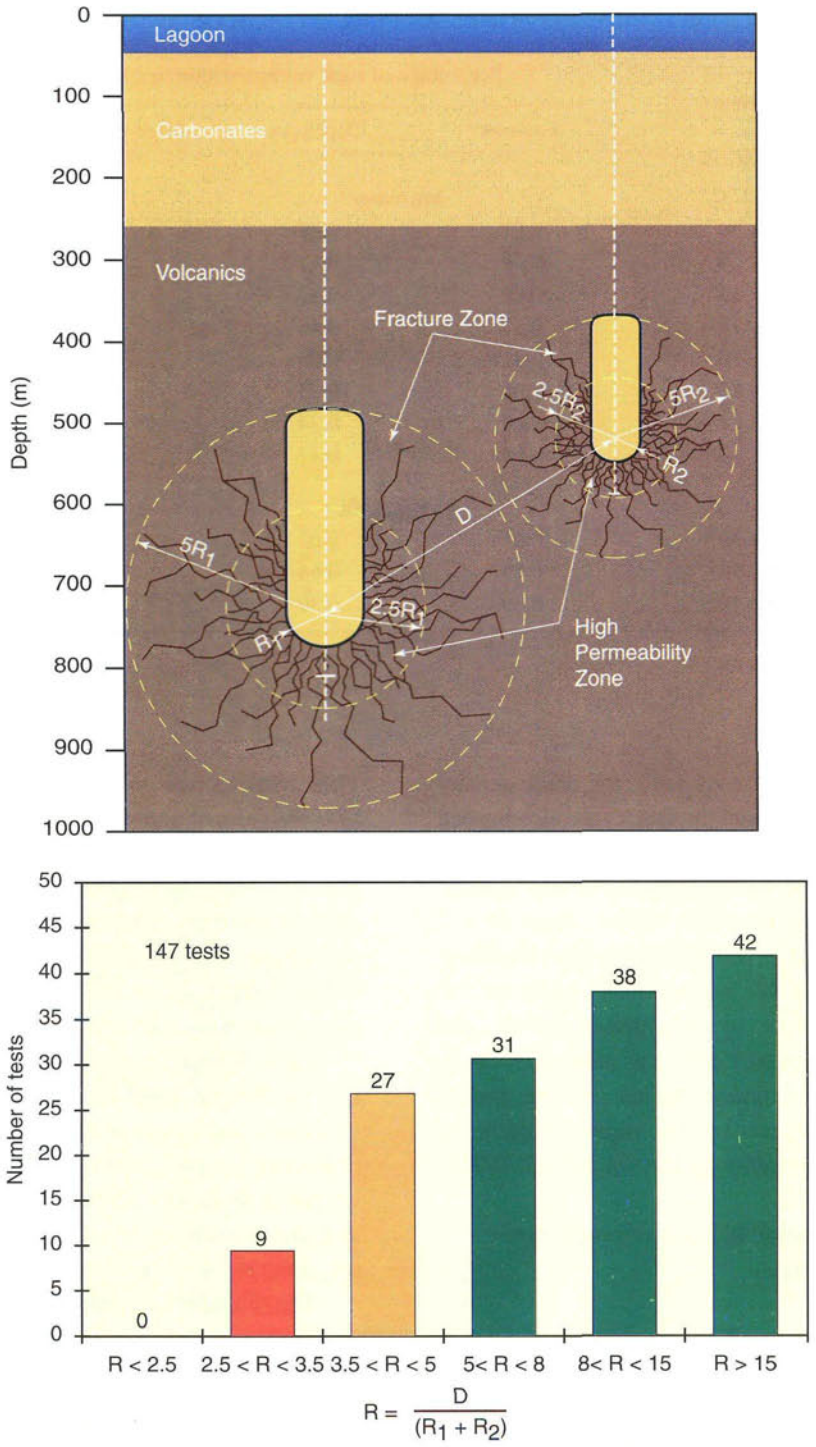


FIG. 57. Distance between a new test cavity and the nearest previous test cavity. Tests where there is a possibility of overlap of the fracture zone with that of another test are shown in red and orange, with the red being more likely. (Adapted from French Liaison Office Document No. 6.)

possibility, because of the relatively small pillar of rock between adjacent chimneys, of enhanced downward displacement of the overlying rock. This displacement is limited and likely to be very small since the large cavity–chimneys are filled with rubble and the voids are filled with water under pressure. Numerical modelling (Fairhurst et al. 1998) indicates that, even for the hypothetical case of two 150 kt yield tests at the minimum separation of $5R_c$ (i.e. with a pillar of $3R_c$) with overlapping damaged zones, the increased deformations are

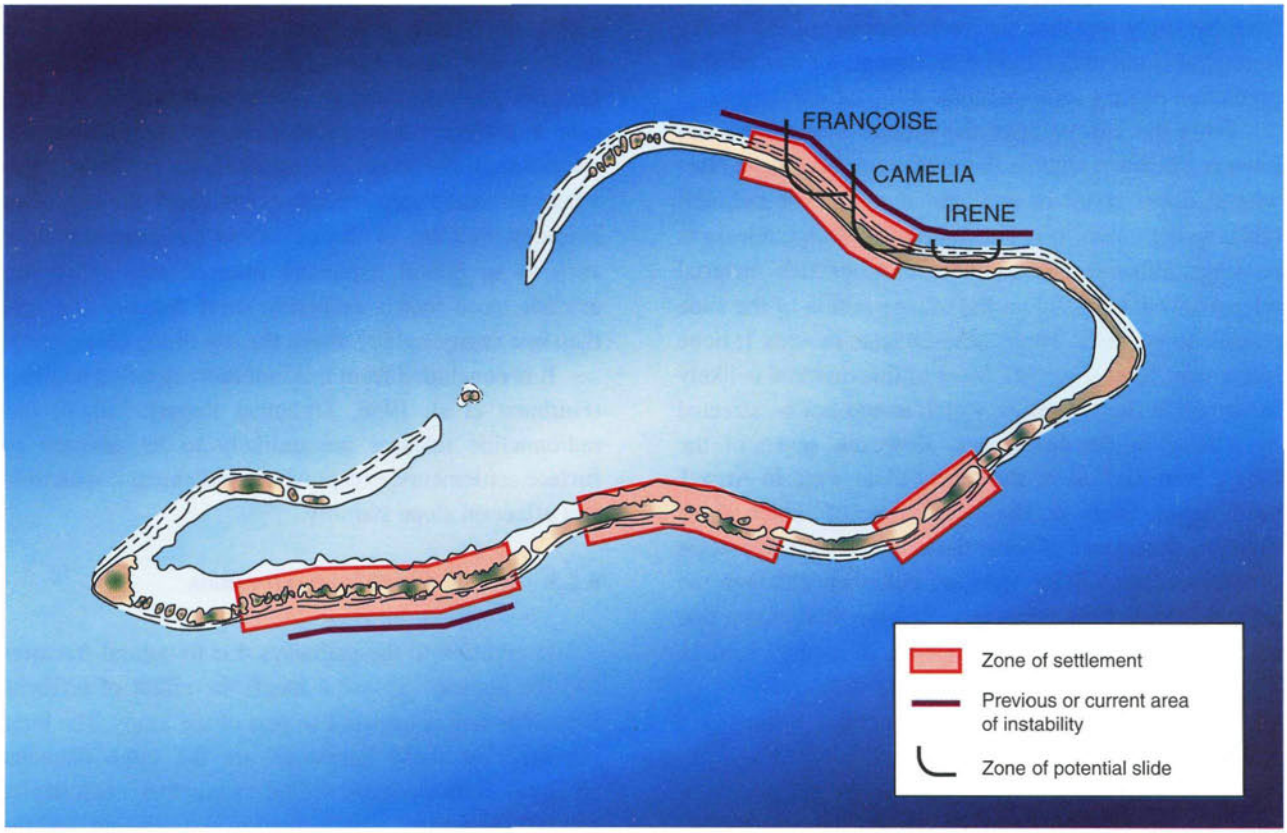


FIG. 58. Areas affected by settlement and carbonate instabilities on Mururoa Atoll. (Adapted from French Liaison Office Document No. 7.)

negligibly small compared with those resulting from one such test.

6.2.2.3. Slope failure

The underground nuclear testing at Mururoa has caused destabilization of the atoll flanks in the form of submarine slope failures in the southwest zone and slow (creeping) movements of some parts of the rim in the north zone. Some destabilization of the flanks has also occurred in the northeast area of Fangataufa (French Liaison Office Document No. 7).

Figure 58 shows the areas of subsidence and slope instability on Mururoa Atoll. The slope failures in the southwest of Mururoa occurred between 1977 and 1980. The largest of these events, involving three rock slides with a total volume of 360 million cubic metres, was triggered by the Tydée explosion on 25 July 1979 (French Liaison Office Document No. 7). The first rock slide, with an estimated volume of 110 million cubic metres, produced a wave front with a height of 2.5 m which completely submerged parts of Mururoa and the airstrip on neighbouring Fangataufa. Geophysical measurements have shown that the volcanic base was unaffected by the slides.

Geodesic surveys have revealed three potential instabilities in three adjacent areas in the north zone of the Mururoa rim: Irène, Camélia and Françoise (Fig. 58). The regions, which are delimited by a series of cracks, are slowly moving towards the ocean, although the rate of creep has been decreasing. The movements are being continuously monitored at the surface and at depth. Inclinometer measurements in the Camélia region reveal the existence of sharp discontinuities in the horizontal displacements at a depth of about 400 m, corresponding to the occurrence of very weak chalky limestone (French Liaison Office Document No. 7).

The potential for a slide of the unstable areas in the north zone has been analysed by French scientists (French Liaison Office Document No. 7). They have estimated the most probable and maximum volume rock slides as 40 million and 600 million cubic metres, respectively. An independent study was recently carried out by the IGC (Fairhurst et al. 1998). The conclusion

from the study was that the creep response of the chalky limestone is not understood well enough for any reliable prediction of long term stability.

From the viewpoint of the present Study, the main issue is whether a slide in the north zone (or indeed elsewhere) could result in accelerated release of radionuclides to the ocean. It is concluded that such a release is possible, although the amount of radioactive material released would depend on the exact position of the slide relative to the tests. There were 28 tests in Area 1, none larger than 10 kt (Fig. 44). Most of this material is likely to remain in the volcanics, which would not be affected by a slide in the carbonates. However, seven of the CRTV tests and all of the safety trials were in Area 1 (with seven trials in the carbonates, of which three involved the release of some fission energy) The precise locations of the CRTV tests are unknown although the French Liaison Office has informed the Study team that all the safety trials were carried out in an area west of Françoise and outside of the potential slide areas.

The possible release of radionuclides following a slide is considered further in Section 7, which deals with disruptive events and extreme natural phenomena. Non-radiological consequences, such as the destructive impact of a wave front generated by a slide, are outside the terms of reference of the Study.

6.2.2.4. Surface settlement

French geodesic surveys have established that all the testing areas along the rim have suffered settlement as the result of underground testing (Fig. 58). The largest settlements are 2 2 m deep in the north zone (French Liaison Office Document No 7) and, as a consequence, some sections of the road along the rim have been submerged.

According to Bouchez and Lecomte (1996), surface settlement on Mururoa is caused by the impact of a layer thrown in ballistic flight by the ascending wave from the test explosion. This layer subsequently falls back under gravity, compacting the carbonates to a depth of about 120 m. A recent independent analysis of this phenomenon has disagreed with this interpretation (Fairhurst et al. 1998). The alternative explanation is based on a shear deformation mechanism involving lateral movement of the submerged flanks of the atoll. This analysis suggests a link between surface settlement and the stability of the carbonate slopes.

It is important to note, however, that, irrespective of the mechanism, these surface settlements are restricted to the upper part of the carbonates. Except for the CRTV tests, modelling studies show the existence of an undamaged elastic region in the upper volcanics (Fairhurst et al. 1998). In contrast to the subsidence craters observed in the Nevada Test Site (discussed by Bouchez and Lecomte (1996)), these surface settlements do not indicate a preferred geological pathway for radionuclide release from the explosion cavity Even for those cases where no intact volcanic cap exists above the explosion chimney, bulking of the collapsed carbonates will be such as to inhibit explosion induced subsidence that extends more than a relatively short distance (i e. less than one cavity radius) above the top of the chimney

It is concluded from this and more detailed analyses (Fairhurst et al. 1998, Technical Report, Vol. 4) that radionuclide releases are unlikely to be affected by surface settlements, except where settlement has an indirect effect on slope stability

6.2.3. Effect of artificial intrusions

In addition to the pathways due to natural fractures and the nuclear explosion itself, the effect of artificial intrusions was considered as part of the Study. The most important of these intrusions are the large diameter (1.52 m) vertical shafts drilled to emplace each device and later backfilled with cement prior to testing, and the small diameter boreholes drilled into the atoll for sampling purposes

6.2 3.1. Cement stemming plug

The main barrier to release of radionuclides is a 100–200 m long homogeneous cement stemming plug used to backfill each shaft; this is illustrated in Fig. 46 and described by Bouchez and Lecomte (1996). As poured and cured, this plug should have a lower permeability than the adjacent basalt volcanics. Also, the porosity of the cement, probably 6–10%, should be well distributed with few, if any, vertical cracks Thus, it seems likely that the permeability of the plug, typically 10^{-8}–10^{-10} m/s (Berner 1996), will be substantially lower than that of the surrounding rock. Moreover, its cross-sectional area will be much lower than that of the chimney. Thus, the groundwater flux from an intact cement plug will be insignificant compared with that from the surrounding rock

Degradation of the plug could conceivably occur, mechanically during the explosion or by chemical attack and degradation of the cement.

Mechanical damage

As shown in Fig. 46, the stemming plug is located above the top of the chimney. At that distance from the zero point of the explosion, the shock wave will have

decayed to a level where only moderate shear damage could occur. However, since the wave velocity in the cement plug will be lower than in the adjacent rock, passage of the wave will cause the rock to expand around the plug, effectively confining and strengthening it. Thus, it is considered unlikely that the concrete plug will be weakened preferentially with respect to the rock.

Chemical attack

Berner (1996) has assessed the consequences of chemical attack by sea water on the cement. Dissolution of portlandite ($Ca(OH)_2$) will increase the porosity (from 6% to ~10%) but it seems probable that the permeability of the plug will decrease owing to precipitation of brucite ($Mg(OH)_2$) Using a reasonable estimate of groundwater velocity, Berner estimates that it will take between 5000 and 1 million years for all the portlandite to dissolve. (The aggregate would of course remain, forming in itself an effective barrier.) On the basis of this analysis, it appears most unlikely that the cement plug will seriously degrade before the radionuclides produced by the nuclear explosion have decayed to insignificant levels.

6.2.3.2. Sampling boreholes

Soon after each test, a small diameter, inclined borehole is drilled directly into the base of the cavity in order to obtain core samples of the vitrified lava for analysis. Clearly, this drill hole, coming into direct contact with the hot cavity water, is a potential route by which radionuclides could be brought to the surface. The inclined nature of the hole accentuates this possible pathway by creating internal convection cells within the sampling borehole (Fairhurst et al. 1998).

Clarification was sought from the French Liaison Office on the conditions of these re-entry holes and the Study team was advised that, at the end of the coring operation, the holes were cemented in the volcanics but not in the carbonates, but that a packer was placed at the top of the borehole. Assuming that this procedure has been followed in each hole, this potential pathway for release would be eliminated.

In addition to these re-entry boreholes, a number of boreholes have been used for monitoring purposes both in a few chimneys and in the carbonates. Some of these sampling boreholes were used during the Study's underground water sampling campaign (Section 6.6). Large diameter (1.52 m) holes, originally drilled for device emplacement but never used, have also been used for monitoring purposes. The Study team was advised by the French Liaison Office that these holes had been left open but are now sealed at the top. Although this is likely to reduce radionuclide releases into the lagoon, and is one possible explanation for the lower levels of tritium found during the Study's aquatic sampling programme (Section 4), the holes could still provide preferential pathways for fluids in the carbonate zone since they are unsealed over most of their height.

6 3. HYDROGEOLOGY OF MURUROA ATOLL

The hydrogeological system of Mururoa Atoll is described by Guille et al. (1995). The porous structure of the atoll in both the volcanic and carbonate zones is fully saturated with water. Groundwater circulation in the atoll is governed essentially by buoyancy forces due to the geothermal flux heating the system from below. Cooler and denser ocean waters penetrate at depth from the flanks of the atoll, flow towards the central, warmer regions, gradually heat up, become lighter and move upwards towards the lagoon. This phenomenon is known as 'endo-upwelling'; the influx of nutrient rich deep sea water is believed to be the cause of the generally high biological productivity of lagoons (Swartz 1958, Samaden et al 1985, Rougerie and Wauthy 1993). Groundwater velocities in the volcanic rocks are generally very low. In the carbonate formations, which have much higher permeabilities, velocities are larger and there is an inward, near horizontal flow of cold water from the ocean.

Figure 59 shows the typical circulation pattern and temperature profiles with depth in the ocean and beneath the rim and lagoon at Mururoa. In ocean waters, temperatures decrease rapidly with depth from about 25°C at the surface to about 10°C at 450 m and then less rapidly at greater depths Beneath the atoll, temperature decreases with depth in the carbonates and then increases in the volcanics This is an indication of a much higher permeability in the carbonate rocks The lower temperatures beneath the rim (compared with the lagoon) are caused by inflow of the cooler ocean water.

Flow in the carbonates is also affected by the existence of extensive, highly transmissive karstic formations at several levels within the carbonates. There is evidence that at least some of these layers are in communication laterally with the ocean. This raises the possibility that some groundwater (and radionuclides), under the action of tidal pressure fluctuations, may move laterally through the carbonate layer directly to the ocean without release first to the lagoon

Nuclear testing has changed the hydrogeological system in two ways: by creating zones of increased permeability around each test location and by generating energy in situ which results in a significant increase

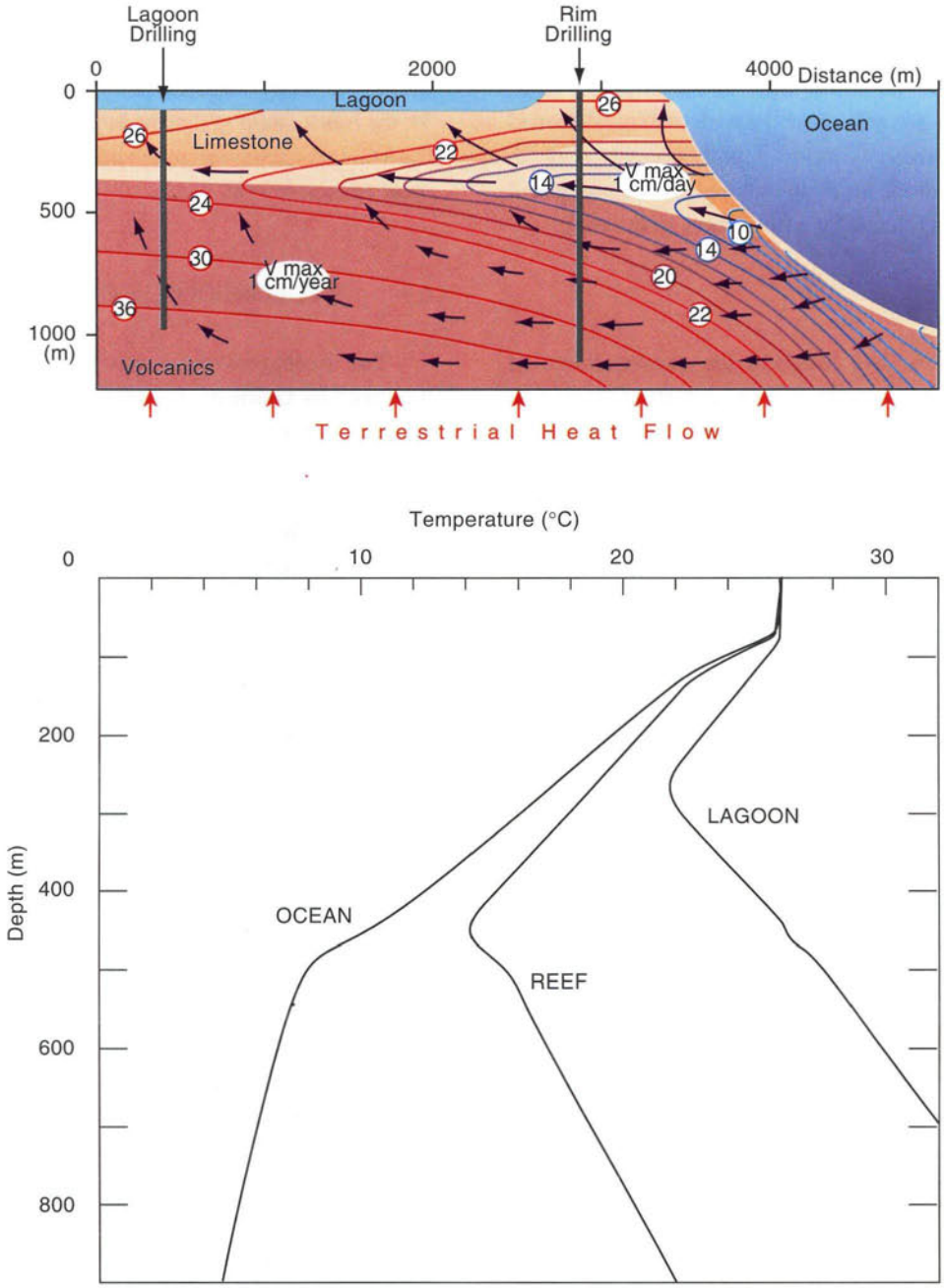


FIG. 59. Typical empirical temperature profiles, isotherms and groundwater flow paths beneath Mururoa Atoll. (Adapted from Guille et al. (1995) and Bouchez and Lecomte (1996).)

in temperature (typically 25–50°C) above the ambient level within the cavity–chimney after the explosion. Thus, warm water from the cavity–chimney rises as a plume, carrying with it any radionuclides that might be present in the cavity–chimney water. Figure 60 depicts natural and test induced flow patterns following nuclear testing.

6.3.1. Hydrological modelling

The hydrological processes of interest in atoll hydrology include groundwater flow through porous and fractured rock, transport of heat and transport of solutes. However, even though the volcanic and carbonate rocks in atolls are fractured, and exhibit variability at many

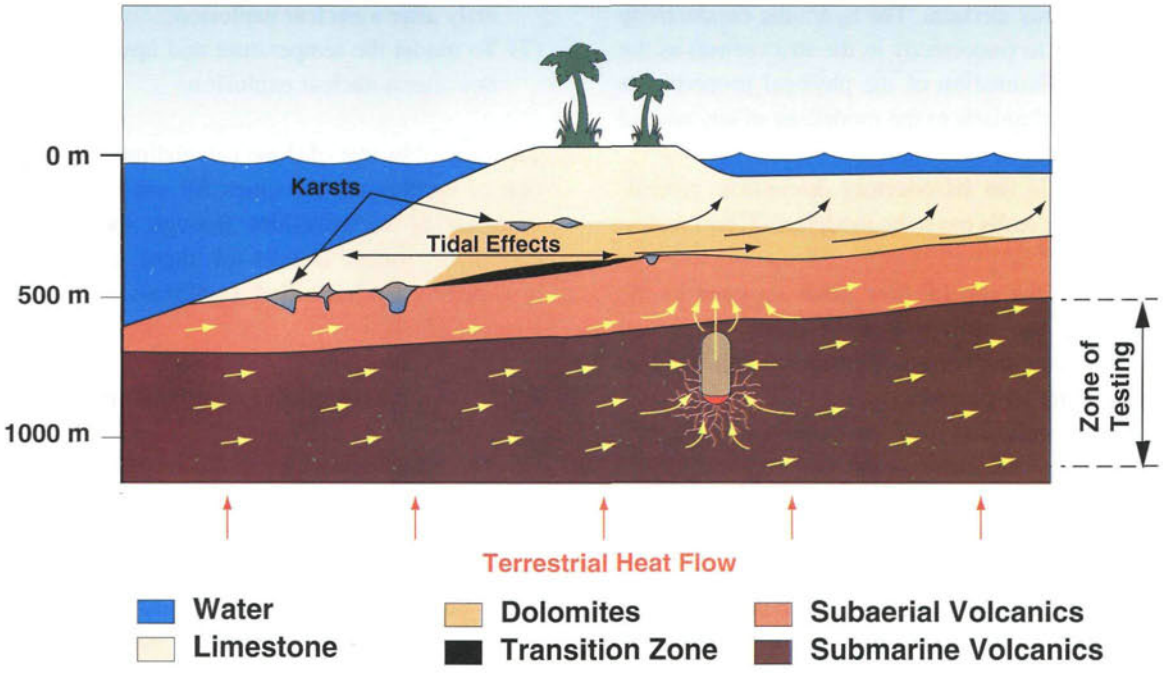


FIG. 60. Natural and test induced groundwater flow beneath Mururoa Atoll.

scales, from a practical point of view, when considering groundwater flow at the atoll scale, there are few alternatives to representing the rock by an equivalent porous medium.

In mathematical terms, groundwater flow in a porous medium is described by Darcy's law:

$$q = -\frac{k}{\mu}(\nabla p + \rho g) \qquad (6)$$

where

q is the specific discharge (vector) or Darcy velocity (m/s),
k is the permeability tensor (m^2),
μ is the dynamic viscosity of the fluid ($kg \cdot m^{-1} \cdot s^{-1}$),
p is the pore pressure (N/m^2),
ρ is the fluid density (kg/m^3),
g is the vector of acceleration due to gravity (m/s^2).

The Darcy velocity, or specific discharge, is the volumetric rate of flow per unit area through which flow occurs (i.e. it is a hypothetical discharge rate assuming that water moves through the entire cross-sectional area in question). It has the same dimensions as velocity, but it is not the speed at which the fluid moves.

To determine the average fluid velocity in the pores, it is necessary to divide the Darcy velocity by the effective porosity of the rock through which flow occurs. Thus, if the effective porosity of the rock is 10% of the total volume of the rock, the average fluid velocity in the pores is ten times the Darcy velocity.

For many calculations in hydrology, where the total volumetric flow is the property of interest, Darcy velocities are the most appropriate measure of flow. The distinction between Darcy velocity and actual fluid velocity is important in questions where the actual velocities of water movement in the interstitial pathways through a rock are of interest, for example when modelling the 'breakthrough' of a fluid containing radionuclides.

To make predictions of groundwater flow and transport of heat or solutes, it is necessary to define the geometry of a flow system, the physical properties of the porous medium and the fluid, and the boundary conditions, such as temperatures or fluctuating water levels, which drive the flow. Of these, the most difficult to determine are the physical properties of the medium, in particular the equivalent or effective hydraulic conductivity. The hydraulic conductivity, K, is the volume of water, at the existing kinematic viscosity, that will move in unit time under unit hydraulic gradient through a unit

area measured at right angles to the direction of flow through the porous medium. The hydraulic conductivity is often referred to (incorrectly in the strict sense) as the 'permeability' Estimation of the physical properties is an important prerequisite to the modelling of any natural hydrogeological system.

As implied in the introductory discussion, groundwater flow in the atolls has to be modelled on two scales:

(a) *Atoll scale*· the general flow fields imposed by the location of the atolls within the ocean, subject to heat flow from the crust, and surface conditions, e.g. lagoon water temperature;
(b) *Explosion scale:* the local perturbation of the atoll scale or regional groundwater flow regime by the enhanced permeability and thermal drive regime imposed by each explosion.

A state of the art numerical modelling program, FEFLOW (Finite Element Subsurface Flow System), was used to simulate the groundwater flow regime for each of the two scales described above. Both two dimensional and three dimensional analyses were carried out.

The analyses using FEFLOW were based on the following assumptions:

— *Porous medium.* slightly compressible, inert and continuous with heterogeneous hydrodynamic and thermal properties;
— *Fluid.* constant salinity water subject to Darcy's law generalized to rotational flows, with temperature dependent density and viscosity functions;
— *Continuity:* full mass conservation and advective–dispersive–diffusive transport equations.

The FEFLOW model was used in a number of ways, including the following:

(1) To compare FEFLOW results with the groundwater flow regimes on the atoll scale as described by Guille et al. (1995),
(2) To compare FEFLOW results with the temperature profiles observed in boreholes on Mururoa (Guille et al. 1995);
(3) To examine differences between 2-D (axisymmetric) and 3-D model results for Mururoa,
(4) To examine the sensitivity of the regional water regime to various assumed parameters, e.g. carbonate and volcanic rock permeabilities,
(5) To examine the influence of (i) a high conductivity, high dispersivity karstic layer in the lower carbonates, and (ii) anisotropic permeability of the carbonates,
(6) To model the refilling of a cavity–chimney immediately after a nuclear explosion;
(7) To model the temperature and upward flow velocities after a nuclear explosion

The final objective of these calculations was determination of appropriate velocities for use in modelling the transport of radionuclides through the volcanic and carbonate zones. Details of these calculations are provided by Fairhurst et al. (1998) and in the Technical Report, Vol. 4.

6.3.2. Atoll hydrogeology prior to nuclear testing

The most important parameters in the modelling of flow in an atoll are the hydraulic conductivities in the various layers. There are no direct and compatible French observations of pressures and flows at Mururoa or Fangataufa that might allow the direct measurement of bulk scale effective hydraulic conductivities. The approach taken in the Study (and indeed that taken by French modellers) is to use the temperature profiles beneath the rim and lagoon to estimate average hydraulic conductivities in the volcanic and carbonate rocks. This

TABLE XXXIV. REFERENCE VALUES OF PARAMETERS USED IN FEFLOW SIMULATIONS

Parameter	Carbonates	Volcanics
Matrix parameters		
Hydraulic conductivity, K (m/s)	10^{-4}	10^{-7}
Porosity, ε	0.4	0 1
Specific storage coefficient, S (m^{-1})	10^{-4}	10^{-4}
Thermal conductivity, λ_s ($J{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}K^{-1}$)	2	2 5
Volumetric heat capacity, $(\rho c)_s$ (10^6 $J{\cdot}m^{-3}$ K^{-1})	2 2	2 2
Longitudinal thermal dispersivity, α_L (m)	10	10
Transverse thermal dispersivity, α_T (m)	1	1
Fluid parameters		
Salinity (g/L)	34	34
Thermal conductivity, λ_l ($J\ m^{-1}\ s^{-1}{\cdot}K^{-1}$)	0 65	0 65
Volumetric heat capacity, $(\rho c)_l$ (10^6 $J\ m^{-3}$ K^{-1})	4 2	4.2
Density and viscosity	High order temperature dependent functions are used	

involves calculation of the temperature profiles using a coupled transport code for water and heat with assumed hydraulic conductivities The calculated temperature profiles are then compared with observed temperature profiles and adjustments made to the hydraulic conductivities to obtain the best match between measured and predicted temperature profiles.

Temperature data such as those shown in Fig. 59 have been interpreted and modelled by Guille et al (1995) and Bouchez and Lecomte (1996). Further modelling has been carried out by Henry et al. (1996) for a complete idealized cross-section through Mururoa Atoll. The modelling was carried out using a code known as METIS (Goblet 1981), which solves the equations for density coupled transport of water and heat in a 2-D cross-section.

The purpose of the modelling by Guille et al. (1995) and Bouchez and Lecomte (1996) was to carry out an approximate calibration of a model by comparing calculated and observed temperature profiles as mentioned above. They concluded that effective hydraulic conductivities are about 10^{-7} m/s in the volcanics and 10^{-4}–10^{-5} m/s in the carbonates. The hydraulic conductivity in the volcanics is, in reality, an upper limit because they concluded that thermal conduction dominates in the volcanic rocks.

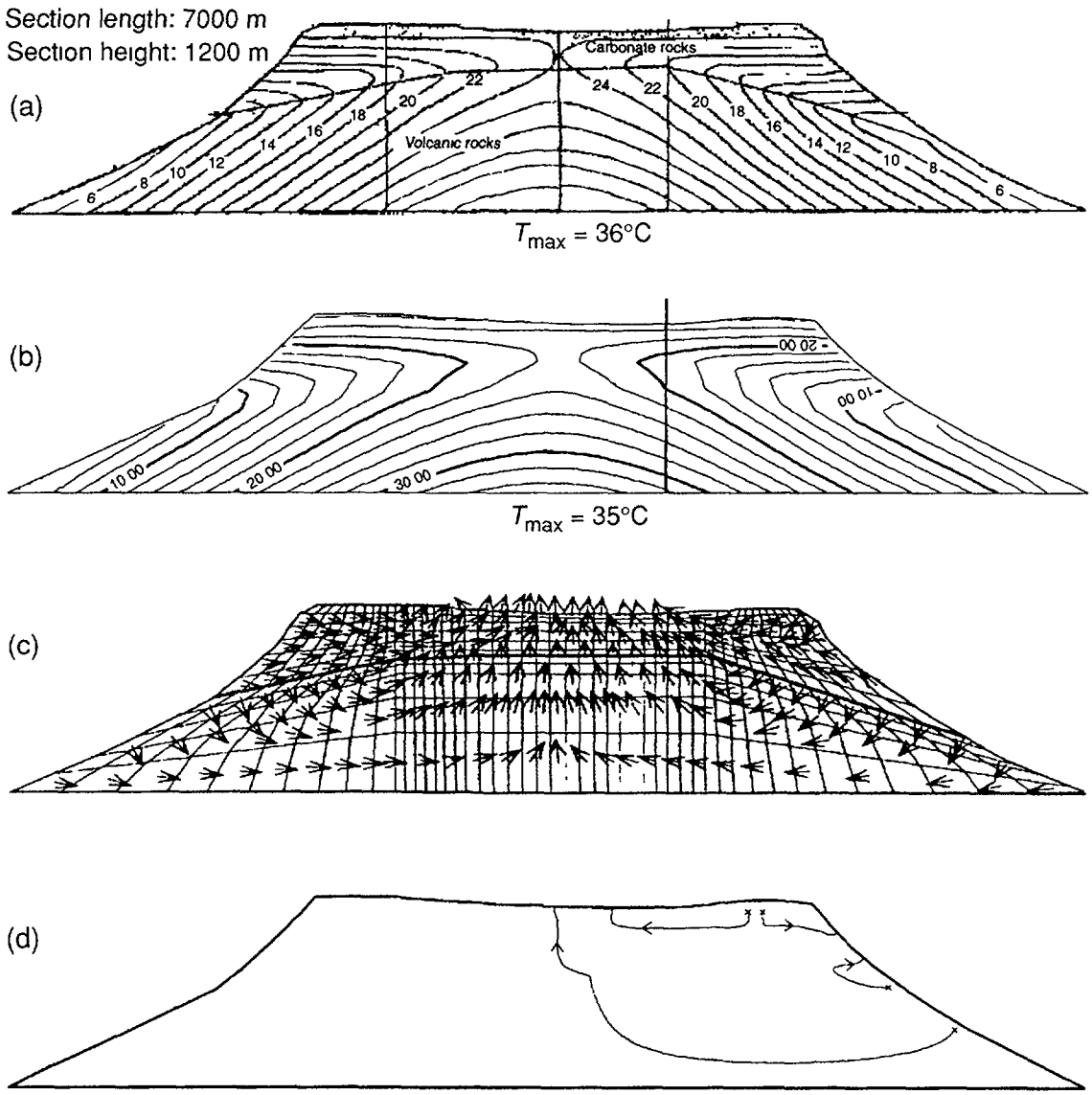


FIG. 61 Comparison of isotherms and flow paths simulated by METIS (Henry et al 1996) and FEFLOW (Perrochet and Tacher 1997) (a) original isotherms after Henry et al., (b) isotherms given by FEFLOW using original parameters from Henry et al , (c) original velocity vectors after Henry et al., (d) typical flow paths given by FEFLOW using original parameters from Henry et al

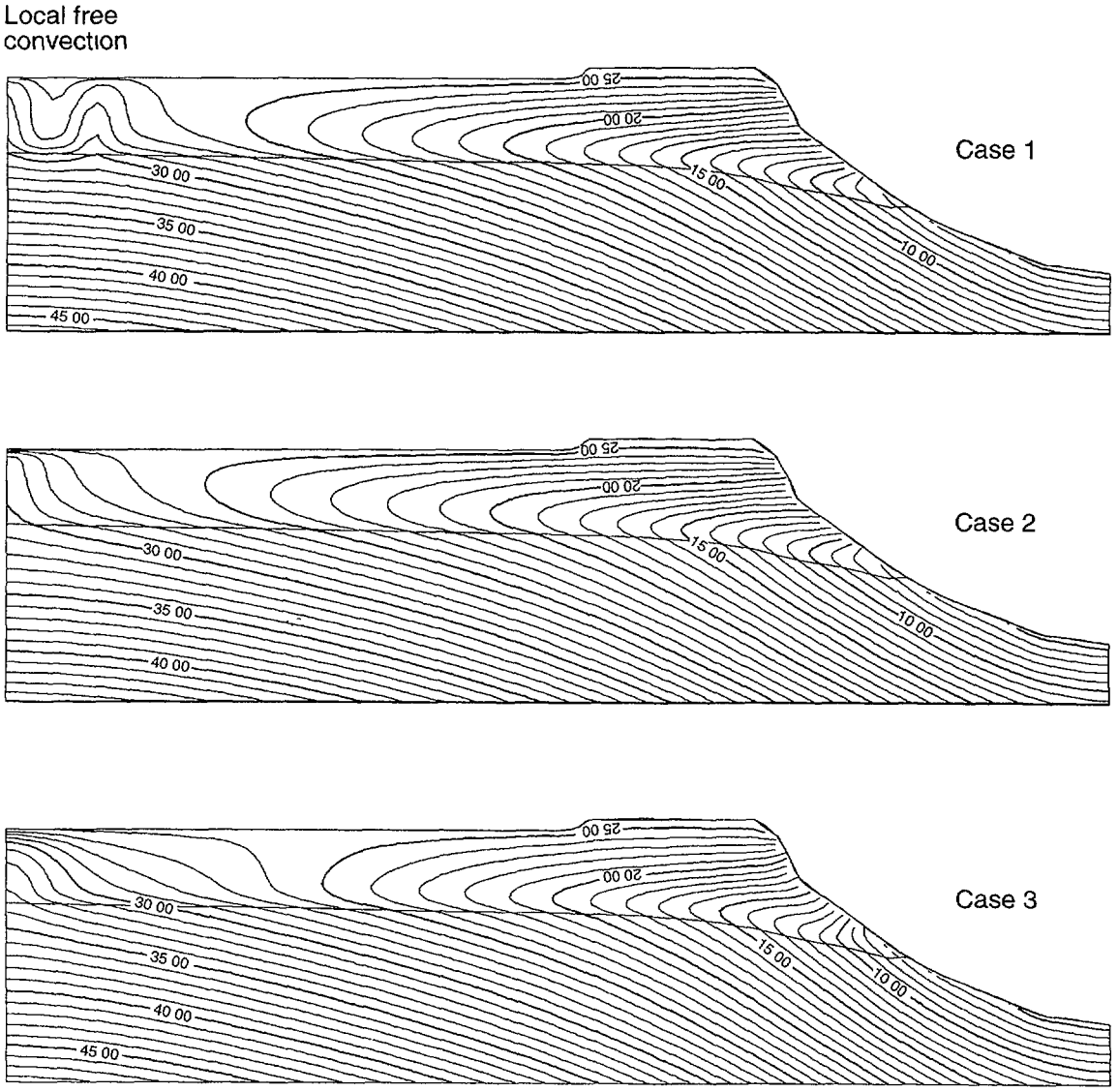


FIG 62. Simulated isotherms for cases 1–3 to study the effect of changes in model parameters in the carbonate formations (Perrochet and Tacher 1997)

Henry et al. (1996) present sensitivity analyses using various combinations of hydraulic conductivities in the volcanics and carbonates In the volcanics, the small effective hydraulic conductivities lead to small velocities and, therefore, negligible dispersion; thus, the transport of heat is dominated by conduction. In the carbonates, the velocities are three orders of magnitude larger, and dispersion dominates as the primary mechanism for transport of heat The authors concluded that large scale effective hydraulic conductivities in the volcanics and carbonates are of the order of 10^{-7} and 3×10^{-4} m/s, respectively.

Independent modelling of density coupled transport of water and heat for the Study was carried out at the Ecole polytechnique fédérale, Lausanne, Switzerland, by Perrochet and Tacher (1997) on behalf of the IGC (Fairhurst et al. 1998) using FEFLOW (Diersch 1996). In order to test the equivalence of METIS and FEFLOW, at least under standard conditions, an effort was made to reproduce a number of results obtained by French researchers.

The reference values of parameters used in the modelling computations for the Study are given in Table XXXIV. It is important to note that, although precise physical data were used where available (densities, heat capacities, etc.), some key parameters (e.g. hydraulic conductivities) may vary significantly with position, it is sufficient for the purposes of the

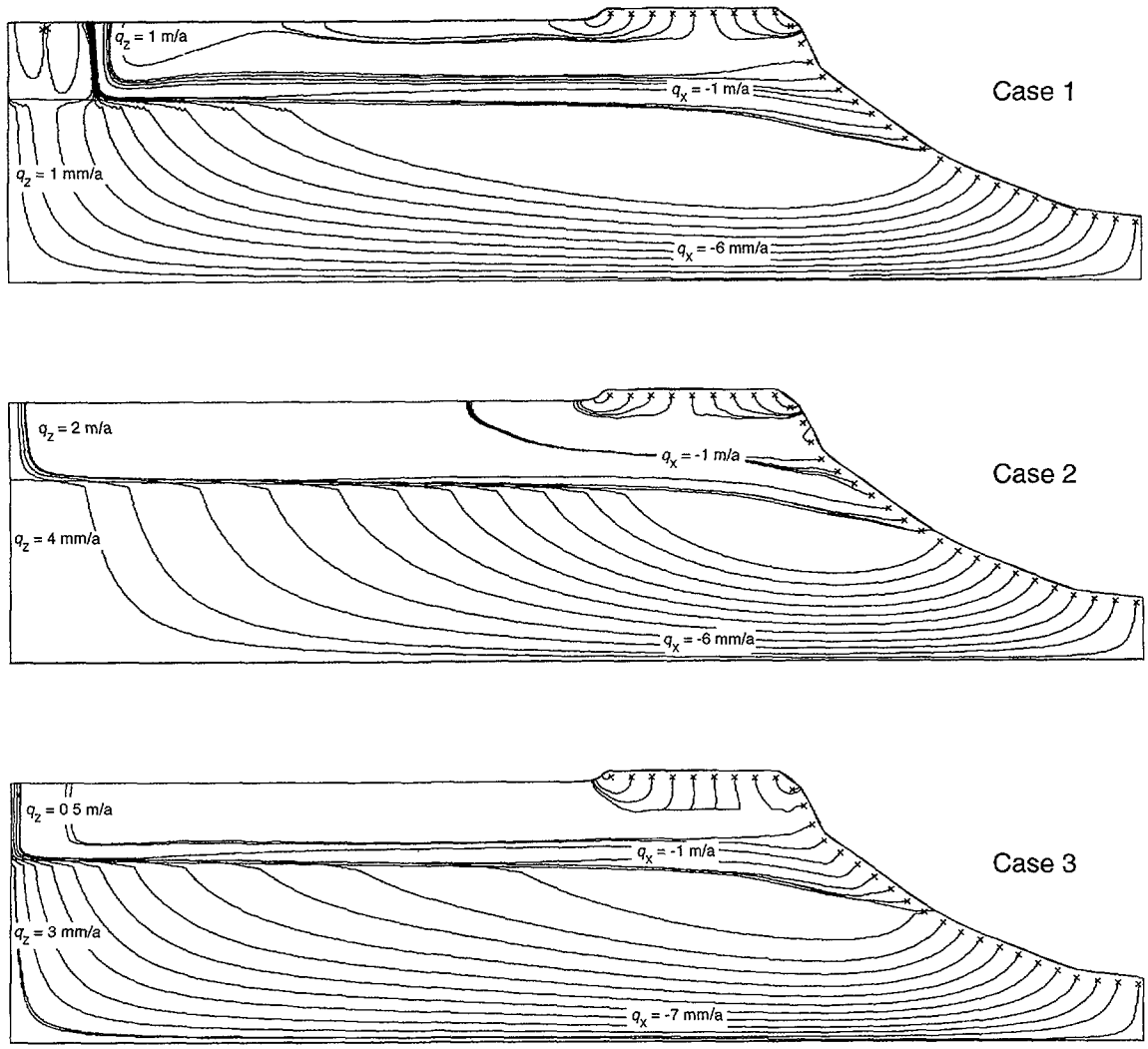


FIG 63 Simulated flow paths and typical Darcy velocities for cases 1–3 shown in Fig 62 (Perrochet and Tacher 1997) Crosses denote starting points for flow paths.

Study to estimate their average values to within a factor of 5–10.

The first runs using FEFLOW were aimed at comparing results with those obtained by Henry et al. (1996) for an idealized cross-section through Mururoa Atoll Temperature distributions obtained by French researchers using METIS and by the Study team using FEFLOW agree reasonably well (Figs 61(a) and (b)). However, the flow paths computed by FEFLOW (Fig. 61(d)) are different from the velocity vectors published by Henry et al (1996) (Fig. 61(c)), and clearly show the existence of a stagnation point at a shallow depth beneath the rim of the atoll, consistent with water from under the rim flowing both inwards towards the lagoon and outwards towards the ocean

In subsequent calculations, the FEFLOW model was further refined and the number of grid points was increased to 20 000 linear triangles. With these improvements, there was a decrease in the predicted extent of penetration of cold water from the flanks and this resulted in higher temperatures (by 1–3°C) near the centre of the volcanic formation. The maximum Darcy velocities are about 10 mm/a in the volcanics and 2 m/a in the carbonates (Perrochet and Tacher 1997).

Many simulations were carried out to study the effect of various parameters on temperature profiles and flow velocities These sensitivity studies, described in detail by Perrochet and Tacher (1997), demonstrate the following:

— Decreasing the hydraulic conductivity in the volcanics by an order of magnitude from 10^{-7} to 10^{-8} m/s does not significantly affect the predicted spatial distribution of temperatures, from which it is

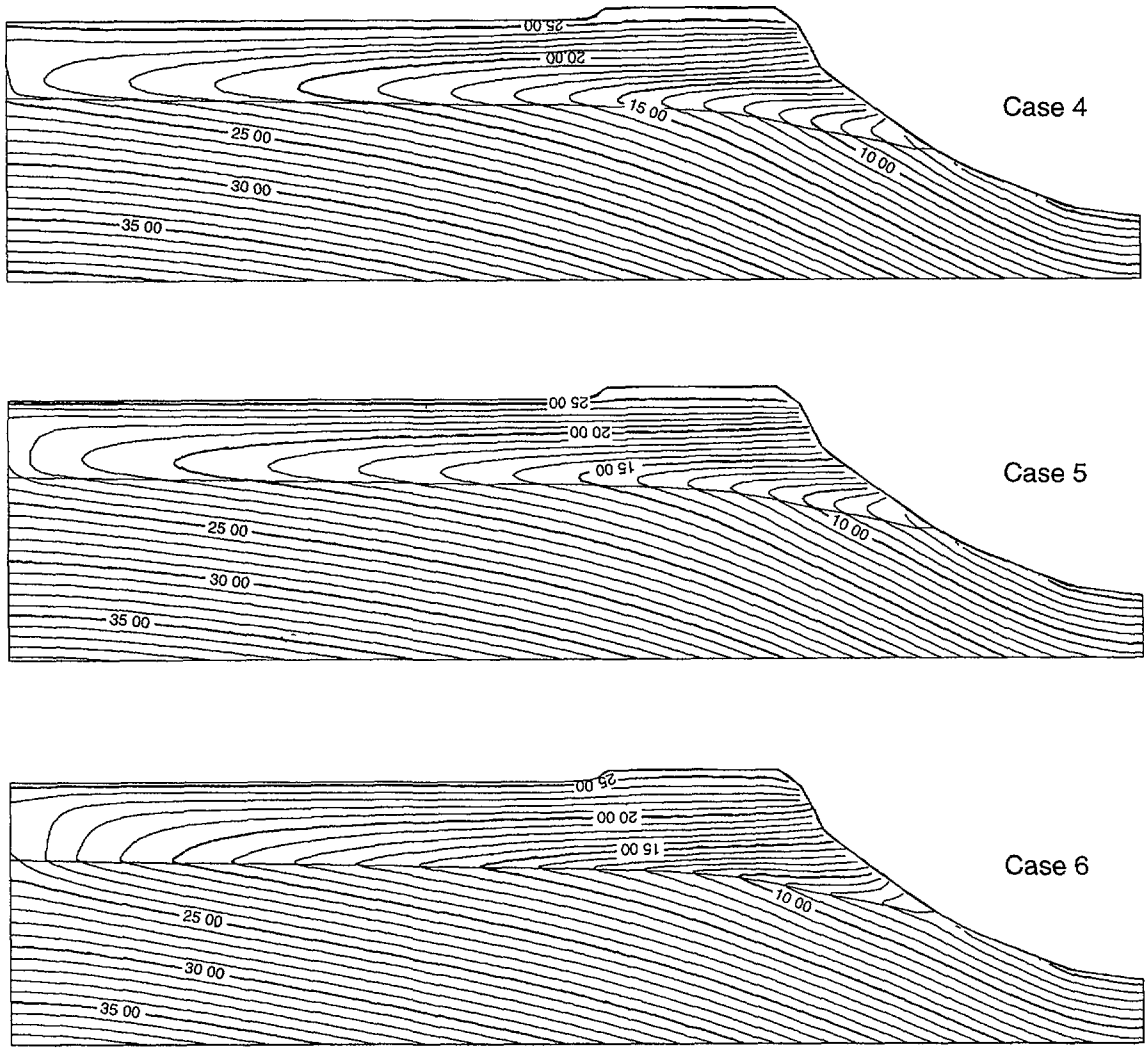


FIG 64 Simulated isotherms for cases 4–6 to study the effect of changes in model parameters in the carbonate formations (Perrochet and Tacher 1997)

inferred that, for any hydraulic conductivity less than about 10^{-7} m/s, heat transfer within the volcanics is dominated by conduction.

— Increasing the hydraulic conductivity in the volcanics by an order of magnitude to 10^{-6} m/s decreases the predicted temperature at the interface between volcanics and carbonates at any particular distance from the centre of the atoll and, more importantly, results in temperature profiles in both the volcanics and the carbonates which are unlike the measured values shown in Fig. 59.

— Increasing the hydraulic conductivity in the carbonates by an order of magnitude to 10^{-3} m/s significantly increases the extent to which ocean water is drawn into the atoll, resulting in a temperature inversion in the depth profile at all distances from the centre of the atoll, not only near the rim.

— Introducing into the carbonates a thin layer of extremely high conductivity (10^{-2} m/s), to represent a karst near the interface between volcanics and carbonates, has a similar effect to increasing the hydraulic conductivity and ensures that the minimum temperature in any temperature profile occurs in that layer.

— Increasing the depth of the domain of simulation from 1200 to 2000 m has negligible effects on the spatial distribution of temperatures.

— Decreasing the geothermal heat flux from 4500 to 3000 $J \cdot d^{-1} \cdot m^{-2}$ decreases temperatures deep in the volcanics, and changes the slope of the geothermal

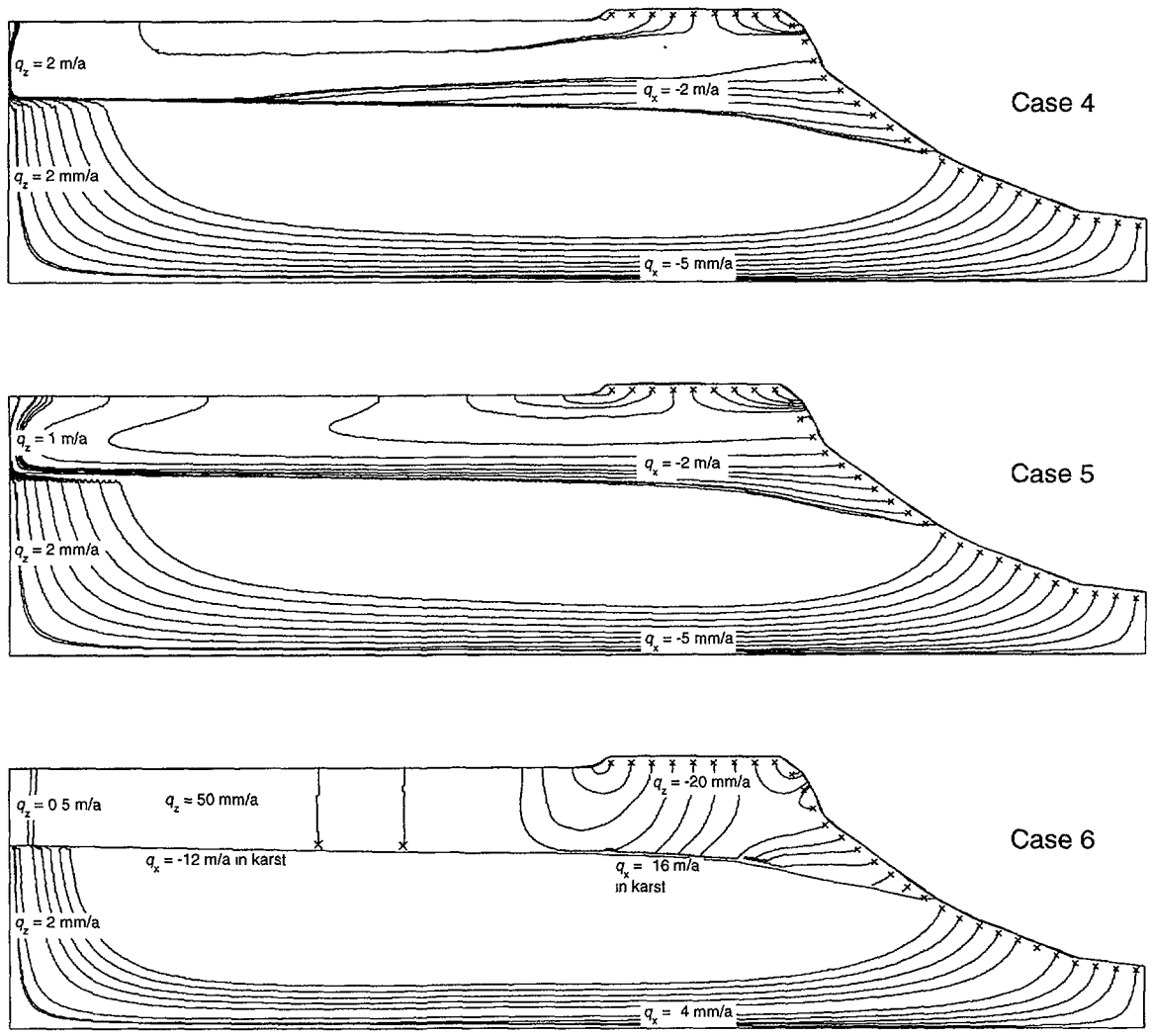


FIG 65 Simulated flow paths and typical Darcy velocities for cases 4–6 shown in Fig 64 (Perrochet and Tacher 1997) Crosses denote starting points for flow paths.

profile within the volcanics to a value which is too small relative to observations, but does not have a significant impact on temperatures within the carbonates, which are more influenced by ocean temperatures along the flank of the atoll.

In general, these simulations confirm that the reference case is a good fit to the experimental measurements of temperatures within the atoll. It is concluded that the hydraulic conductivities are less than 10^{-7} m/s in the volcanics and about 10^{-4} m/s in the carbonates, in agreement with the conclusion of Henry et al. (1996).

In the carbonates, the velocities are three orders of magnitude larger than in the volcanics and advection or dispersion dominates as the primary mechanism for transport of heat. A number of possible combinations of conductivities and porosities were modelled in order to simulate the known inhomogeneities in the carbonate formations:

Case 1: Reference case, as presented in Table XXXIV: linear 2-D model, isotropic hydraulic conductivity $K = 10^{-4}$ m/s.
Case 2: Axisymmetric version of case 1.
Case 3: Two carbonate layers:
- Upper layer, porosity ε = 0 3, isotropic hydraulic conductivity $K = 10^{-5}$ m/s;
- Lower layer, porosity ε = 0.4, isotropic hydraulic conductivity $K = 10^{-4}$ m/s.

Case 4: Reference data set with homogeneous carbonates: isotropic hydraulic conductivity increased by a factor of 5 to $K = 5 \times 10^{-4}$ m/s.

Case 5: Reference data set with anisotropic carbonates:
- Horizontal hydraulic conductivity $K_H = 10^{-3}$ m/s;
- Vertical hydraulic conductivity $K_V = 10^{-4}$ m/s.

Case 6: Reference data set with simulation of a karst:
- Bottom layer 10 m thick karst, $K_H = 10^{-2}$ m/s,
- Remaining layers (homogeneous carbonates): isotropic hydraulic conductivity reduced by a factor of 10 to $K = 10^{-5}$ m/s.

Figure 62 shows isotherms predicted for the first three cases In general, the profiles are similar. In case 1, the reference case, the temperature inversion in the carbonates lies about 1 km from the centre of the atoll. Near the centre of the atoll, the temperature at the base of the carbonates is higher than in the lagoon, allowing the development of local free convection cells. Such cells are not seen in cases 2 and 3, nor in the simulations of Henry et al (1996).

Figure 63 shows corresponding flow paths and velocities for the three simulations shown in Fig. 62. The flow patterns are relatively similar and velocities are very similar to those computed by Henry et al (1996). Horizontal velocities are about 6 mm/a in the volcanics and of the order of 1 m/a in the carbonates. Vertically upward velocities in the carbonates are of the order of 0.5–2 m/a in those parts of the atoll where significant upward flow occurs.

Figure 64 compares the isotherms in cases 4–6, which were designed to simulate the effects of changes in hydraulic conductivity, anisotropy and karstic layers, respectively. In all three cases, the temperature inversion persists to the centre of the atoll and the profiles are in good visual agreement with the data of Bouchez and Lecomte (1996), reproduced in Fig 59 Case 6 results in a sharp gradient in temperature at the interface between the carbonates and volcanics where the karstic layer is assumed to exist. The corresponding flow velocities, shown in Fig 65, are not markedly different from cases 1–3; in the volcanics the velocities are largely horizontal and about 5 mm/a away from the centre of the atoll and about 2 mm/a vertically at the centre. In case 6, the velocities in the karstic layer are about 16 m/a but elsewhere velocities in the carbonates are similar to those in the reference case.

An attempt was made to select optimal parameters in the carbonate zone Figure 66 compares the temperature profiles for four simulations (cases 3–6) In these simulations, the slopes of the thermal gradients are more important than the deviations from the measured (thick) curve because the position of the interface between the volcanics and carbonates is not known precisely. On this basis, it could be argued that, although there are differences in the profiles, each is a reasonable fit to the data, given that the observed temperature profiles are composite average values rather than actual measurements at specific locations.

Towards the end of the Study, the CEA provided ocean bathymetric data, a digital representation of the base of the carbonates at Mururoa, at approximately

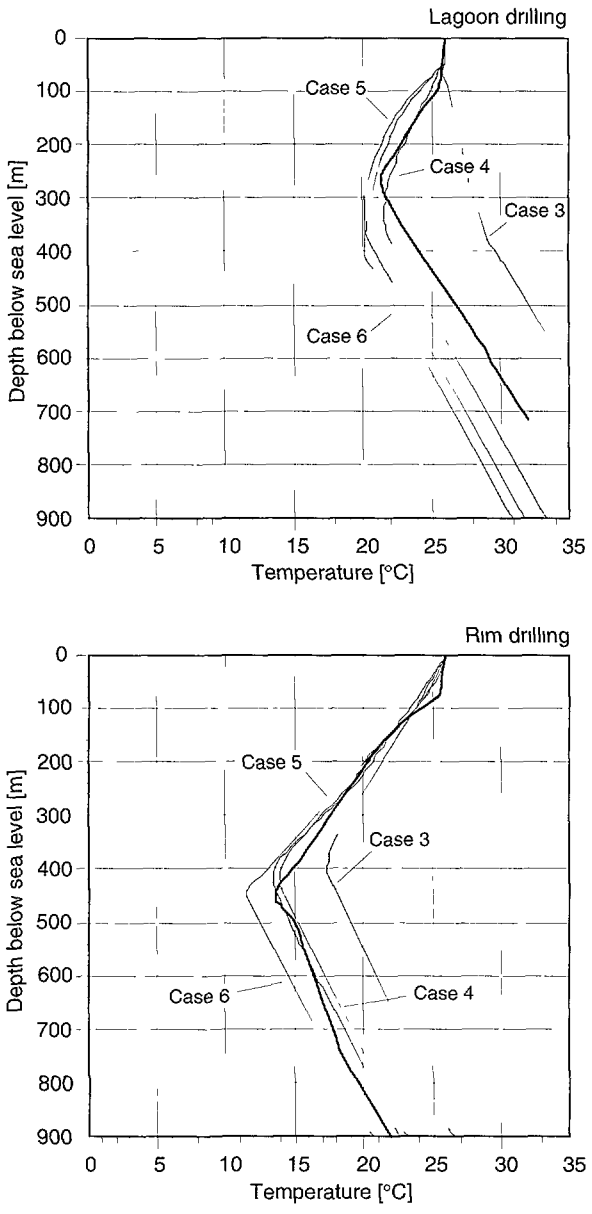


FIG 66 Comparison of temperature profiles from drill hole measurements with simulations for cases 3–6 (Perrochet and Tacher 1997).

100 m grid spacing, and a map of the temperature at the base of the carbonates, interpolated from 90 measurements. These data allowed simulation of geothermal convection in three dimensions.

A 3-D model was constructed using FEFLOW, extending to a depth of 1700 m below sea level. Figure 67 shows 3-D images of Mururoa Atoll, illustrating the thermal structure inside the atoll. The temperature

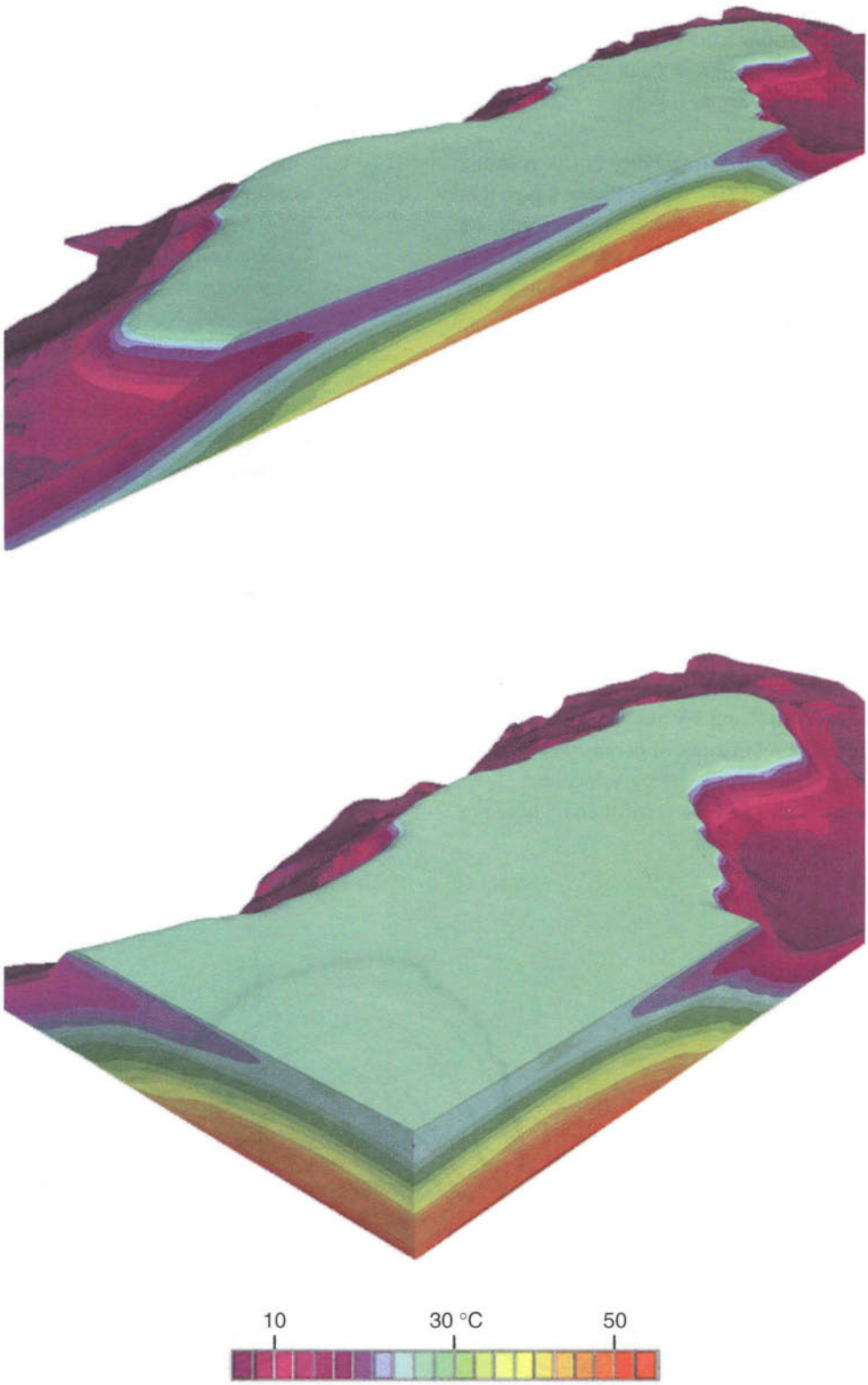


FIG. 67. Northeast–southwest section through 3-D model of Mururoa Atoll showing simulated underground isotherms viewed from the northwest (vertical and horizontal scales are the same).

inversion in the carbonates is clearly evident, as is the fact that the penetration of cooler water into the atoll depends on the 3-D geometry of the atoll. Figure 68 shows that the measured and simulated temperature contours at the base of the carbonate formations are in reasonable agreement.

The major conclusions from the steady state modelling, which are not very different from those presented by the French authorities, are as follows:

(a) The large scale natural permeability of the volcanic rocks is of the order of 10^{-7} m/s or lower. Given that the volcanic rock permeability, as measured on cores, is about 1000 times lower, it is concluded that flow in the volcanics occurs mainly in fractures with an unknown density and aperture distribution.
(b) Different combinations of permeabilities in the carbonates can explain the observed temperature profiles. The scenario considered the most likely by the Study team includes a highly permeable karstic layer above the volcanics, with a transmissivity of 0.1 m^2/s (e.g. a 10 m layer with a hydraulic conductivity of 10^{-2} m/s), covered by a thick series of carbonates with an average isotropic hydraulic conductivity of 10^{-5} m/s. Alternatively, the carbonates could be made of one single equivalent isotropic layer with a conductivity of 5×10^{-4} m/s or a single anisotropic layer with horizontal and vertical conductivities of 10^{-3} and 10^{-4} m/s, respectively.
(c) These preferred combinations of parameters produce the following values for the Darcy velocities:
   — Volcanics: 2 mm/a in the vertical and 5 mm/a in the horizontal direction;
   — Carbonates: 0.5–2 m/a in both the vertical and horizontal directions.
(d) These Darcy velocities can be transformed into water velocities if the rock porosity is known. For the carbonates, a reasonable estimate of porosity is 20–40%. For the volcanics, the French documentation gives an average value of 10–20% for the matrix porosity (i.e. the small scale pores in the basalt). However, if the flow takes place in the fracture network then a value of 1% or lower could be used. With these values, typical water velocities are:
   — Volcanics, with a fracture porosity of 1%: 0.2–0.5 m/a both vertically and horizontally;
   — Carbonates: 2–7 m/a both vertically and horizontally.

The focus of the hydrogeological modelling has been on Mururoa Atoll, or idealized cross-sections intended to represent sections through Mururoa. Although no specific calculations were carried out for Fangataufa, there is no reason to expect that hydraulic conductivities and velocities would be fundamentally different.

6.3.3. Atoll hydrogeology after nuclear testing

The phenomena associated with a nuclear explosion were described in Section 5.4. From the viewpoint of hydrology, the most important consequences of a nuclear test are the generation of heat and the fracturing of the rock, which increases its permeability.

Most of the heat generated by a nuclear test is deposited in the proximity of the zero point. This results

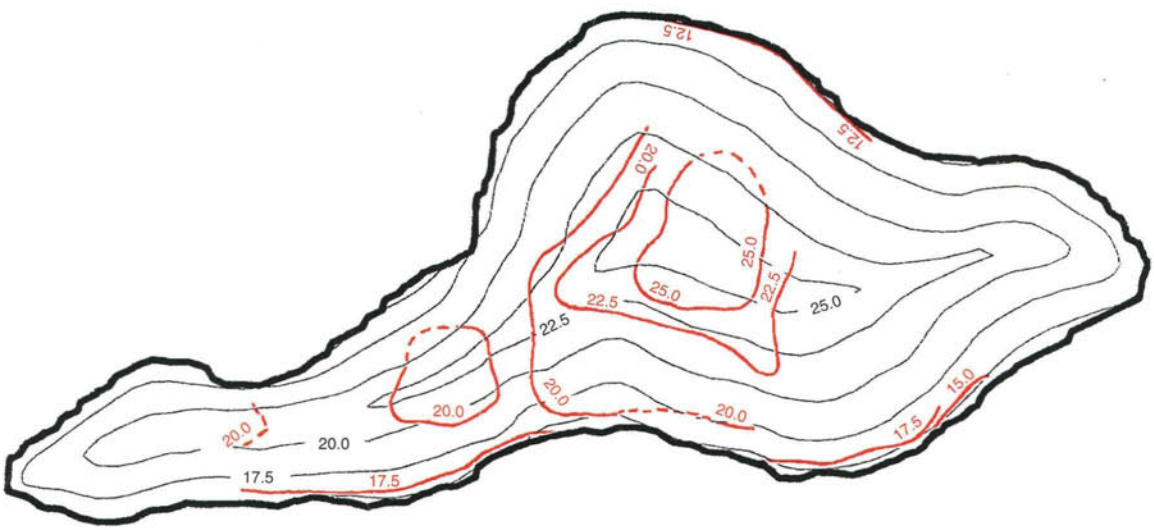


FIG. 68. Simulated and measured isotherms (shown in red) at the interface between the volcanic and carbonate formations.

in melting and vaporization of rock in the cavity and production of steam due to vaporization of interstitial water in the volcanic rocks. With collapse of the overlying rock, thermal circulation cells are set up within the chimney and thermal energy contained within the initial spherical cavity becomes uniformly distributed throughout the rubble and infiltrating water.

The maximum temperature rise within the chimney can be estimated by assuming that all the heat generated by the nuclear explosion is dissipated in water and rock within the chimney and cavity. The radius of the cavity is proportional to the cube root of the yield, which implies that the volume is directly proportional to the energy release (Eq. (1) in Section 5.4 1). The volume of the chimney is also, to a first approximation, proportional to yield (Eq. (2)). It follows, therefore, that the equilibrium temperature in the chimney will be relatively independent of yield. Knowing the volume of the chimney and the heat capacities of the water and rock, the maximum temperature rise can be shown, from a simple heat balance, to be about 50°C. In practice, the temperature rise will be somewhat lower because not all the energy is deposited as heat in the chimney (e.g. a small fraction is dissipated in the shock wave well away from the source) and some heat losses occur during the equilibration process. Consequently, within a few months of a nuclear test, the water temperature within the cavity–chimneys for all tests will be between 25 and 50°C above the pre-test value. This temperature will slowly decrease over the next few hundred years through the combined effects of convection and conduction. Even after 500 years, when the thermal plume has completely dissipated, the velocity in the vicinity of the test will be higher than the pre-test value because of the increased permeability in the cavity–chimney and surrounding rock.

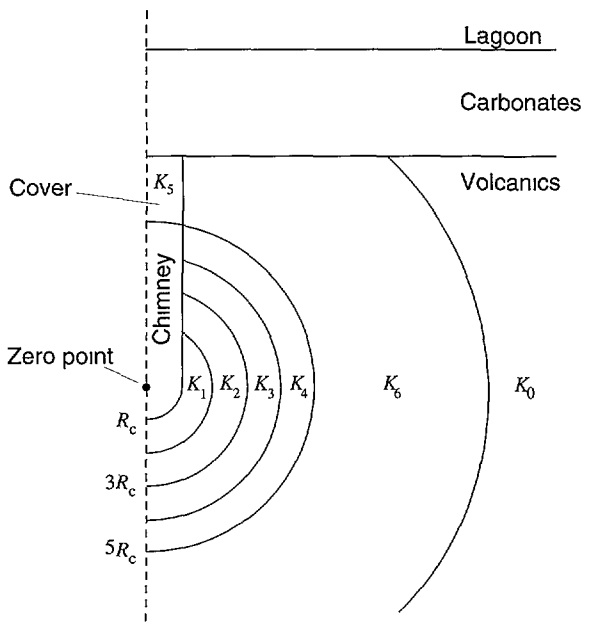


FIG. 69. Representation of post-test hydraulic conductivities for modelling purposes (Perrochet and Tacher 1997).

6.3.3.1. Effect of test induced fracturing on hydrogeology

The extent of fracturing caused by a nuclear explosion was discussed in Section 6.2.2. It is very difficult to calculate the resulting permeability of fractured rocks beyond the chimney from physical information on their fracture properties. However, it is highly likely that the permeability will increase in the surrounding rocks and will decrease with distance from the centre of the cavity. The Study team decided to define and test several scenarios (designated F0–F3) involving different fracture zones of varying permeability. The scenarios examined are as follows:

Scenario F0: No increase in fracturing after test,
Scenario F1 Decrease in intensity of fracturing with radial distance from zero point,
Scenario F2: Increased fracturing confined to volcanic cover above chimney,
Scenario F3: Extensive fracturing.

In all cases, the hydraulic conductivity was assumed to be 10^{-2} m/s in the chimney and 10^{-4} m/s in the carbonate formations. Scenario F3 also includes a thin hemispherical crush zone (Section 6.2.2.1) in the cavity with a conductivity of 10^{-9} m/s Depending on the depth of the test, the fracture zone can reach the carbonate formations, allowing high flow rates from the chimney. Scenarios F0 and F3 are the extreme scenarios whereas F1 is an intermediate case and F2 corresponds to a conductivity increase in the volcanic layer above the test extending to the interface with the carbonate formations. Figure 69 defines the fracture zones and Table XXXV gives the assumed hydraulic conductivities in those zones for each of the scenarios.

For a small number of tests, the French scientists have made detailed field observations of the time for water to infiltrate back into the chimneys after a nuclear explosion. These observations provide the best data for selecting the most appropriate scenarios for modelling of the post-test hydrology (French Liaison Office Document No. 5)

Modelling of filling rates was carried out by the Study team using a transient 2-D axisymmetric flow

TABLE XXXV. SCENARIOS OF HYDRAULIC CONDUCTIVITY (m/s) IN VOLCANICS TO REPRESENT POSSIBLE FRACTURING IN DAMAGED ZONES AROUND A TEST CAVITY

	F0	F1	F2	F3	Zone of application
K_0	10^{-7}	10^{-7}	10^{-7}	10^{-7}	Regional background
K_1	10^{-7}	10^{-5}	10^{-7}	10^{-3}	$1–2R_c$
K_2	10^{-7}	5×10^{-6}	10^{-7}	5×10^{-4}	$2–3R_c$
K_3	10^{-7}	10^{-6}	10^{-7}	5×10^{-4}	$3–4R_c$
K_4	10^{-7}	5×10^{-7}	10^{-7}	5×10^{-4}	$4–5R_c$
K_5	10^{-7}	10^{-6}	10^{-6}	10^{-4}	Volcanic cover
K_6	10^{-7}	10^{-7}	10^{-7}	10^{-4}	$5–10R_c$

model in a manner similar to the French calculations (French Liaison Office Document No. 5). The Study took no account of gas compression at the top of the chimney because this effect can be shown to be negligible until 70–80% of the total chimney volume is filled.

Five data points are available for the rate of filling of a cavity from a 14.5 kt test (French Liaison Office Document No. 5, fig. 21). French scientists matched the filling rate with a model based on a regional background hydraulic conductivity of 6×10^{-8} m/s and an increased conductivity of 2×10^{-6} m/s within a radius of $2\,3R_c$ from the location of the explosion. Calculations for three scenarios are shown in Fig. 70(a), together with Study calculations using the scenario adopted by the French scientists (CEA curve). Scenarios F2 and F0 agree reasonably well with the experimental data, at least as well as the French model Scenario F1 would result in filling much faster than observed and F3 is too fast to be shown in Fig 70(a). The data obtained in the field for this 14.5 kt test are consistent with only slight damage to the surrounding rock beyond the chimney, as assumed in scenario F2.

The only other detailed data available are measurements of pressure in the chimney for a 3 2 kt test (French Liaison Office Document No. 5, fig. 22). These data have been converted to filling rates. Calculations are shown in Fig. 70(b). In order to match the observations, the CEA used a conductivity of 5.5×10^{-7} m/s as a regional background value and 2×10^{-6} m/s within a radius of $2\,5R_c$. For this test, the Study scenario F1 matched the data far better than F0 and F2. This finding is consistent with the French conclusion that it was necessary to increase the hydraulic conductivity value above the pre-test level in order to explain the faster rate of filling.

Estimates of filling times are available for nearly half of the underground nuclear tests. The French scientists have estimated maximum effective hydraulic conductivities based on these data (French Liaison Office Document No. 5, fig. 23). A range of values of regional background conductivity are given for an assumed value of 2×10^{-6} m/s within a radius of $1.6R_c$. More than half of the estimates of regional conductivity are less than 10^{-7} m/s and another 40% are between 10^{-7} and 3×10^{-7} m/s. These results suggest that, if 10^{-7} m/s

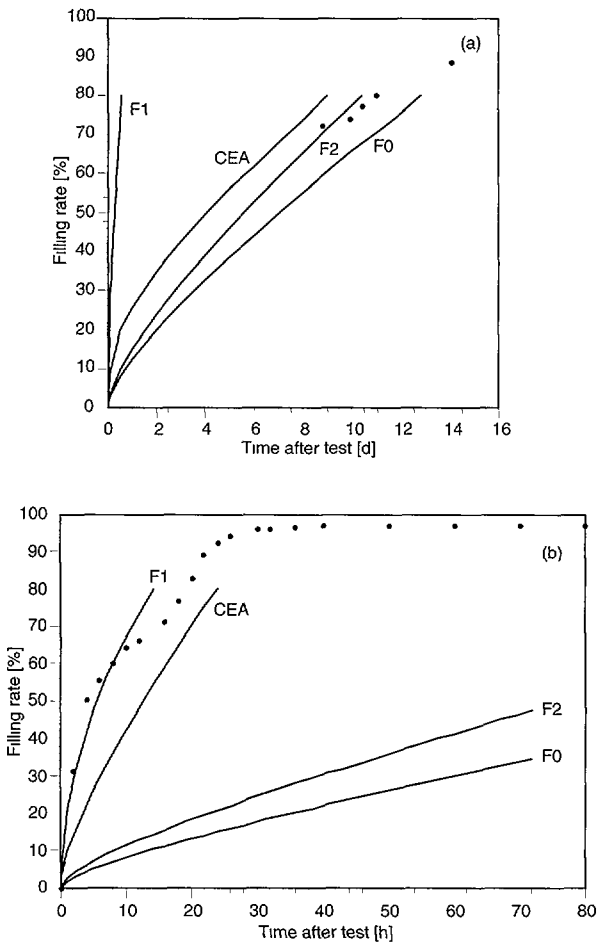


FIG. 70 Comparison of measured filling rates predicted by the French Liaison Office with three permeability scenarios used in the Study for (a) 14 5 kt test, (b) 3 2 kt test (the fourth scenario cannot be shown on this scale, as indicated in the text) (Perrochet and Tacher 1997)

were chosen as a fixed parameter and if filling rates were used to calculate an effective conductivity within a radius of 1.5–2R_c, nearly all tests would imply values less than 10^{-5} m/s in that zone, and scenario F3 would significantly overestimate the extent of damage

The main conclusions from these simulations are as follows.

(a) In some tests there is little change in permeability outside of the chimney
(b) Scenarios F1 and F2 appear to represent upper limits for modelling increases in permeability.
(c) Scenario F3 is too conservative under all reported conditions.

6.3.3.2. *Geothermal convection cells in the medium term*

Once the cavity–chimney is full of water, the dominant hydrological process of interest is the growth and decay of a geothermal convection cell caused by the temperature and density differences between hot water in the chimney and cooler ambient water in the surrounding basalt. This phenomenon has been described by Bouchez and Lecomte (1996) both qualitatively and, to some extent, quantitatively. The convection cell is essentially radially symmetric, with hot water rising vertically above the chimney and cool ambient water entering the bottom and sides of the chimney. Convection provides a mechanism for dissipation of heat in that heat is carried upwards by the rising water at the same time as being transported outwards by conduction

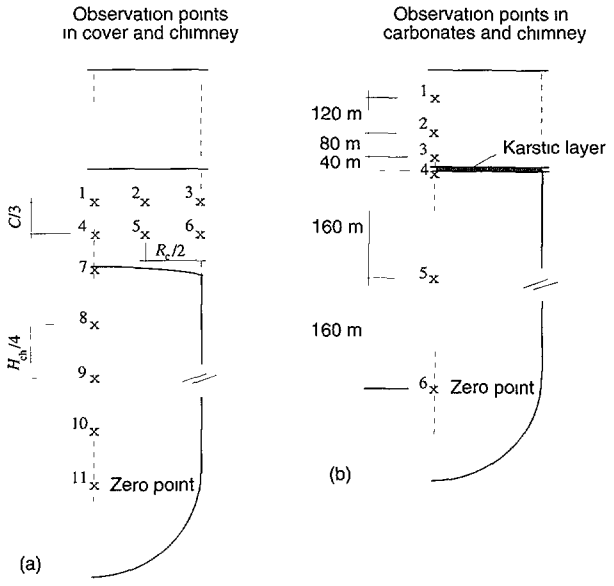


FIG. 71 Locations of points where temperatures and Darcy velocities are computed for: (a) tests with volcanic cover, (b) tests without volcanic cover (150 kt tests only, H_{ch} = 320 m) (Perrochet and Tacher 1997) C *is cover thickness*

French numerical modelling was referred to by the Atkinson Mission (New Zealand Ministry of Foreign Affairs 1984, annex V, fig. 22) but few details were provided. An attempt was made by Hochstein and O'Sullivan (1985, 1988) to model the thermal convection, but their results were obtained using very coarse finite difference grids and without access to accurate French information. In the absence of relevant theoretical results, the best way to understand the geothermal convection cells is to use numerical methods, and this is the approach followed by the French scientists and the Study team.

Modelling of convection near a chimney by Bouchez and Lecomte (1996) shows that for a 100 kt test, with 140–150 m of volcanic rock above the chimney and hydraulic conductivity enhanced by a factor of 10 relative to the background conductivity of 10^{-7} m/s (essentially scenario F2 in Table XXXV), the initial temperature rise in the chimney of 25°C decays to zero over a period of about 500 years. The vertical velocity in the volcanic cover decays less slowly initially, but relatively faster at later times, reaching the upward velocity induced by the natural geothermal gradient after 400 years. During the first five years, the Darcy velocity exceeds 0 25 m/a

To check the French results, 15 simulations (both 2-D axisymmetric and 3-D) were performed using FEFLOW for a number of combinations of yield, initial temperature increase in the chimney, thickness of volcanic cover and spatial distribution of hydraulic conductivity Two test yields were modelled 5 kt (a relatively small explosion, requiring a small thickness of cover) and 150 kt (the upper limit of underground tests reported at Mururoa and Fangataufa). Initial temperature differences were assumed to be either 25 or 50°C, as discussed earlier. The volcanic cover above the chimney was assumed to have thicknesses of 15 and 100 m, being very conservative values for small and large yields, respectively (Table XXX), and 0 m for the case of a chimney which reaches the carbonates (CRTV tests). Alternative hydraulic conductivity distributions were considered corresponding to scenarios F0–F3, as defined in Table XXXV. The results are reported in detail by Perrochet and Tacher (1997).

Simulations were carried out to calculate the temperatures and velocities for periods of 500 years at an array of grid points (Fig. 71) distributed uniformly in the volcanic cover above the chimney or, for the case of no

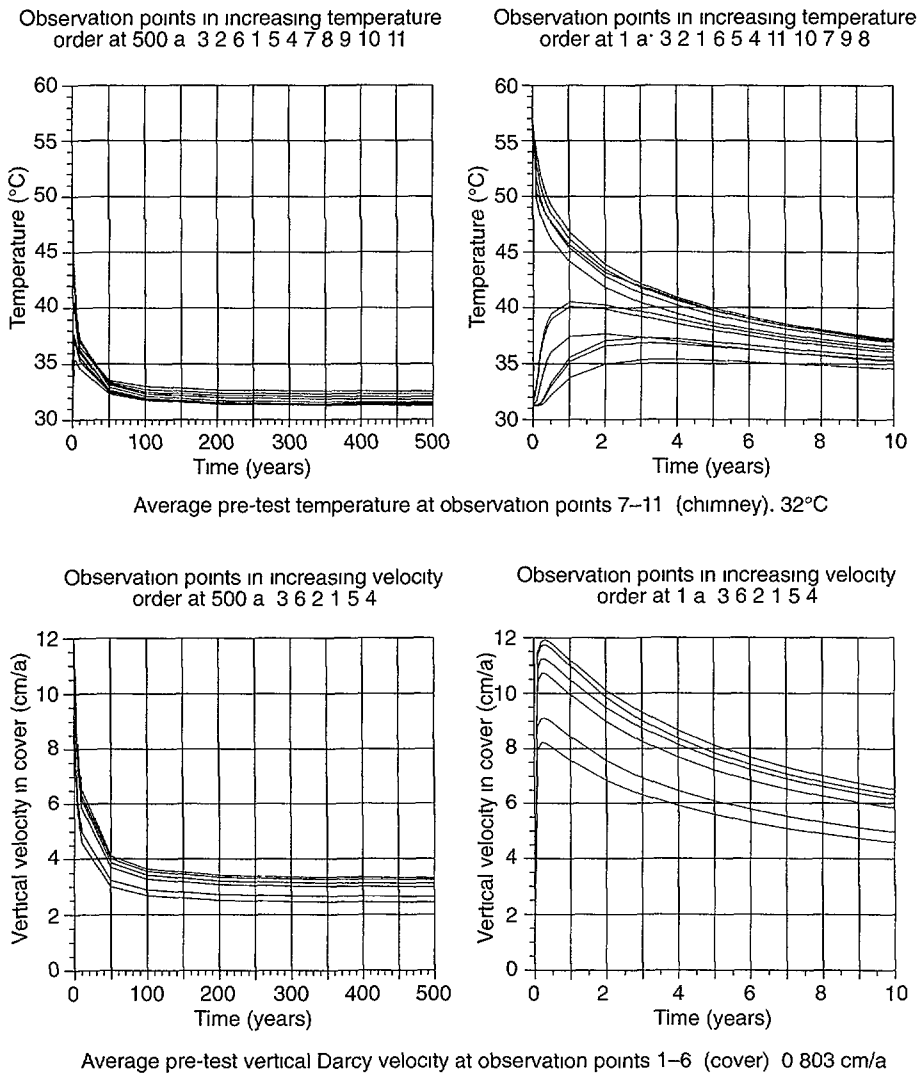


FIG 72. Variation of temperature and Darcy velocity with time following a 5 kt test with 15 m of volcanic cover, a temperature rise of 25°C and no increase in hydraulic conductivity above pre-test level (scenario F0) (Perrochet and Tacher 1997) Observation points are shown in Fig. 71.

volcanic cover (CRTV tests), in the carbonates up to 120 m above the chimney. Figures 72 and 73 compare two simulations at different yields, 5 and 150 kt, for scenario F0 (no increase in fracturing). The peak Darcy velocities are fairly similar. 8–12 cm/a for the 5 kt test and 5–9 cm/a for the 150 kt test.

Figure 74 shows a worst case simulation, a 150 kt test with 100 m of cover, an initial temperature rise of 50°C and significantly higher permeability out to 10 cavity radii (scenario F3). The peak Darcy velocities are in the range 30–70 m/a. This simulation can be considered applicable to tests with inadequate cover (Category 2, described in Section 5.9), such as the Lycos test at Fangataufa.

Another extreme case is shown in Fig. 75 a 150 kt test with a temperature rise of 50°C and no volcanic cover. (This was a modelling calculation of a hypothetical test to give an indication of the likely velocities to be encountered It must be emphasized that no test exceeding 80 kt had a cover of less than 150 m (Table XXX). Nevertheless it provides a reasonable approximation for all CRTV tests since peak velocities are insensitive to yield.) The peak Darcy velocities in the carbonate layer are 40–50 m/a.

Table XXXVI gives values of Darcy velocities above the cavity–chimney as a function of time for all scenarios. A number of general conclusions can be drawn from these data:

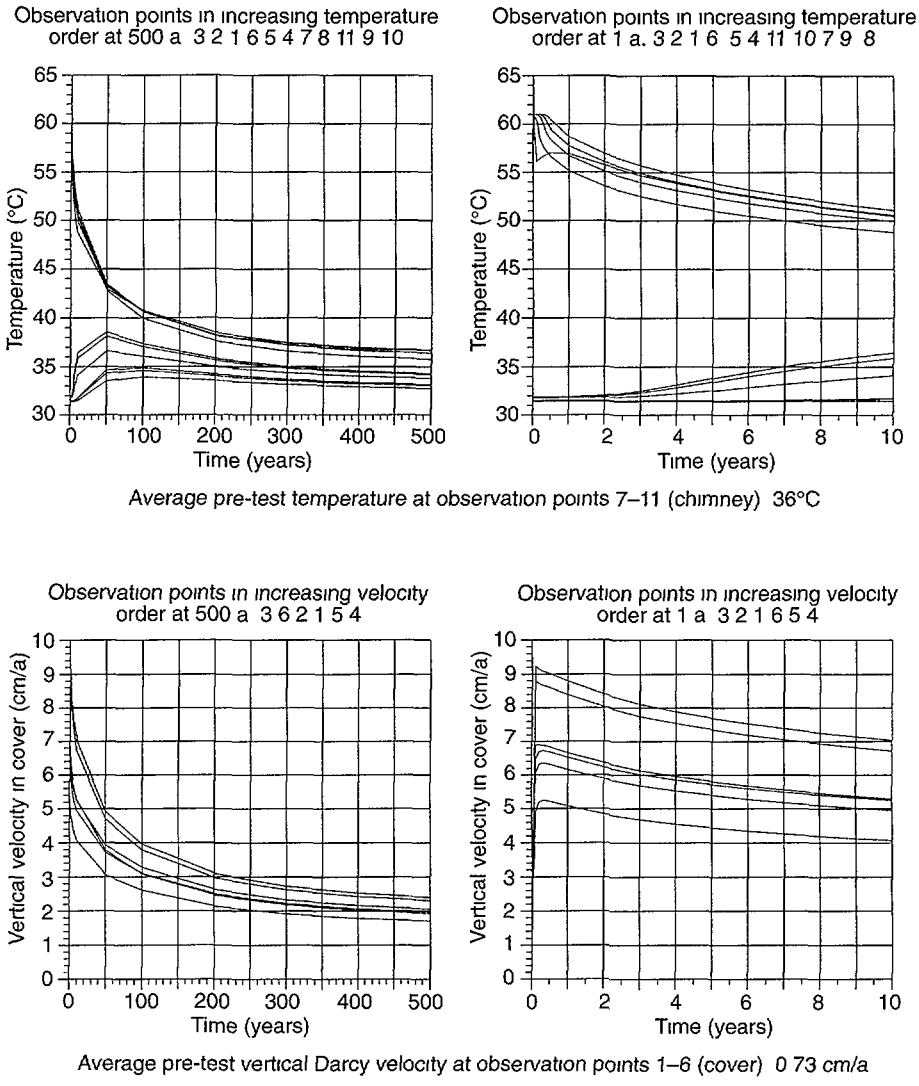
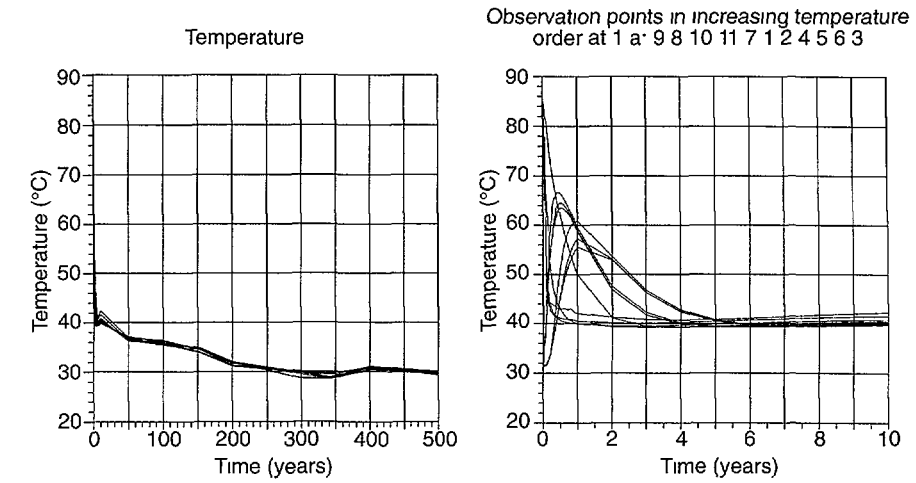


FIG. 73. Variation of temperature and Darcy velocity with time following a 150 kt test with 100 m of volcanic cover, a temperature rise of 25°C and no increase in hydraulic conductivity above pre-test level (scenario F0) (Perrochet and Tacher 1997) Observation points are shown in Fig. 71

(a) Velocities are relatively insensitive to yield.
(b) Increasing the temperature rise from 25 to 50°C roughly doubles the peak velocities.
(c) Peak velocities are increased by about a factor of 5 between scenarios F2 and F0 and a factor of 10 between scenarios F1 and F0.

Figures 76 and 77 show colour plots of the migration of the thermal plume vertically above the cavity–chimney for the cases where there is no karstic layer at the base of the carbonates (Fig. 76) and where a karst layer with large longitudinal dispersivity (α_L = 1000 m) exists (Fig. 77). It is seen that a karstic layer is very effective in dissipating the thermal plume.

As indicated earlier (Section 5.9), of the safety trials carried out in the carbonates, four produced no nuclear yield and three resulted in a total energy release of about 0.45 kt. For the former, there is essentially no perturbation of the steady state hydrological regime and the Darcy velocities can be estimated from Figs 63 and 65. For the three safety trials that went critical, the cavity–chimney will have a radius of about 7 m and a height of about 35 m. Mathematical simulation of these conditions indicates a peak Darcy velocity of 18 cm/d immediately after the explosion (Perrochet and Tacher 1997) Because of the small size of these trials, heat is dissipated fairly rapidly and the velocity decreases accordingly (Table XXXVI).



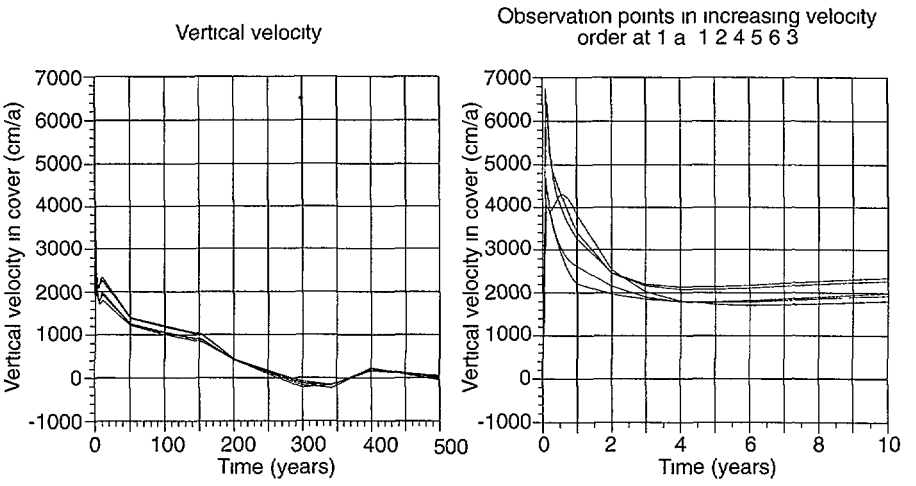


FIG 74 Variation of temperature and Darcy velocity with time following a 150 kt test with 100 m of volcanic cover, a temperature rise of 50°C and significantly higher hydraulic conductivity to 10R_c (scenario F3) (Perrochet and Tacher 1997) Observation points are shown in Fig. 71

6.3.3.3. Long term impact of a large number of tests

Steady state simulations were carried out to determine whether the large number of tests carried out under Mururoa Atoll would have any effect on the long term hydrological regime. Using the information on the spatial distribution of tests provided by the French Liaison Office (reproduced as Fig 44), test locations were chosen at random within the designated areas and damage zones were simulated.

Successive simulations with hydraulic conductivities of 10^{-6}, 10^{-5} and 10^{-4} m/s in the damage zones yield temperature distributions virtually identical to the pre-test distributions. The pre-test, steady state total discharge into the lagoon is of the order of 60 000 m^3/d. This value shows very little sensitivity to the presence of all 137 tests (and associated damage zones) in the model. With hydraulic conductivities of 10^{-4} m/s in all the damage zones, for example, the total discharge into the lagoon is increased by less than 1%. It is concluded that there will be no significant long term change in the overall hydrogeology of Mururoa Atoll as a result of underground nuclear testing. The same conclusion also applies to Fangataufa Atoll since the damage zones on Fangataufa are, on a percentage basis, only slightly larger than those on Mururoa (Table XXXIII).

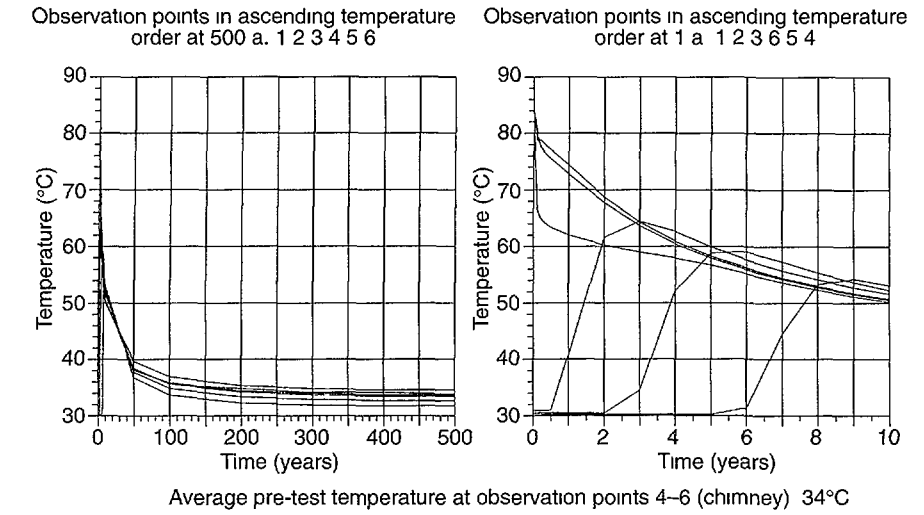


FIG 75 Variation of temperature and Darcy velocity with time following a 150 kt test with no volcanic cover, a temperature rise of 50°C and no increase in hydraulic conductivity above pre-test level (scenario F0) (Perrochet and Tacher 1997) The test modelled is a hypothetical extreme. a 150 kt test with an initial temperature rise of 50°C and with no cover (no such tests were ever carried out). Observation points are shown in Fig 71

6.3.3 4. Summary and discussion of post-explosion hydrogeology

Three major conclusions can be drawn from the simulations reported above:

(a) The vertical velocity above a test chimney is not as sensitive to the extent of fracturing and the resulting permeability as might be intuitively expected. The reason is that the water rising from the chimney must be replaced by water flowing radially towards the cavity–chimney. Even if the rock is damaged at some distance from the cavity–chimney, eventually this water has to come from undamaged zones where the permeability in the volcanics is very low and unchanged from the pre-test value For instance, for a 150 kt test, if the extreme scenario F3 (permeability increase by a factor of 1000) is used, the velocity above the chimney is increased by a factor of 5 compared with scenario F2 (permeability increase by a factor of 10).

(b) Since the cavity and chimney are well mixed chambers because of their constant internal convection, the uncontaminated water entering the chimney is instantly mixed with the contaminated water inside the chimney. As a consequence, it can readily be

TABLE XXXVI. EFFECTS OF PARAMETERS ON DARCY VELOCITY ABOVE CAVITY–CHIMNEY
(runs 1–12 are axisymmetric 2-D simulations)

Run	Yield (kt)	ΔT (°C)	Cover (m)	Scenario	Darcy velocity[a] (m/a)		
					Peak velocity	After 10 years	After 100 years
1	5	25	15	F0	0 12	0.07	0 03
2	5	25	15	F1	1.4	0 7	0 35
3	5	25	15	F2	0.5	0.3	0.15
4	5	50	15	F0	0.24	0 1	0 04
5	5	50	15	F1	3 3	1.2	0 4
6	5	50	15	F2	1 3	0.5	0.2
7	150	25	100	F0	0 09	0 07	0 04
8	150	25	100	F1	1 2	0 7	0.4
9	150	25	100	F2	0.64	0 4	0 25
10	150	50	100	F3	6	2.5	1
11	150	50	0	F0	50	35	7
12	150	50	0	F3	60	22	17
13[b]	150	50	0	F0	34	16	3
14[b]	150	50	0	F0	5	5	0 5
15[b]	150	50	0	F0	4	1.5	0 5
16[c]	0 2	50	0	F0	60	4	na[d]

[a] Based on velocity at grid point 4 for runs 1–10 and grid point 3 for runs 11–16

[b] 3-D simulations run 13 assumes no karst, run 14 assumes a karst with longitudinal dispersivity of 100 m and run 15 assumes a karst with longitudinal dispersivity of 1000 m

[c] Safety trial in carbonate, no change in permeability.

[d] na not available

shown that, provided that there is no leaching from the lava, the concentration of radionuclides in the chimney decreases exponentially with time. The time needed to transfer to the carbonates a given fraction of a non-sorbing radionuclide initially present in the water (such as tritium) can be calculated: it is a function of the ratio of the Darcy velocity above the chimney to the height of the chimney. Typical values for the transfer of 90% of a non-sorbing stable nuclide are tens to hundreds of years. Sorbed radionuclides take much longer and will be modelled in a later section.

(c) The vertical velocity above a test site is almost independent of the yield of the test This is due to the fact that the volume of the cavity–chimney scales linearly with the yield, which makes the temperature increase similar for all tests. The buoyancy forces are thus of the same order whatever the yield. Were the temperature increase to change from 25 to 50°C, the velocity would be increased by almost a factor of 2.

The simulations described in Section 6.3.3.2 can also be used to select appropriate Darcy velocities for modelling of radionuclide transport and to give an approximate indication of the breakthrough times for a passive tracer, such as tritium. In Section 5.9, the various tests are divided into seven categories and it is appropriate to summarize the post-test hydrogeology according to that classification.

Category 1

Category 1 comprises the 121 regular tests with a wide range of yields. However, as already noted, yield has only a minor effect on upward velocity from the chimney. For these conditions, scenario F2 is a conservative scenario. Runs 3 and 9 (Table XXXVI) are close to the normal conditions and, allowing for a temperature increase of 50°C, indicate that an appropriate conservative Darcy velocity for modelling purposes would be about 1 m/a

For regular tests, a passive tracer should begin to reach the carbonates after about one year but it will take several hundred years for 90% to empty from the cavity–chimney. For radionuclides such as ^{3}H, ^{90}Sr and ^{137}Cs, decay alone will ensure that little activity escapes to the biosphere; moreover, in the case of ^{90}Sr and ^{137}Cs there will also be retardation due to sorption.

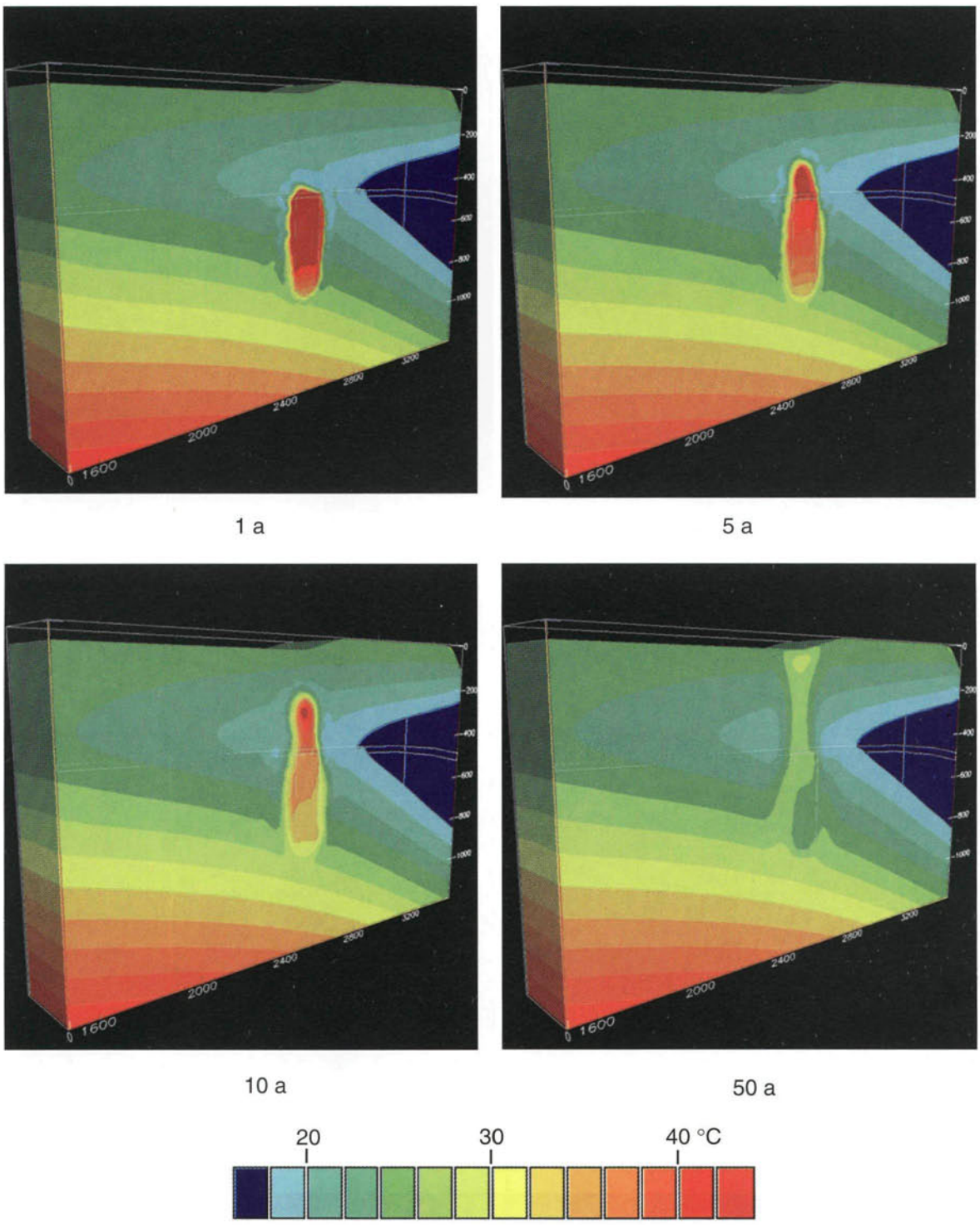


FIG. 76. Three dimensional simulation over time of isotherms for a 150 kt test with no volcanic cover, a temperature rise of 50°C in the chimney, no increase in hydraulic conductivity above the pre-test level (scenario F0) and no karst layer at the volcanic–carbonate interface (Perrochet and Tacher 1997). The test modelled is a hypothetical extreme: a 150 kt test with an initial temperature rise of 50°C and with no cover (no such tests were ever carried out).

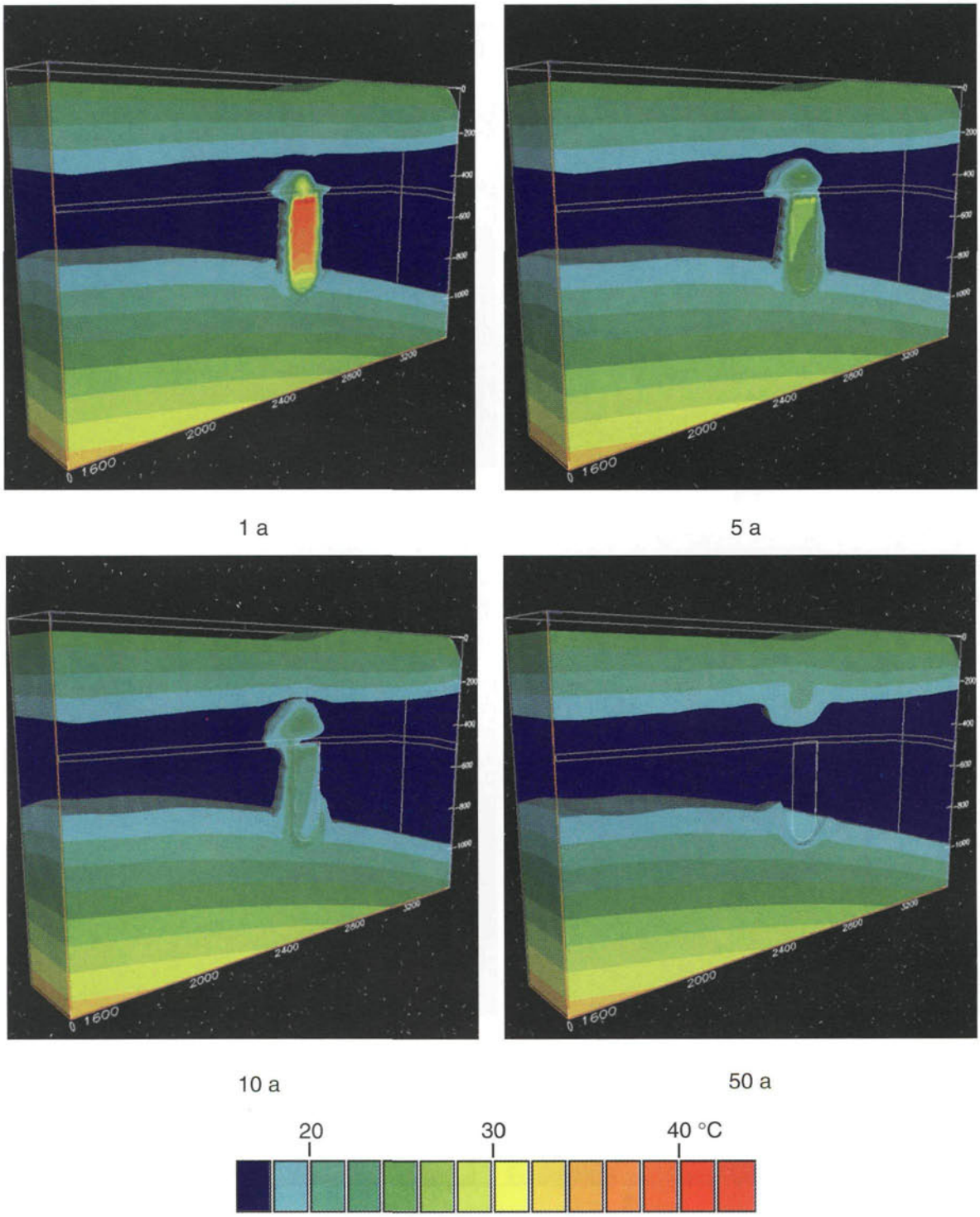


FIG. 77. Same scenario as Fig. 76 but with a karst layer and large longitudinal dispersivity (α_L = 1000 m) (Perrochet and Tacher 1997). The test modelled is a hypothetical extreme: a 150 kt test with an initial temperature rise of 50°C and with no cover (no such tests were ever carried out).

Category 2

Category 2 comprises three or four tests with inadequate cover of volcanic material. This can be modelled by assuming a high degree of fracturing, such as in scenario F3. Run 10 is an appropriate model for these conditions with peak Darcy velocities of up to 6 m/a In the transport calculations carried out in the Study, Darcy velocities of up to 20 m/a are considered initially.

For tests with inadequate cover, a passive tracer would begin to enter the carbonates soon after the explosion and it would take only about 20 years for 90% to be released to the carbonates.

Category 3

Category 3 comprises 12 CRTV tests. Runs 11–13 approximate these conditions. A Darcy velocity of 20 m/a has been assumed for such tests.

For CRTV tests, a passive tracer would begin to enter the carbonates immediately after the explosion and it would take only about 12 years for 90% to be released to the carbonates

Category 4

Category 4 comprises the three safety trials that went critical in the carbonates. Run 16 approximates these conditions but the Study assumed a Darcy velocity of 2 m/a for radionuclide transport calculations since this is the upper limit for vertical flow in the carbonates (Figs 63 and 65)

Category 5

Category 5 comprises the four safety trials in the carbonates that did not go critical. For these trials, the appropriate Darcy velocity is the upper limit for vertical flow in the carbonates, 2 m/a.

Categories 6 and 7

Category 6 comprises the three safety trials in the volcanics (none of which went critical), while Category 7 comprises the two shafts containing buried waste For both categories, the appropriate velocity for modelling purposes is the steady state Darcy velocity in the volcanics (about 2 mm/a). However, for simplicity, a very conservative Darcy velocity of 1 m/a, the same as for regular tests, was assumed.

The Darcy velocities indicated above will be used in radionuclide transport calculations in Section 6.5. In general, they are very conservative since they are based on peak rather than average velocities and also assume a degree of fracturing that is somewhat greater than that which can be deduced from chimney filling rates.

6.3.4. Magnitude and effects of tidal fluctuations

The discussion of hydrogeology up to this point has considered only steady state flows Several authors have found evidence that salinity distributions in the carbonate formations of atolls are significantly influenced by tidal oscillations within them There is also a theoretical explanation for this phenomenon, at least conceptually, in that an oscillatory motion can be shown to cause mixing in the presence of some kind of trapping or exchange mechanism. Oberdorfer et al. (1990) showed that, in order to simulate the observed mixing of salt with a steady state flow and transport model, it would be necessary to use extremely large dispersivities which would in other circumstances be considered unreasonable. The same would be expected to apply to transport of heat, because the transfer of heat by conduction to the solid matrix provides an exchange mechanism which could lead to increased effective dispersion in a similar manner

Clearly, tidal pumping can occur if there is a significant phase difference between the ocean and the lagoon For Fangataufa, this phase difference is about 20 min, while at Mururoa it is only a few minutes. Nevertheless, French scientists have observed, during sampling of monitoring wells, fluctuations in concentrations in the carbonate zone corresponding to tidal cycles at Mururoa Atoll. The Study team made similar observations (Technical Report, Vol. 4). The effect appears to be greater under the rim than under the lagoon.

French scientists have modelled tidal effects in terms of 'equivalent' dispersion coefficients (French Liaison Office Document No. 10). This approach is open to criticism because appropriate values of dispersivities depend on the scale of the problem, on the precise nature of the quantity being transported and on the way in which this quantity interacts with the surrounding medium All the steady state results presented above use dispersivities α_L and α_T in the classical way, because without new research there is no theoretical basis for representing dispersion in any other way. At the same time, it is possible to provide some insight into how representation of dispersion could or should be improved. Perrochet and Tacher have also employed FEFLOW to simulate flow, decoupled from geothermal transport, using small time steps to compute tidal fluctuations within the atoll Alternatively, a finite element model can be used which represents tidal fluctuations in terms of sinusoids and

computes the spatial distribution of amplitudes and phase lags directly, without time stepping (Townley 1993).

Fluctuations in velocities caused by tides are not trivial, and a significant volume of water can flow into and out of an atoll during each tidal cycle Consider a cross-section 5000 m long and 1200 m deep, with a specific storage coefficient of 10^{-5} m^{-1}. If the range in heads at all points in the aquifer during each tidal cycle (twice the amplitude) were 0.8 m, then the total volume of water flowing into and out of a 1 m slice of aquifer in each tidal cycle would be 48 m^3. If such a volume were to enter the carbonates in thin karstic layers, the corresponding velocities would be much greater than the velocities due to geothermal convection.

Although tidal flows have no effect on the rate of release from test cavity–chimneys in the volcanic zone, they are important since they can mix water in the carbonate zone (especially the karsts) and thereby affect the rate of release of radionuclides to both the lagoon and directly to the ocean. No modelling of tidal flows has been carried out in the Study but the issue is discussed further in Sections 6.5 and 6.6.

6 4. SOLUTION SOURCE TERM

6.4.1. Nuclear tests

In Section 5, the underground inventory of radionuclides was calculated and estimates were made of the partitioning of radionuclides between the various phases: lava, rubble, gas and water. In order to convert this inventory into a solution source term, i e. the concentration of radionuclides in the water of each cavity–chimney, it is necessary to understand and then model the physical and chemical processes that occur within the cavity–chimney after a test.

As indicated previously (Section 5.4), water begins to infiltrate back into the cavity–chimney within a few hours after a nuclear explosion. Owing to the high pressure at this depth, volatile or gaseous radionuclides (such as tritium, noble gases and iodine isotopes) initially present in the gas phase will dissolve in the water

Most of the radionuclides are present in the solid phases, either the rubble or the lava. The lava mostly solidifies at the base of the cavity but is also distributed around the walls of the cavity and possibly into fissures beyond the cavity. In order to be available for transport to the biosphere, the radionuclides must first be released from the solid phases This process is known as leaching. Experimental evidence shows that the rubble is more leachable than the lava and that release of radionuclides from lava and rubble occurs by different mechanisms The leaching of lava is a slow, rate limited process whereas the release from the rubble is generally assumed to be an equilibrium controlled process between groundwater and radionuclides sorbed on solid surfaces

6.4.1.1 Leaching of lava

The lava formed from a nuclear explosion is essentially remelted basaltic rock except that most of the residual fuel, some fission products and the structural materials in the nuclear device will be incorporated into the melt and ultimately into the solidified mass. The melt solidifies at about 1130°C and the resultant glassy lava cracks on cooling as a result of stresses induced by the temperature gradients within the cavity. The physical form of the lava is not known precisely but it will be extensively cracked, forming pieces variable in size, ranging from large pieces to grain sized particles.

Extensive studies have been made of the leaching of glasses used for immobilization of high level radioactive waste and, although the composition of basaltic lava differs somewhat from the borosilicate waste glasses, the mechanisms of leaching are essentially the same. The rate of release of a given radionuclide from glass, $R_{lava}(t)$, depends on many factors: glass composition, surface area, temperature, time, solution composition and especially the degree of saturation of the solution. At constant temperature, the release rate of a radionuclide is given by:

$$R_{lava}(t) = \frac{L(t)}{\rho_{lava}} \frac{S(t)}{V(t)} A_{lava}(t) \qquad (7)$$

where $L(t)$ is the leach rate of the glass itself (mass per unit surface area per unit time), $S(t)$ is the surface area of the lava, $A_{lava}(t)$ is the activity of a radionuclide in the lava, ρ_{lava} is the density of the lava and $V(t)$ is its volume.

The process of leaching of waste glasses or natural basaltic glasses is complex. Experimental measurements of release rates based on concentrations of matrix elements or radionuclides in solution indicate that the leach rate decreases with time. This decrease is due to a number of factors: the formation and growth of a hydrated or gel layer through which radionuclides must diffuse; the retention of some elements within the gel layer; and the reduction in the driving force for diffusion as the concentration of elements in solution approaches the saturation limit.

Smith (1993) reviewed the published data on the short term leaching of nuclear explosive melt glasses. He concluded that·

— The leaching of melt glass is affected by glass composition: glasses enriched in calcium and potassium have a higher leach rate than those enriched in silica and alumina
— Leaching experiments using 1 mm grains of glass provide more realistic leaching data than those involving very fine particles (<250 μm).
— Leach rates for ground melt glass at 25°C decrease with time from 5×10^{-4} g glass m^{-2} d^{-1} initially to 5×10^{-6} g glass·m^{-2}·d^{-1} after 400 days.
— For the first 200 days, leach rates for different elements decrease in the following order: ^{131}I > $^{129,132}Te$ > $^{124,127}Sb$ > ^{137}Cs > ^{237}U > $^{58,60}Co$ > $^{103,106}Ru$ > ^{140}Ba > $^{141,144}Ce$ > ^{54}Mn > ^{88}Y > ^{95}Zr > $^{239,240}Pu$, and range (in units of fraction leached per day) from 9×10^{-4} for ^{131}I to 3×10^{-7} for $^{239,240}Pu$.

A number of studies have been reported on the weathering (or alteration) of natural basaltic glasses that have been exposed to water over very long periods. Arai et al. (1989) and Yusa et al. (1990) studied Japanese natural glasses ranging in age from 280 to 2800 years The natural alteration rate was found to be 2–3 nm/a. Cowan and Ewing (1989) studied the formation of secondary minerals on Hawaiian basaltic glasses ranging in age from 12 000 to 28 000 years and estimated the natural rate of basalt alteration to be 0.002–0.005 vol.%/a. Jercinovic and Ewing (1987) studied the corrosion of basaltic glasses from subglacial–volcanic deposits, submarine deposits and the ocean floor It was concluded that there was good agreement between the corrosion processes observed in the laboratory with borosilicate waste glasses and those observed for natural basaltic glasses of great age.

A vast body of data obtained from leaching studies of glasses designed for long term disposal of high level waste shows that, after an initial time dependent leaching period (as described in the experiments mentioned above), the corrosion rate of the glass is constant (Grauer 1983, 1985 and references therein). The corrosion rate corresponds to the rate of hydration of fresh glass surfaces. Under such conditions, the leach rate is the same for all elements (and radionuclides) and independent of time so that

$$L(t) = L \tag{8}$$

where L is the long term leach rate. In this expression, 'leaching' is defined as removal from the glassy phase and not necessarily release into solution Depending on the chemical properties, some elements (most notably plutonium and other actinides) will be retained with the secondary phases which form on the surface of the glass or other adjacent surfaces. The dissolution of these phases is governed by the supply of fresh leachant and is best described by an equilibrium process (Section 6.4.1.2).

French scientists have carried out a systematic study of the leaching of basaltic glasses as a function of pH, temperature and surface to volume ratio (French Liaison Office Document No. 8). The leach rate is relatively constant with pH over the range 4–8 but increases outside these limits. The effect of temperature on leach rate is described by the Arrhenius equation

$$L = L_0 \exp\left(-\frac{E_a}{R'T}\right) \tag{9}$$

where E_a is the activation energy, R' is the gas law constant and T is the temperature (K). The value observed for the activation energy at near neutral pH was 60 kJ/mol, in reasonable agreement with earlier values for basaltic glass of 65 kJ/mol (Crovisier and Eberhart 1985) and for borosilicate glass of 75 kJ/mol (Grambow 1984) These high values indicate that the rate of leaching is controlled by chemical reaction at the glass surface.

To estimate the long term leach rate L, French scientists followed the dissolution of lithium from basaltic glass since this element is not retained within secondary phases. At 25°C and a surface/volume ratio of 2000 m^2/m^3, the steady state leach rate was found to be 2.5×10^{-6} kg·m^{-2}·a^{-1}.

If lava particles are assumed to be spherical beads, a radionuclide balance can be written as follows:

$$\frac{dA_{lava}}{dt} = \frac{3}{\tau - t} A_{lava}(t) - \lambda A_{lava} \tag{10}$$

where $\tau = \rho_{lava} r_0 / L$ is the time required for complete alteration of the lava, r_0 is the initial radius of the glass beads and λ is the decay constant of the radionuclide The analytical solution of this equation yields the release rate:

$$R_{lava}(t) = \frac{3A_{lava,0}}{\tau}\left(1 - \frac{t}{\tau}\right)^2 e^{-\lambda t} \tag{11}$$

where $A_{lava,0}$ is the initial activity of the radionuclide in the lava.

In the Study, $L = 3 \times 10^{-6}$ kg m^{-2} a^{-1} was taken as the reference case. The particle size is unknown but a conservative assumption for the particle diameter of 1 mm (i.e. $r_0 = 5 \times 10^{-4}$ m) was made. This gives τ = 450 000 years. This value is in reasonable agreement with the French estimate of 200 000 years (French Liaison Office Document No. 8) and a corresponding

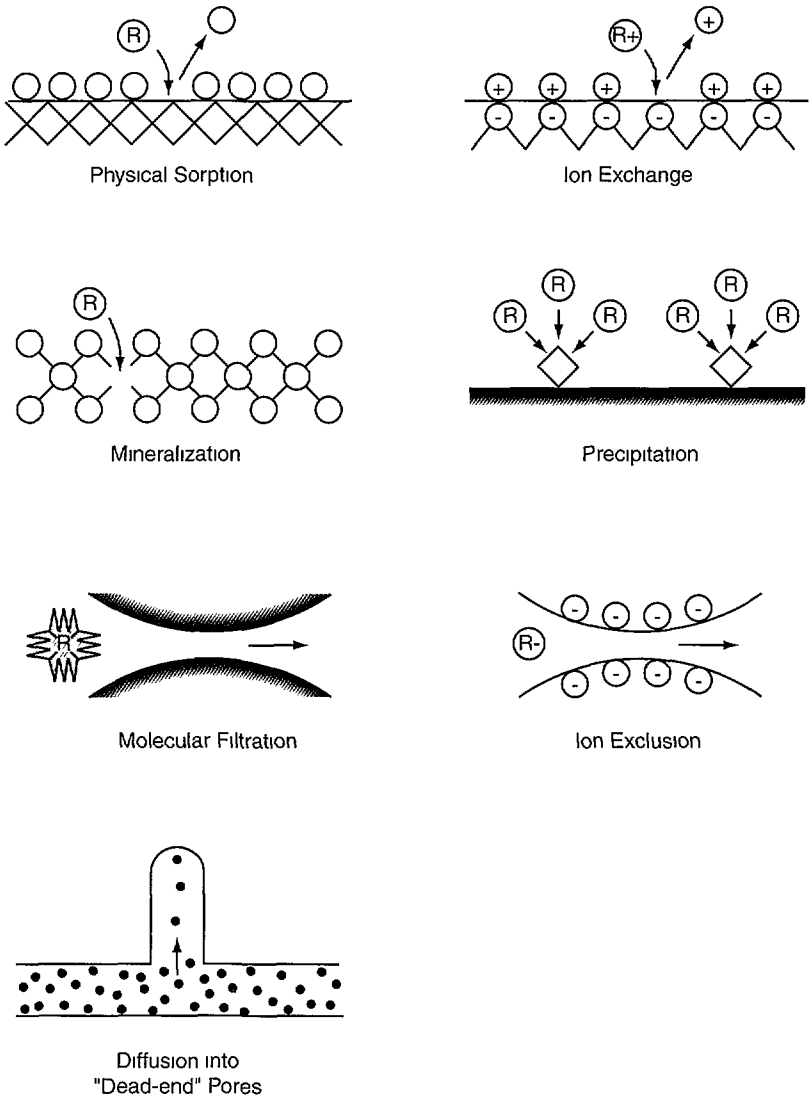


FIG 78. Sorption and retardation mechanisms affecting radionuclide transport in geological media (R: radionuclide species) (From McKinley and Hadermann (1985).)

value of 150 000 years for waste glass in a deep repository (National Cooperative for the Storage of Radioactive Waste (Nagra) 1994b).

It follows from the above analysis that the leaching of the lava is a slow process but persists for a very long time For short lived isotopes, the release due to leaching of the lava is negligible.

6 4 1.2. Release from rubble

Radionuclides which are still in the gas phase when the lava solidifies will deposit onto the surface of the rubble or will dissolve in the infiltrating water. After the cavity–chimney fills and is well mixed by temperature gradients within the cavity–chimney, a distribution will be established between the radionuclides on the altered rock surfaces and in solution This adsorption–desorption phenomenon is complex and occurs by a number of mechanisms, including physical adsorption, ion exchange and co-precipitation (Fig. 78) The extent of sorption of radionuclides is generally characterized by the distribution coefficient K_d, defined as:

$$K_d = \frac{\begin{array}{c}\text{concentration of species sorbed on solid}\\ \text{(mass per unit mass of solid)}\end{array}}{\begin{array}{c}\text{concentration of species in solution}\\ \text{(mass per unit volume of solution)}\end{array}} \qquad (12)$$

The units of the distribution coefficient are volume per unit mass: m^3/kg or L/kg. The distribution coefficient for a particular species is a function of many variables: rock type, porosity and degree of alteration (especially to

clay minerals), composition of the solution (especially pH and Eh) and concentration and oxidation state of the sorbing species (in mass rather than activity units). In practice, however, K_d is often assumed to be a constant and this is a reasonable approximation in a given system if the concentrations of absorbing species are low and the pH and Eh do not vary greatly.

Because a fraction of the sorbing species may form very stable surface complexes or diffuse into the solid matrix, experimentally determined distribution coefficients may not strictly describe the distribution at equilibrium Consequently, in the desorption process, less material is desorbed than was initially adsorbed. To describe this behaviour correctly, a distribution ratio is normally used instead of K_d. The Study will only use the K_d nomenclature and will conservatively assume reversibility in the sorption–desorption processes. This allows compatibility with the French conservative approach.

Values of K_d are available in the literature for many different rock types and solutions, and were experimentally determined by French scientists for a few key radionuclides using Mururoa basalt (French Liaison Office Document No. 8). Table XXXVII summarizes these data for all the radionuclides selected for modelling (Section 5.8). The rationale for selection of the particular values used in the Study is given in the Technical Report, Vol. 4. In some cases, two values were used because of uncertainties in the oxidation state or for sensitivity analysis. In general, very conservative (i.e. low) values were chosen, especially for plutonium and other long lived actinides.

For a known value of K_d, the initial concentration of a radionuclide in the cavity–chimney water (i.e. the initial solution source term) can be calculated simply from the following equation:

$$C_{cch} = \frac{A_{cch}}{V_{cch}\varepsilon_{cch}R_f} \quad (13)$$

where A_{cch} is the activity in the cavity–chimney (excluding that in the lava), V_{cch} is the volume of the cavity–chimney, ε_{cch} is its porosity and R_f is the retardation factor given by:

$$R_f = 1 + \frac{\rho_r(1-\varepsilon_{cch})}{\varepsilon_{cch}} K_d \quad (14)$$

The total activity on the rubble can be calculated from the radionuclide inventory for a particular test and the data on the partitioning between the phases (Table XXXI) The estimated values of ε_{cch} and ρ_r are 0.3 and 2430 kg/m^3, respectively The cavity–chimney volume can be calculated from Eqs (1) and (2) (Section 5). Because the cavity–chimney volume is approximately proportional to yield, the initial concentration is relatively independent of yield.

The change of concentration in cavity–chimney water with time can be calculated assuming that the water is always mixed and is discharged from the cavity–chimney at a specific discharge rate (or Darcy velocity), v_D. Then a mass balance gives

$$\frac{dC_{cch}}{dt} = -\lambda C_{cch} - \frac{v_D}{H_{ch}\varepsilon_{cch}R_f} C_{cch} \quad (15)$$

where H_{ch} is the height of the chimney The first term in this equation describes radioactive decay within the

TABLE XXXVII. SUMMARY OF K_d (m^3/kg) DATA FOR RADIONUCLIDES ON BASALT

Radionuclide	Literature[a]	French data[b]	The Study[c]
^{3}H	0	0	0
^{14}C	0		0
^{36}Cl	0		0
^{55}Fe	na[d]		0.01/0 03
^{59}Ni, ^{63}Ni	0 05		0 01/0.03
^{60}Co	na		0.01/0 03
^{79}Se	0 005–0.02		0/0 01
^{85}Kr	0		0
^{90}Sr	0.1	0.02	0.008/0 1
^{93}Zr	0.5		0 5
^{99}Tc	0–0 02		0/0.01
^{106}Ru	na		0.01/0 03
^{107}Pd	0 05		0 05
^{121}Sn^{m}, ^{126}Sn	0 05		0 01/0.03
^{125}Sb	na		0.0/0 03
^{129}I	0		0
^{134}Cs, ^{135}Cs, ^{137}Cs	0 3	0.2–0 4	0 3
^{147}Pm	na		0.05
^{151}Sm	0 05		0.05
^{152}Eu, ^{154}Eu, ^{155}Eu	0.05		0.05
^{236}U	0.003–0 01		0 01
^{237}Np	na		0 2/0 5
Pu (all isotopes)	0 04–0 5	10	0 5
^{241}Am	0 05	10	0 05

[a] Source. Serne and Releya (1981).
[b] Sources French Liaison Office Documents Nos 8 and 10
[c] Where two values are quoted, the first (more conservative) is the reference case
[d] na. not available

TABLE XXXVIII. COMPARISON OF MEASURED AND PREDICTED RADIONUCLIDE CONCENTRATIONS IN CAVITY–CHIMNEY WATER

Test	Time	Concentration (Bq/m^3)		
		^{3}H	^{90}Sr	^{137}Cs
Aristée	After 200 d	1×10^{10}	3×10^6	7×10^5
Lycos	After 3 a	5.5×10^9	4×10^5	1.4×10^5
Boros	After 200 d	3×10^9	2×10^7	4×10^6
	After 1500 d	3×10^8	1×10^7	2×10^6
Ajax	After 17 a	na[a]	7×10^5	1.3×10^5
Predicted (Eq (13))	0	1×10^{10}	6×10^5 [b] 8×10^6 [c]	2.5×10^5

[a] na. not available.
[b] For $K_d = 0.1$ m^3/kg (Table XXXVII)
[c] For $K_d = 0.008$ m^3/kg (Table XXXVII)

cavity–chimney while the second describes the loss of activity through advection. The solution to (15) is

$$C_{cch} = C_{cch,0} e^{-\bar{\lambda} t} \tag{16}$$

where $C_{cch,0}$ is the initial cavity–chimney water concentration and

$$\bar{\lambda} = \lambda + \frac{v_D}{H_{ch}\left[\rho(1-\varepsilon_{cch})K_d + \varepsilon_{cch}\right]} \tag{17}$$

The second term in Eq. (17), which accounts for removal of activity by water flowing through the cavity–chimney, is most important at high Darcy velocities or for non-sorbing species (such as tritium).

For a few selected tests, French scientists have measured the concentration of radionuclides in cavity–chimney water and this allows the predicted concentrations (using Eq. (13)) to be compared with actual concentrations. Table XXXVIII shows this comparison for Aristée (a Category 1 test), Lycos (a Category 2 test), and Boros and Ajax (two of the 12 CRTV tests (Category 3)). Considering that the predicted concentrations were determined for a generic test of 100 kt without any adjustment of parameters, the agreement is satisfactory and indicates that the chosen K_d factors for ^{90}Sr and ^{137}Cs are reasonable.

The model described above has two main weaknesses. First, it assumes sorption equilibrium between the liquid phase and the bulk rock in the cavity–chimney. The size of the broken rock in the cavity–chimney varies considerably and reaching overall equilibrium might take considerable time. This is not quantifiable but neglecting irreversible sorption and choosing relatively low K_d values are conservative. Second, the model assumes a constant water flow into the overlying rocks. The Study compensated for this limitation by choosing a conservative Darcy velocity corresponding to peak rather than average velocities (Section 6.3.3.4).

Although the concept of distribution coefficient has been introduced in the context of sorption onto rubble within the cavity–chimney, the concept is equally useful in modelling transport through the geosphere. Accordingly, the values of K_d in Table XXXVII will also be used for modelling transport through the volcanic rock above the test cavity (Section 6.5)

6.4.1.3. *Analytical equations for combined release from chimney and rubble*

A radionuclide mass balance within the cavity–chimney, allowing for leaching of the lava, decay and outflow through the top of the chimney, gives:

$$\frac{dA_{cch}}{dt} = R_{lava} - \lambda A_{cch} - Q C_{cch} \tag{18}$$

where Q is the volumetric flow rate from the cavity–chimney. Substituting Eqs (11) and (13) in Eq. (18) and solving the differential equation gives, for $t < \tau$,

$$C_{cch} = e^{-\lambda t}\left[\frac{\beta}{\alpha} - 2\frac{\beta t}{\alpha\tau} + \frac{2\beta}{\alpha^2\tau} + \frac{\beta t^2}{\alpha\tau^2} - \frac{2\beta t}{\alpha^2\tau^2} + \frac{2\beta}{\alpha^3\tau^2} + e^{-\alpha t}\left(C_{cch,0} - \frac{\beta}{\alpha} - \frac{2\beta}{\alpha^2\tau} - \frac{2\beta}{\alpha^3\tau^2}\right)\right] \tag{19}$$

and, for $t \geq \tau$,

$$C_{cch} = C_{cch}(t = \tau)e^{-(\lambda+\alpha)(t-\tau)} \quad (20)$$

where $\alpha = v_D/\varepsilon_{cch}H_{ch}R_f$ and $\beta = 3A_{lava,0}/\varepsilon_{cch}VR_f\tau$ are constants.

If leaching from the lava is insignificant, $\beta = 0$ and Eq. (19) simplifies to Eq. (16) Equations have also been derived to take account of ingrowth and decay of radionuclides from the neptunium decay chain and these are given in the Technical Report, Vol. 4.

Once the concentrations in the cavity–chimney are calculated, the release rates from the cavity–chimney can be simply determined from its cross-sectional area and the Darcy velocity:

$$J = QC_{cch}$$

$$= \pi R_c^2 v_D C_{cch} \quad (21)$$

For the CRTV tests, J is also the release rate into the carbonates.

There are three main differences between the source term calculated in the Study and that used by the French scientists:

(a) Plutonium and americium are assumed in the French analysis to be totally contained within the lava, whereas some partitioning (5%) onto the rubble is assumed in the Study.[7]
(b) The K_d values assumed for the actinides in the Study are lower than those assumed by the French scientists.
(c) In contrast to the French 'worst case' analysis, the Study uses a mechanistic approach for all radionuclides and all test categories, whereby maximum consequences are determined by the use of very conservative values for key parameters.

6.4.2. Safety trials

As shown in Fig. 52, of the ten underground safety trials, seven were in the carbonates and three were in the volcanic zone. Three of the safety trials in the carbonate zone (Category 4 in Table XXIX) resulted in a small nuclear yield. Since the backfill surrounding these tests contained crushed basalt, a lava would have been produced and the residual plutonium will be associated with a matrix of silicate, calcite and dolomite. Plutonium release will be governed by leaching of the glassy matrix and can be treated in the same way as for the regular nuclear tests.

6.4.2.1. Plutonium release from safety trials

Although the quantities of material were small (a total of 14.8 kg of plutonium), the four safety trials in the carbonates without nuclear yield are important because of the permeability of the carbonates and the chemical form of the plutonium. It is assumed that the conventional explosive ruptured the container and that the plutonium, initially present as a metal, oxidized rapidly upon contact with sea water and released hydrogen in the process (Lai and Goya 1966). From experimental measurements it is known that this reaction produces either (a) PuO as an intermediate product and hydrous Pu(IV) oxide that is finely dispersed by the hydrogen gas, or (b) PuOH, plutonium monoxide monohydride (Haschke 1992, 1995). PuO and PuOH are not stable in water and undergo further oxidation mainly to plutonium dioxide (PuO_2) and/or hydrous plutonium(IV) oxide, $PuO_2{\cdot}xH_2O$, and, to a lesser extent, amorphous $Pu(OH)_4$, often referred to as 'Pu(IV) polymer'. Hydrous plutonium(IV) dioxide and Pu(IV) polymer are known to form colloids in water under certain conditions and therefore are often referred to as 'Pu(IV) colloid'.

The solubility of plutonium and other actinides in sea water depends not only on the solid phase but also on the oxidation state of the radionuclides in solution and the concentration of species in solution that can form soluble radionuclide complexes (Silva and Nitsche 1995). Complexation of radionuclides increases their solubility and may also increase release rates. In water, inorganic ligands, such as hydroxide, chloride, sulphate and carbonate, and organic molecules, such as humic and fulvic acids, can form soluble complexes with plutonium.

A number of studies of the solubility of plutonium in various waters, including synthetic sea water, have been conducted in connection with radioactive waste repository selection, for example in the USA. These studies are discussed in detail in the Technical Report, Vol. 4. In summary, these studies showed that the solubility controlling phase in saturated solutions of tetravalent plutonium is, to a large degree, amorphous $Pu(OH)_4$. Its solubility in water depends on the chemical composition of the water and varies between 1.1×10^{-6}M (6.0×10^8 Bq/m^3) and 4.5×10^{-7}M (2.5×10^8 Bq/m^3). In brine with a composition close to that of sea water a solubility of 3.5×10^{-7}M (1.9×10^8 Bq/m^3) was found An undersaturation experiment where amorphous $Pu(OH)_4$ was brought into contact with seawater-like brine gave a somewhat lower solubility of 8×10^{-8}M (4.4×10^7 Bq/m^3)

[7] As indicated in Table XXXI (Section 5), the literature indicates that a value of 2% for partitioning onto the rubble would be appropriate However, the more conservative value of 5% was assumed in the Study.

It is possible that low crystallinity PuO_2 may convert to amorphous $Pu(OH)_4$. On the basis of the solubility of $Pu(OH)_4$ in laboratory experiments, the solubility of plutonium (that may be released as a result of the safety trials) should be about 10^{-8}M (5.5×10^6 Bq/m^3), which is about the value for amorphous $Pu(OH)_4$. This is a very conservative assumption and does not consider the much lower solubility of PuO_2. The assumption in the French study — based on one measurement in a sample taken from a safety trial cavity within a few hours of the trial (French Liaison Office Document No. 8, ch. 4) — that practically all of the deposited activity is present as plutonium(IV) dioxide and less than 1% exists as plutonium hydroxide, may be supported by the results of Haschke (1995), but it is by no means conservative.

The French scientists report maximum $^{239+240}$Pu concentrations of 8 Bq/m^3 (1.5×10^{-14}M ^{239}Pu), which were measured in the close vicinity of a non-yield safety trial 15 years after the trial was conducted. This result may indicate that: (1) only very small amounts of plutonium are dissolved and most of the plutonium is still in solid form; (2) dissolved plutonium is retained on the surface of the rocks in the carbonates; and/or (3) the dissolved plutonium is diluted by sea water far below the solubility limiting concentration.

6.4.2.2. *Speciation of soluble and colloidal plutonium*

In aqueous solution, plutonium can exist in four different oxidation states, Pu(III), Pu(IV), Pu(V) and Pu(VI). The distribution between the oxidation states depends on the pH and Eh of the water. Low pH values tend to favour the lower oxidation states, whereas the higher oxidation states become more accessible at near neutral and basic pH values. The same behaviour can be observed for reducing or oxidizing Eh conditions where the oxidation states Pu(III) and Pu(IV) or Pu(V) and Pu(VI), respectively, are stabilized (Silva and Nitsche 1995).

Pentavalent plutonium has been found to be the main oxidation state in various natural waters (Choppin and Kobashi 1990). Seventy-seven per cent of plutonium was present as Pu(V) in 0.22 μm filtered waters from the Irish Sea near a nuclear fuel reprocessing plant. Laboratory experiments showed that mainly pentavalent and small amounts of hexavalent plutonium solution species are in steady state equilibrium with solid amorphous $Pu(OH)_4$ (Rai and Swanson 1981, Nitsche et al. 1992a, b). The solutions were filtered through filters a few nanometres in size (2 or 4 nm) to exclude colloidally suspended plutonium. In surface and sea waters, ratios of colloidal plutonium to dissolved plutonium were as high as 250:1 when the colloidal material was separated by filtration through 0.22 μm filters.

Tetravalent plutonium can exist in groundwaters under certain conditions in colloidal form. Two different types of colloid have been identified in groundwater: (a) intrinsic plutonium or real colloids that are mainly produced through plutonium hydrolysis, and (b) pseudocolloids that are formed by sorption of either plutonium ions or intrinsic colloids on groundwater colloids. Groundwater colloids are composed of inorganic or organic water constituents or a mixture of both, or microorganisms (Silva and Nitsche 1995, Kim 1991). Their size is below 0.45 μm. Their migration behaviour can be very different from that of soluble species and precipitates, and their role in the plutonium transport process is not well understood (McCarthy and Zachara 1989). Colloid formation can increase the plutonium concentration above the solubility limit and therefore the overall amount of plutonium that is available for transport.

Penrose et al. (1987) observed the reduction of Pu(V) in laboratory solutions of near neutral pH (5–7) by sediment suspensions that were obtained from a deep, high sedimentation area of Lake Michigan in the USA. The sediment had less than 3% organic matter, which may be enough to act as the potential reducing agent. As little as 0.1 mg/L humic material in filtered sea water was sufficient to reduce Pu(VI) (10^{-10}M) to 30% Pu(V) and 70% Pu(IV) (Choppin 1991). Such mechanisms may reduce the soluble plutonium to amorphous $Pu(OH)_4$ or even $Pu(OH)_3$.

If the reduced plutonium remained bound to the sediments, it would be less likely to take part in the dissolution process. This reduced plutonium is likely to remain bound to the sediments, which could explain the high distribution coefficients for plutonium measured in lagoon sediments (Table XXI). The French data are in agreement with this observation. Plutonium was mainly present as Pu(V) and Pu(VI) in lagoon surface waters and as Pu(IV) and Pu(III) in lagoon sediments (French Liaison Office Document No. 8).

Intrinsic colloid and pseudocolloid transport can play an important role for a variety of radionuclides in addition to plutonium. The French study does not address colloidal radionuclide transport. Although intrinsic plutonium colloid formation can probably be excluded, the formation of plutonium pseudocolloids may still occur.

6.4.2.3. *Plutonium source term for transport modelling*

In the Study, it is assumed that dissolution of plutonium from safety trials is controlled by the solubility

limit with the solubility ranging from 10^{-7}M to 10^{-9}M. The plutonium will dissolve very slowly from this solid at a rate determined by the flow of groundwater in the region where the plutonium is deposited The release rate into the carbonate zone is then given by Eq. (21), where the cross-sectional area is assumed to be 20 m^2 and the Darcy velocity 2 m/a, and C_{cch} is the solubility limit (10^{-7}–10^{-9}M or 6×10^7 to 6×10^5 Bq/m^3). Under these conditions, the rate of dissolution of the plutonium is only 0.01–1 g/a. Since the plutonium inventory in one safety trial is about 3.7 kg, it can be readily shown (after allowing for decay) that the time for total dissolution is between 3500 and about 60 000 years.

Both the plutonium in the volcanics and that in the carbonates can be modelled in the same way except that the latter is clearly more important because of the high permeability of the carbonates and the proximity to karsts and the biosphere.

The possibility of colloid or pseudocolloid formation, either from the residues of safety trials or from leaching of the lava, cannot be excluded at this stage. If present, such colloids could be transported through the volcanics and/or the carbonate zone at a much faster rate than plutonium in true solution. To take account of this possibility, the Study assumed that 10% of the plutonium in the liquid phase is present irreversibly sorbed on colloids. The assumption of irreversibility is very conservative, as is probably the value of 10%.

6.5. GEOSPHERE TRANSPORT

Radionuclide transport in the geosphere is a complex phenomenon because of the heterogeneity of geological media and the numerous physical and chemical processes occurring between species in solution and in the solid phase (which comprises many minerals and alteration products that cannot be fully characterized). For these reasons, complete and accurate description of transport through real geological systems is likely never to be possible. However, it is possible to gain an understanding of radionuclide transport using relatively simple models which, because of their conservative nature, permit estimates to be made of upper limits of radionuclide release from geological systems. Measurements taken in the field allow such models to be calibrated and validated for their intended purpose.

The simplest model of radionuclide transport assumes 1-D flow through a homogeneous porous medium — the single porosity model. The mean rate of transport is described by a velocity (assumed constant) and a dispersive term which accounts for mechanical dispersion and molecular diffusion (if considered significant). Radioactive decay is normally incorporated into the model. Sorption processes are usually described by a linear isotherm, i.e. a constant distribution coefficient (Eq. (12)). Such models have been used extensively to model transport of radionuclides through geological media Their popularity is based on the fact that they successfully model a variety of transport problems and that analytical solutions can be obtained for simple initial and boundary conditions.

The weakness of the single porosity model is that it does not adequately describe fluid movement in many geological systems, especially in hard rock where flow is confined to a relatively few pathways along well defined fractures and much of the porosity is 'dead volume' in which the water is stagnant. To account for flow in such systems the dual porosity model was introduced, in which the fluid phase is divided into a mobile and an immobile component (Grisak and Pickens 1980). Interchange between the mobile phase (conducting fractures) and immobile phase (the porous matrix) occurs only by molecular diffusion.

The dual porosity model was chosen for modelling of radionuclide transport in the Study. Figure 79 shows transport in fractured rock along with the idealized dual porosity model. The parameters required for this model are shown in the diagram along with the selected values considered appropriate to model transport in the volcanic rock above the chimney of a regular test Specific information on the fracturing of volcanics is sparse. As a base case, it was assumed in the Study that the fracture width is 1 mm and the fracture frequency is 10 per metre. This gives a fracture porosity of 0.01 and a velocity of water in the fractures that is 100 times the Darcy velocity. This results in relatively high advective transport of nuclides In this respect the Study model is conservative compared with a single porosity model such as that used in the French calculations.

The mathematical formulation of the model has recently been described in detail by Jakob (1997). In general, solution of the equations for transport in the fractures and porous media requires numerical methods The code used in the dual porosity model has one main disadvantage when applied to the situation at the atolls: the water velocities must be assumed to be constant over time To compensate for this limitation, conservative values for the Darcy velocity have been chosen on the basis of peak velocities predicted by the hydrology modelling (Section 6.3.3.4).

As noted in Section 6.4, the same K_d has been used for modelling inside and outside the cavity–chimney This is justified because the inner surfaces of the rubble and intact volcanics are essentially the same. For some radionuclides (Table XXXVII), two values of K_d were

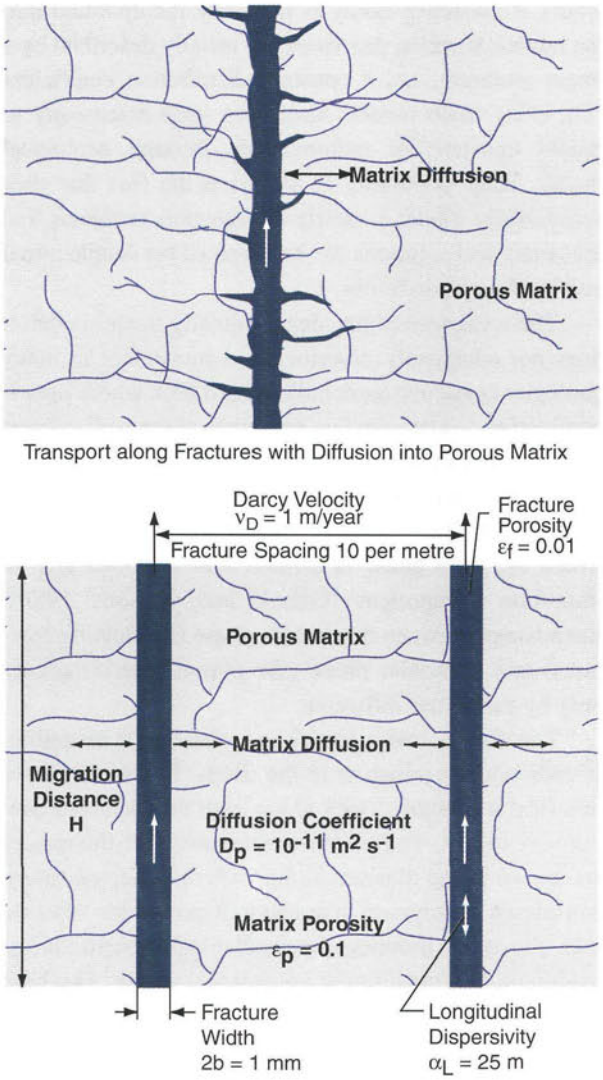


FIG. 79. Transport in fractured rock and idealized dual porosity model.

modelled but in all cases the lower (more conservative) value was used for the reference case.

6.5.1. Release into carbonates

The primary containment barrier for the majority of tests is the volcanic rocks, which are relatively impermeable, despite damage from the testing. Modelling of transport in the Study is based on the classification of the tests into the seven categories described in Section 5.9 and shown in Fig. 52.

Category 1 (regular tests)

For the four key radionuclides, ^{3}H, ^{90}Sr, ^{137}Cs and ^{239}Pu, the procedure used was as follows:

(1) The inventories for generic tests with yields of 5, 25, 60 and 100 kt were calculated (these are tabulated in appendix 4 of the Technical Report, Vol. 3).
(2) The dimensions of the cavity–chimneys for generic tests with yields of 5, 25, 60 and 100 kt were determined using Eqs (3) and (4) (Section 5.4.1).
(3) The concentrations of radionuclides in the cavity–chimney water were determined from the equations in Section 6.4.
(4) Transport rates through the volcanics were calculated using the dual porosity model for each yield classification (5, 25, 60 and 100 kt) and each thickness classification (25, 75, 150 and 250 m). The model gave release rates as a function of time for the 16 classifications (4×4).
(5) The contributions from all the classifications were summed to give the total release in accordance with the number of tests in each classification (Table XXX). It was also possible, where appropriate, to determine release rates from the different atolls or from different locations (rim or lagoon).

A less rigorous procedure was used for those radionuclides considered of lesser radiological importance (^{14}C, ^{36}Cl, ^{79}Se, ^{99}Tc, ^{125}Sb, ^{129}I, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{93}Zr, ^{106}Ru, ^{107}Pd, $^{121}Sn^m$, ^{126}Sn, ^{134}Cs, ^{135}Cs, ^{147}Pm, ^{151}Sm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{236}U, ^{237}Np, ^{238}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{242}Pu). Only two tests were modelled, a 5 kt test with 25 m of volcanic cover and a 100 kt test with 250 m of cover. The total release rate from regular tests could then be estimated by multiplying the low yield, shallow test by 90 and the high yield, deep test by 20 (at Mururoa) and 8 (at Fangataufa). (This corresponds to a total of only 118 regular tests rather than the 121 making up Category 1, but the release from the total yield of the Category 1 tests has been estimated.)

The reference Darcy velocity for normal tests was 1 m/a, corresponding to a velocity in the fractures of 100 m/a. However, because measurement of tritium concentrations in the carbonates is very important in validating the model parameters, three Darcy velocities were simulated for tritium transport in the volcanics: 0.1, 1 and 10 m/a.

Categories 2 and 3

For tests where the volcanic cover was missing (Category 3, CRTV tests) or inadequate (Category 2), low (1 m/a), medium (2 m/a) and high (20 m/a) Darcy velocities were considered; however, the reference case was based on the most conservative value (i.e. 20 m/a). For CRTV tests, the average yield was assumed to be

5 kt. Release rates into the carbonates can be calculated simply from the source term (Eq. (21)).

For the four tests where the cover was inadequate, the yields were estimated from the seismic data as follows: Enée, 50 kt; Lycos, 87 kt; Mégarée, 54 kt; and Nestor, 47 kt; and the inventory was calculated by linear interpolation of the data for generic 25, 60 and 100 kt tests (Technical Report, Vol 3).

Category 4 (safety trials in the carbonates that went critical)

The three safety trials in this category were modelled in the same way as regular tests (in particular, 95% of the plutonium was assumed to be in the lava), except that release was assumed to occur directly into the carbonate zone with a Darcy velocity of 2 m/a and a higher matrix porosity.

Category 5 (safety trials in the carbonates that did not go critical)

It was assumed that plutonium is the only radioactive element released from the four safety trials in this category. These were modelled assuming solubility limited dissolution and a Darcy velocity of 2 m/a. For the reference case, the solubility of plutonium was assumed to be 10^{-7}M, equivalent to 6×10^7 Bq/m^3. A 10 m migration barrier of intact carbonate was assumed between the test location and a karstic zone within the carbonates. The K_d in the carbonates was assumed to be 0.5 m^3/kg (500 L/kg).

Category 6 (safety trials in the volcanics)

The transport rates from the three safety trials in this category (none of which went critical) were modelled in the same way as the Category 5 trials. The Darcy velocity in the volcanics was taken (very conservatively) to be 1 m/a The thickness of volcanic cover is unknown but was assumed to be 150 m for the reference case.

Category 7 (waste shafts)

About 20 TBq of plutonium was placed in the two waste shafts, which were drilled to a depth of 1180 m Transport to the carbonates was modelled assuming a Darcy velocity of 1 m/a and a plutonium solubility of 10^{-7}M.

For each radionuclide of interest, release rates into the carbonates were calculated as a function of time for each of the seven categories. The total release was then estimated by adding the contributions from the various categories. Graphs showing release rates versus time for a large number of tests and trials can be found in Hadermann and Pfingsten (1998) and the Technical Report, Vol 4.

In the computation of the release rates, a simplifying assumption was made that all tests were carried out at time zero, whereas in reality they were spread over 21 years. This assumption has the effect of increasing the maximum release rate but has little effect on the cumulative release in the medium to long term. For short times, the release rates are dominated by Category 2 and 3 tests (tests with inadequate cover and CRTV tests, respectively) at Mururoa and the Lycos test at Fangataufa. The CRTV tests were all carried out between 1976 and 1980 (French Liaison Office Document No 6), but the names and dates of only two of these tests are known: Ajax (1977) and Boros (1980). The dates of the tests with inadequate cover were 1977 for Nestor and Enée, 1985 for Mégarée and 1989 for Lycos. The 'effective' time zero for these release rate curves is therefore estimated to be 1979 for Mururoa and 1989 for Fangataufa.

6.5.1.1. *Modelling results*

The predicted rates of release of the four key radionuclides (^{3}H, ^{90}Sr, ^{137}Cs and ^{239}Pu) into the carbonate zones at Mururoa and Fangataufa are shown in Figs 80–82 The release rates calculated are the rates at which the various radionuclides cross the interface between the volcanic and carbonate zones.

For Mururoa, the predicted highest release rate of tritium to the carbonates (about 10 000 TBq/a) occurs in the first year (1979) and is attributed mainly to the CRTV tests (Fig. 80). The peak contribution from the regular (Category 1) tests occurs after about 20 years, i.e. in 1999 For Fangataufa, the predicted maximum release rate of tritium is about 1000 TBq/a in 1989.

For ^{90}Sr (Fig. 81), the maximum predicted release rate, occurring in the first year, is about 4 TBq/a for Mururoa and 1.5 TBq/a for Fangataufa. The release rate is fairly constant for the first 50 years and declines thereafter, owing in part to decay.

For ^{137}Cs, the curves of release rate with time are similar in shape to those for ^{90}Sr but the values are lower The maximum predicted releases occur in the first year and are 0 2 TBq/a for Mururoa and 0 05 TBq/a for Fangataufa. The systematic lower release rates for ^{137}Cs compared with ^{90}Sr are attributable to the higher K_d for ^{137}Cs in the volcanics.

The release curves for ^{239}Pu are more complex (Fig. 82). For short times, the releases are dominated by desorption of the 5% of the plutonium assumed to be

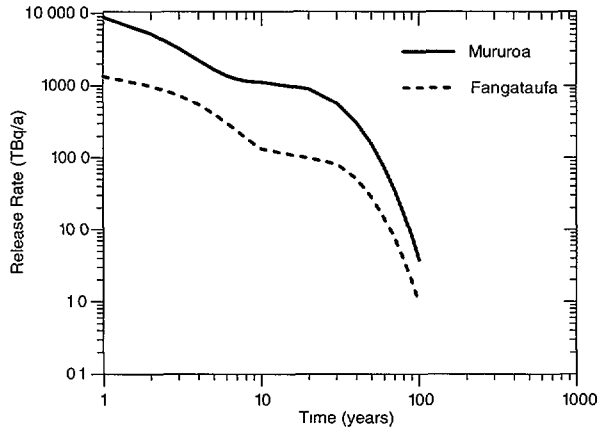


FIG. 80 Predicted rates of ^{3}H release into the carbonates at Mururoa and Fangataufa Year 1 is 1979 for Mururoa and 1989 for Fangataufa

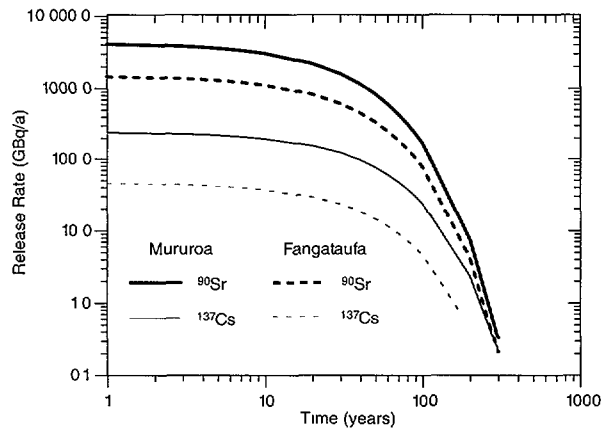


FIG 81 Predicted rates of ^{90}Sr and ^{137}Cs release into the carbonates at Mururoa and Fangataufa Year 1 is 1979 for Mururoa and 1989 for Fangataufa

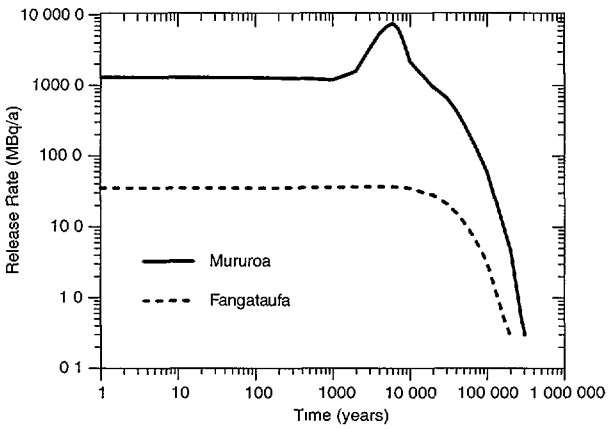


FIG 82 Predicted rates of ^{239}Pu release into the carbonates at Mururoa and Fangataufa Year 1 is 1979 for Mururoa and 1989 for Fangataufa.

partitioned on the rubble resulting from CRTV tests and tests with inadequate cover. In this respect, the Study calculations differ from the French modelling, which assumes that all the plutonium partitions into the lava. For Mururoa, the broad peak in predicted release rate between 2000 and 10 000 years is mainly due to releases from the safety trials in the carbonates (Category 5) This peak does not occur in the Fangataufa curve because no underground safety trials were conducted at Fangataufa. The release from the lava becomes important after about 50 000 years but the extent of release is limited by the half-life of ^{239}Pu (24 110 years).

Release rates to the carbonates have also been estimated for all the other radionuclides listed in Table XXXVII. The predicted maximum release rates of the more significant radionuclides are listed in Table XXXIX. In all cases, the maximum release occurs in the first year (owing to the early dominance of the CRTV tests and tests with inadequate cover). These predictions are based on very conservative assumptions for K_d values in the volcanics, especially for ^{14}C and ^{99}Tc, for which no sorption is assumed. For the other radionuclides listed in Table XXXVII, the predicted release rates are not significant because of their low inventory and/or short half-life.

6.5.2. Release from carbonates into lagoon or directly into ocean

Although the carbonate formations at Mururoa and Fangataufa are permeable, they constitute a very large storage reservoir. For example, the volume of water in the Mururoa carbonates is about 1.7×10^{10} m^3, some four times the volume of water in the lagoon. The flow rate from the carbonates into Mururoa lagoon is estimated to be about 60 000 m^3/d (2.2×10^7 m^3/a) (Perrochet and Tacher 1997). The average transit time for a passive tracer from the base of the carbonates to the lagoon is therefore about 800 years, long enough for

TABLE XXXIX. PREDICTED MAXIMUM RATES OF RELEASE (Bq/a) OF SELECTED RADIONUCLIDES INTO CARBONATES

Radionuclide	Mururoa	Fangataufa
^{14}C	1×10^{12}	5×10^{10}
^{36}Cl	2×10^{10}	4×10^{9}
^{60}Co	3×10^{11}	1×10^{10}
^{99}Tc	2×10^{10}	4×10^{9}
^{129}I	8×10^{7}	2×10^{7}
^{241}Am	4×10^{8}	3×10^{6}

decay of essentially all the ^{3}H, ^{90}Sr and ^{137}Cs released into the carbonates.

The assumption of an average transit time for the whole of the carbonate formations (which assumes bulk flow of water upwards into the lagoon) is too simplistic because it ignores mixing within the carbonate zone and preferential flow of the radionuclides in the thermal plume from the tests through fractures in the rock. The effect of these processes is to allow early release of some fraction of the inventory in the carbonates.

The hydrology models developed by Perrochet and Tacher (1997) are based on bulk flow and cannot be used to estimate the residence time distribution of tracer particles originating from different locations within the carbonate formations. In particular, the role of tidal fluctuations in mixing waters within these formations cannot be quantitatively modelled because of the lack of physical data In the absence of such data, two simple models for transport within the carbonate formations are considered.

6 5.2 1 Single porosity model for transport in carbonate formations

The first model is a single porosity transport model with constant velocity and sorption characterized by a single K_d value. There is relatively little information on K_d values for carbonate rocks. However, the Bundesamt fur Strahlenschutz (Federal Office for Radiation Protection) in Germany has made available values for the distribution of radionuclides in Cenomanian and Turonian limestone. These data were gathered for licensing purposes in connection with a potential German radioactive waste repository. The K_d values are very similar to those in Table XXXVII and, in the absence of any other data, these values will be used for modelling transport in the carbonate zone

The single porosity model is 1-D and assumes that all flow is upward towards the lagoon The Darcy velocities used in the carbonates were 1 m/a for regular tests and 20 m/a for Category 2 and 3 tests, except for long lived sorbing radionuclides, for which a value of 2 m/a was considered more appropriate (owing to the decrease in velocity with cooling of the thermal plume).

Figures 83–85 show the predicted release rates for ^{3}H, ^{90}Sr and ^{239}Pu to Mururoa and Fangataufa lagoons using the single porosity model. The predicted release rates for ^{137}Cs were negligible (<1 Bq/a) for all times (because of the relatively high K_d value). Thus, the single porosity model predicts no escape of ^{137}Cs from underground sources.

The predictions for ^{3}H (Fig. 83) show two peaks corresponding to initial releases from the CRTV tests and the tests with inadequate cover and later releases (peaking at about 80 years) from the regular tests The maximum release rates into the lagoons, occurring after about five years, are predicted to be about 2000 and 500 TBq/a for Mururoa and Fangataufa, respectively The predicted current (1998) release rates are about 20 and 200 TBq/a, respectively. (The predicted release rates for Fangataufa are higher than those for Mururoa because of the contribution from the Lycos test, which was the most recent of the tests with inadequate cover.) These are considerably higher than the release rates measured in 1996 (Section 8) of 5 and 0.6 TBq/a for Mururoa and Fangataufa, respectively. This is to be expected given the conservative assumptions but it also

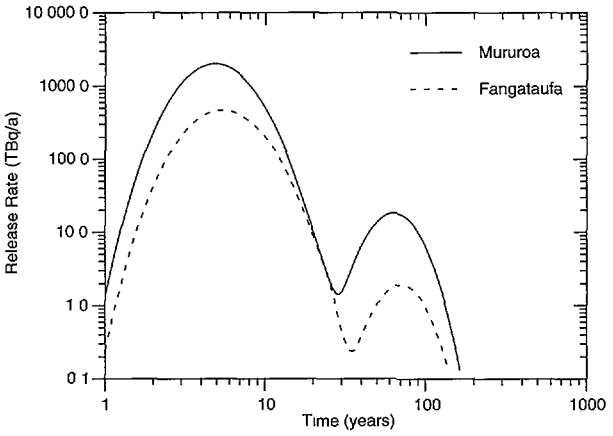


FIG 83. Predicted rates of ^{3}H release into Mururoa and Fangataufa lagoons, based on the single porosity model in carbonate formations Year 1 is 1979 for Mururoa and 1989 for Fangataufa.

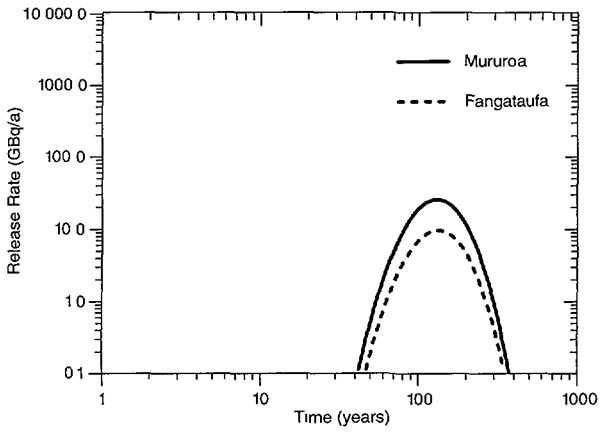


FIG 84 Predicted rates of ^{90}Sr release into Mururoa and Fangataufa lagoons, based on the single porosity model in carbonate formations Year 1 is 1979 for Mururoa and 1989 for Fangataufa

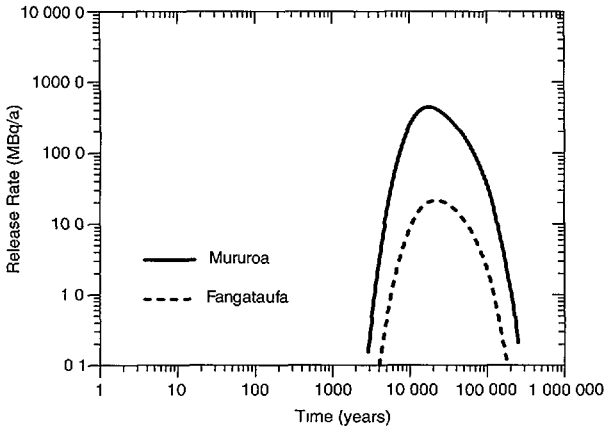


FIG. 85 Predicted rates of ^{239}Pu release into Mururoa and Fangataufa lagoons, based on the single porosity model in carbonate formations Year 1 is 1979 for Mururoa and 1989 for Fangataufa

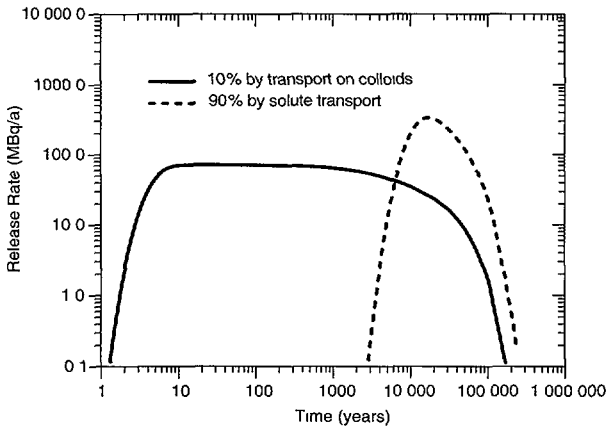


FIG 86. Predicted rate of ^{239}Pu release into Mururoa lagoon for 12 CRTV tests assuming that 10% of the ^{239}Pu is irreversibly sorbed on colloids Year 1 is 1979

TABLE XL. PREDICTED MAXIMUM RATES OF RELEASE OF SELECTED RADIONUCLIDES INTO LAGOONS (Bq/a)

Radionuclide	Mururoa	Fangataufa
^{14}C	3×10^{11}	2×10^{10}
^{36}Cl	6×10^{9}	2×10^{9}
^{60}Co	Negligible	Negligible
^{99}Tc	5×10^{9}	1×10^{9}
^{129}I	4×10^{7}	9×10^{6}
^{241}Am	Negligible	Negligible

indicates the limitations of the single porosity model (or the choice of parameters used in this analysis)

Figure 84 shows the predicted release rates of ^{90}Sr into the lagoons. The current release rates are predicted to be very low (<1 MBq/a). The predicted peak releases occur after about 100 years: the values are 30 and 10 GBq/a for Mururoa and Fangataufa, respectively. These are similar to the estimated release rates from the lagoons in 1996 (Section 8), although these may include a contribution attributable to leaching of lagoon sediments. This is discussed further in Section 8.

Figure 85 shows the predicted release rates of ^{239}Pu into the lagoons. The peak releases, occurring after about 10 000 years, are about 0.5 and 0 02 GBq/a for Mururoa and Fangataufa, respectively. These are at least an order of magnitude lower than the estimated release rates in 1996 attributable to leaching of sediments in the lagoon (Section 8). Thus, on the basis of this modelling, underground sources of plutonium are not expected to give rise to any significant elevation in plutonium concentration in the lagoons.

The effect of 'colloid transport' of plutonium was investigated, for the CRTV tests, by assuming that 10% of the plutonium in the liquid phase moves, as colloids, at the same flow rate as the groundwater ($K_d = 0$). This would result in an early breakthrough into the lagoon, as shown in Fig. 86 (although the activity released is quite small compared with that arising from leaching of lagoon sediments). After a few thousand years, colloid transport is negligible compared with transport of dissolved plutonium.

The release rates into the lagoons have also been estimated for other, less important radionuclides using the single porosity model in the carbonates. It is sufficient here to indicate the predicted maximum release rates (Table XL) which would be expected to occur about five years after a test. The graphs of release rate versus time are given in the Technical Report, Vol. 4. These estimates are also very conservative for the reasons discussed above.

6.5.2.2. *Mixing model for transport in carbonate formations*

Release to lagoon

The second model for transport through the carbonate zone assumes perfect mixing in parts of the carbonates defined in terms of cells characterized by particular cross-sectional and vertical areas. The flux to the lagoon is independent of the cross-sectional area over which mixing occurs but depends on the vertical thickness of the mixed layer. The rationale for this model,

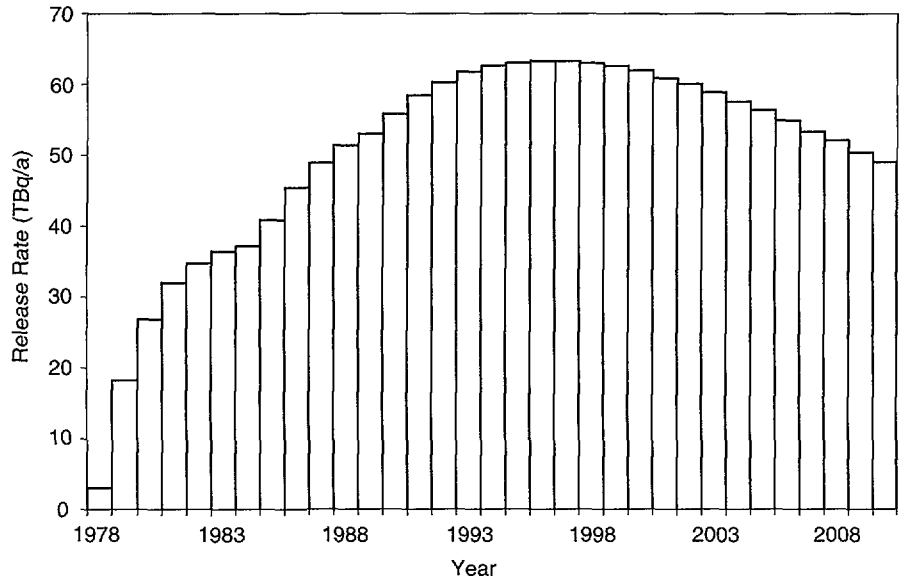


FIG 87 Predicted rates of ^{3}H release into Mururoa lagoon, based on the mixing model (reference case)

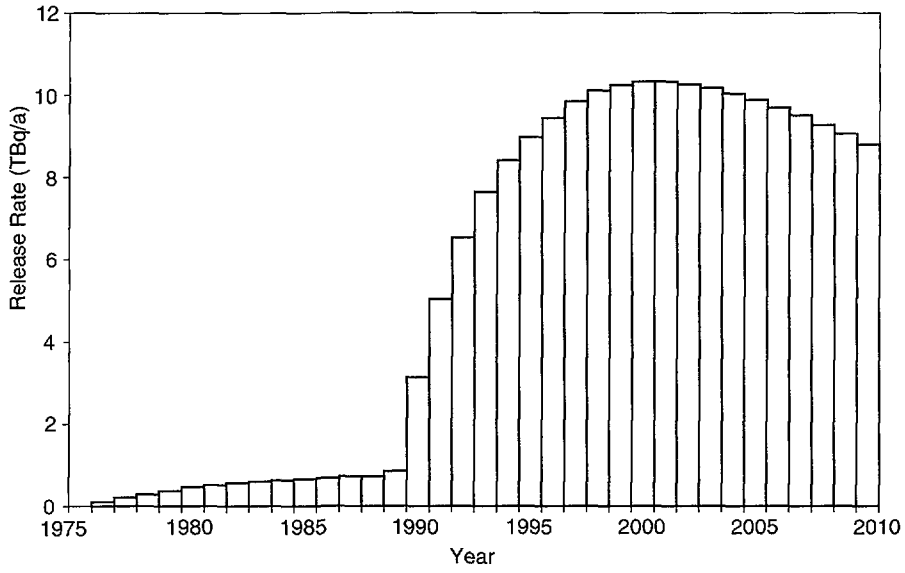


FIG. 88. Predicted rates of ^{3}H release into Fangataufa lagoon, based on the mixing model (reference case)

discussed in detail in the Technical Report, Vol 4, was the observation of mixing due to tidal fluctuations in the karsts and the unexpectedly high degree of lateral dispersion of tritium in the karsts (French Liaison Office Document No. 9).

In the mixing model as applied to tritium, the flux into the lagoon is proportional to the inventory in the carbonates. The model takes no account of sorption and is therefore conservative for sorbing radionuclides (e.g. ^{90}Sr, ^{137}Cs and ^{239}Pu). However, unlike the single porosity model, the mixing model does take account of the time of individual tests. Figures 87 and 88 show the predicted rates of release of tritium into Mururoa and Fangataufa lagoons as a function of time for the reference case where mixing is assumed over the entire depth of the carbonates For Mururoa, the predicted peak release rate of tritium into the lagoon is about 60 TBq/a at about 1997. For Fangataufa, a sharp rise

(attributable to the Lycos test) begins in 1990 The peak release rate of tritium is about 10 TBq/a in the year 2001

Comparison of the single porosity and mixing models for tritium shows that, as expected, the single porosity model gives sharper, higher and earlier peak releases. The mixing model, which predicts a gradual change over several decades, is closer to the historical observations, which suggest only a small change in lagoon concentrations (Section 4) and release rates of tritium over the last ten years (Section 8) Both models predict somewhat higher release rates than have been measured and this is attributed to overestimation of the release rates into the carbonates due to the conservative nature of the modelling assumptions. This is discussed further in Section 6.6.

Release directly to ocean

Although the net flow in the carbonate formations is inwards and upwards, it is considered highly likely that some radionuclides will flow via the karst system directly into the ocean at depth (say 300–400 m) This outward dispersion against the net flow is most probable for tests carried out on the rim because of their proximity to the ocean and the greater influence of tidal fluctuations at the flanks. In the absence of an appropriate model, all that can be done is to assume that the upper limit for the rate of direct release to the ocean is the rate of release to the carbonate zone, i e. the release rate into the carbonates as shown in Figs 80–82 and in Table XXXIX. Assuming that all material released to the carbonate zone goes directly to the ocean would be an extremely conservative assumption which certainly does not correctly represent the actual physical situation. A more realistic estimate is provided in Section 6 6 after assessment of the results of the underground water sampling campaign

For Fangataufa, where only two small tests were carried out on the rim, it is reasonable to assume that there will be no significant direct release to the ocean at depth.

6 6 UNDERGROUND WATER SAMPLING CAMPAIGN MODEL VALIDATION AND REFINEMENT

6.6.1. Introduction

A sampling campaign to collect water samples from monitoring and cavity–chimney wells at Mururoa and Fangataufa Atolls was undertaken in late May and early June 1997 with support from the French Liaison Office. The underground water sampling campaign was designed to fulfil a number of objectives·

(a) To check independently the results of French underground sampling;
(b) To extend the data on underground concentrations to other radionuclides not previously analysed, with particular emphasis on the long lived radionuclides;
(c) To determine the appropriateness of selected K_d values for radionuclides on the basis of measurements of radionuclide concentrations in the cavity–chimneys of two tests;
(d) To determine whether the predictions of transport models are consistent with measured concentrations in the cavity–chimneys and karsts and with estimates of the inventory of radionuclides in the carbonates.

6.6.2. French monitoring well network

During the nuclear testing programme, French scientists monitored the concentration of radionuclides in underground waters Initially the monitoring wells consisted of open large diameter emplacement holes used for underground nuclear explosions; in 1986, testing moved from the rim to the lagoon and wells were subsequently sited in the lagoon. Samples were taken of pumped water during airlift drilling. Emplacement holes were sampled before a nuclear test by use of sample bottles attached to a cable and hoist From 1994 to 1996, dedicated sampling wells were constructed to support a long term monitoring programme. Vertical wells were constructed in the northern rim of Mururoa Atoll as well as in previously uninvestigated portions of Mururoa and Fangataufa lagoons Additionally, the vertical upper sections of radiochemical post-shot holes were adapted for groundwater sampling after isolation from the cavity–chimney Radionuclides targeted in the French sampling and analysis progamme included ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$. Two types of monitoring well were constructed: wells terminating in cavity–chimneys on Mururoa, and wells terminating in the carbonates or volcanics within individual testing areas beneath Mururoa and Fangataufa lagoons and beneath the Mururoa rim.

Wells terminating in cavity–chimneys have a similar construction (Fig. 89). Each well was directionally drilled into the side of a collapsed chimney. A sealed steel casing was installed over the full length of the borehole to prevent contamination from the formation. A polyethylene tube with an 8 mm inner diameter was then inserted into the cased borehole; at Céto, on the Mururoa rim, an obstruction prevented the tube from being lowered beyond the entrance to the chimney.

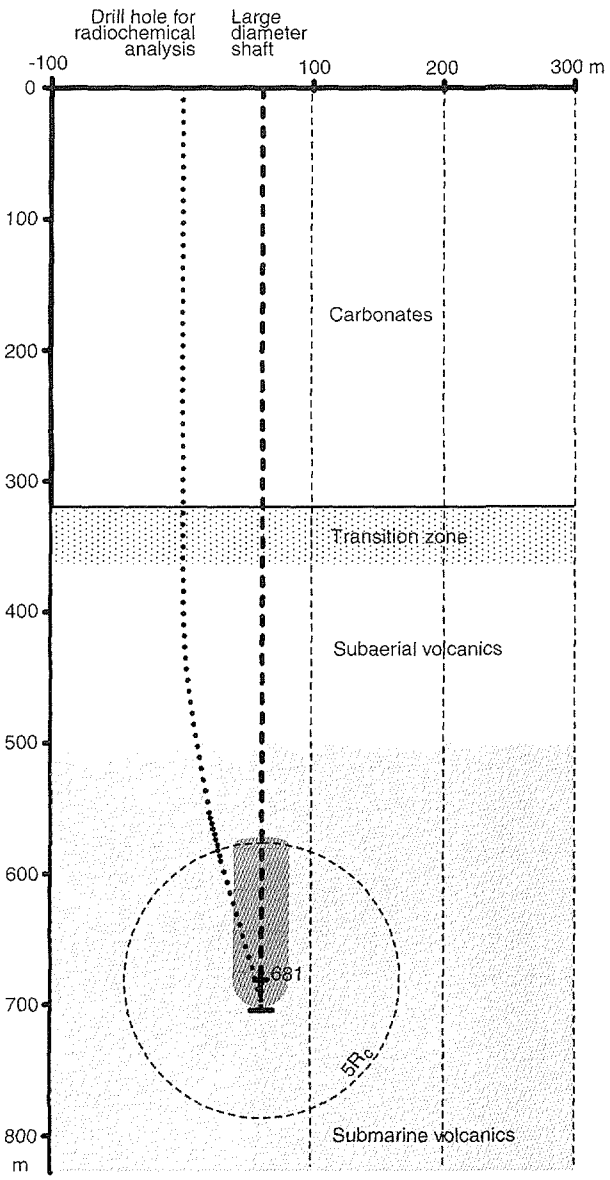


FIG. 89. Aristée cavity–chimney and re-entry drill hole. Zero point depth: 681 m; calculated cavity radius: 21 m; calculated chimney height: 110 m; yield: 6.8 kt. (From French Liaison Document No. 8.)

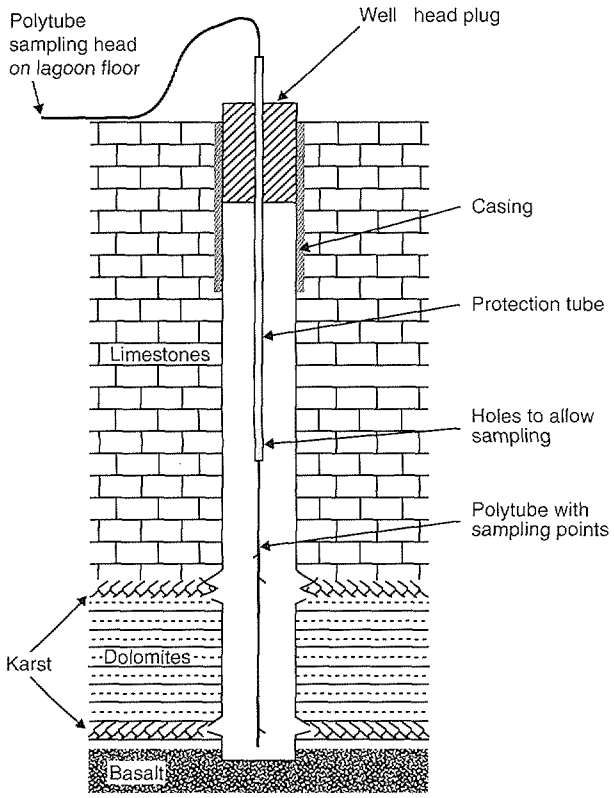


FIG. 90. Typical long term monitoring well in carbonate formations. (From French Liaison Office.)

Representative samples were produced by continuous pumping of the wells.

The monitoring wells terminating in the carbonates or volcanics are constructed with an upper steel casing and well head plug and are otherwise open to the formations over their entire depth (Fig. 90). These wells are equipped with a 'polytube', which consists of a bundle of individual tubes, each with a 4 mm inner diameter, terminating at different depths down the well. Up to four tubes are terminated at each depth interval. In this way, waters from different depths in the carbonates, transition zone and basalt can be produced simultaneously to expedite sampling over the depth of the well. A plug separates the carbonates from the volcanics in the monitoring wells.

Monitoring samples may also be collected from re-entry holes, instrumentation holes and unused large diameter emplacement holes in addition to dedicated wells.

6.6.3. Water sampling in May–June 1997

For the Study, the French authorities provided access to two cavity–chimneys, Céto and Aristée, and 20 other locations, mostly in the carbonate formations. Because of the limited time available, it was not possible to sample all the monitoring wells. Accordingly the Study team decided to take samples from both cavity–chimneys and from nine of the monitoring wells in the carbonates. The locations were chosen to include the most important testing zones and to maximize the usefulness of the data.

The Study team decided on the most appropriate radionuclides for analysis on the basis of the quantities produced in a French nuclear test, a minimum half-life of ten years, relative mobility and radiotoxicity. The

TABLE XLI. UNDERGROUND WATER SAMPLING IN 1997

Date	Well	Location	Sampling depth (m)
28 May	Aristée	Mururoa rim	702 (slant)
29 May	Pieuvre 37	Mururoa lagoon	300
30 May	Fuseau 30	Fangataufa lagoon	193
31 May	Mitre 27	Fangataufa lagoon	239
1 June	Céto	Mururoa rim	513 (slant)
2 June	Géo 10	Mururoa rim	307, 311
3 June	Géo 8	Mururoa rim	274, 276, 278
4 June	Isurus 10	Mururoa lagoon	265
5 June	Murène 16	Mururoa lagoon	230
6 June	Tazard 14	Mururoa lagoon	245
7 June	Géo 5	Mururoa rim	215, 230

Note: Well locations are shown in Fig 93 (Mururoa) and Fig 94 (Fangataufa).

following radionuclides were chosen for analysis by the Study team: ^{3}H, ^{14}C, ^{36}Cl, ^{90}Sr, ^{129}I, ^{137}Cs, $^{239+240}Pu$ and ^{241}Am. This list includes some radionuclides (^{14}C, ^{36}Cl, ^{129}I) not monitored by French scientists and provides a comprehensive measure of the solution source term by including mobile, long lived and toxic species. In addition to the radioactive species, major cations and anions (Na, K, Mg, Ca, Sr, Si, Fe, Cl, SO_4^{2-}) and alkalinity were analysed. Various field parameters (Eh, pH, temperature and pumping rate) were also measured

The concentration of radionuclides in solution (dissolved or in suspension) found in the water samples from the two cavity–chimneys of Céto and Aristée provides a direct measure of the solution source term, which may be compared with the estimates of cavity–chimney water concentrations obtained from the Study models. The range of K_d values for the various radionuclides appropriate to the cavity–chimney environment can also be deduced. Monitoring wells were selected to intercept waters in the vicinity of the safety trials in the carbonates, nuclear tests with chimneys that ascended from the volcanics to the carbonate cover (CRTV tests) and nuclear tests with inadequate volcanic cover. One background location on the Mururoa rim was also selected outside the region affected by underground nuclear testing or the safety trials. Because the monitoring wells are open to the formations, the sampling strategy of the Study targeted well horizons with the highest radionuclide concentration, which in most cases was in the deepest section of the carbonates which included the karst. Polytubes from this single interval were combined and continuously pumped.

The wells sampled during the Study in May–June 1997, their locations and the sampling depths are listed in Table XLI.

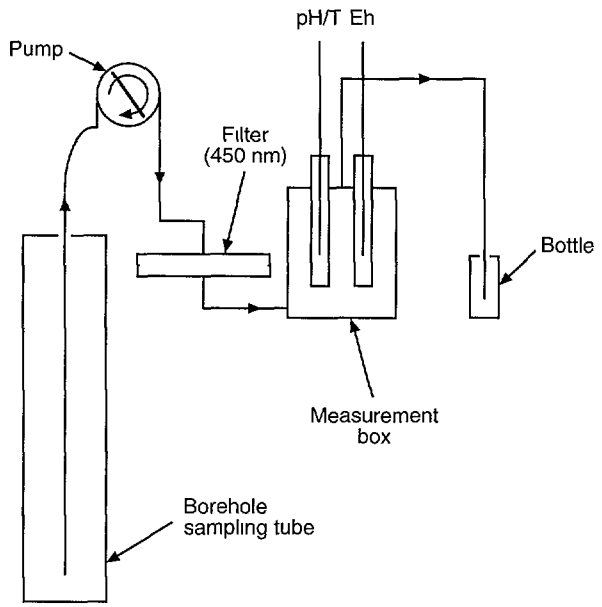


FIG 91 Equipment for sampling and filtration of underground waters

Figure 91 shows the equipment used for sampling underground waters. The sampling tube (for a cavity–chimney well or bore) or tubes (two to four individual tubes for a monitoring well) corresponding to one depth interval were connected to a peristaltic pump and a combined water volume in the tubes was pumped off and discarded An in-line 450 nm filter was attached after the pump and before a high density plastic cell that contained ports for Eh, pH and temperature probes. Both Eh and pH were measured regularly throughout the day, sampling was started only after Eh and pH values had stabilized. The pumping rate was approximately 20 L/h for the cavity bores and approximately 4–5 L/h per tube

TABLE XLII CONCENTRATIONS OF RADIONUCLIDES (mBq/kg) IN FILTERED WATER SAMPLES

Well	^{3}H	^{90}Sr	^{137}Cs	$^{239+240}Pu$	^{14}C	^{36}Cl	^{129}I
Mururoa: cavity–chimney wells							
Aristée	6.1×10^{9}	3.2×10^{5}	1.0×10^{5}	<0.008	<50	3×10^{3}	45
Céto	2.2×10^{10}	2.5×10^{5}	1.1×10^{4}	0.007	1.28×10^{3}	3.1×10^{4}	17
Mururoa: monitoring wells							
Géo 10	7.5×10^{6}	1.6×10^{4}	1.1×10^{4}	<0.03	52	19	0.011
Pieuvre 37	8.5×10^{6}	1.2×10^{4}	9.7×10^{3}	<0.007	<32	1.7	0.012
Géo 8	1.4×10^{6}	1.6×10^{3}	1.1×10^{3}	<0.01	<32	5.4	0.0043
Tazard 14	6.9×10^{6}	53	78	<0.005	<32	3	3×10^{-4}
Murène 16	1.0×10^{7}	103	<2	<0.007	<32	15	0.015
Isurus 10	4.8×10^{5}	64	12	<0.004	<32	<1	9.4×10^{-4}
Géo 5	1.8×10^{4}	8.4	20	<0.03	4.4	<25	$<5 \times 10^{-5}$
Fangataufa: monitoring wells							
Fuseau 30	3.4×10^{6}	340	127	<0.009	<32	3.1	0.010
Mitre 27	1.0×10^{4}	2.2	20	<0.05	12	<6	$<5 \times 10^{-5}$

for the monitoring wells. Approximately 90–100 L of water passed through the filter in the case of the cavity bores and 40–80 L in the case of the monitoring wells. Water samples for tritium measurement were taken after one, two and three combined tube volumes had been passed as well as at the end of sampling. Tritium samples were distilled at the end of the campaign and the condensate was analysed by liquid scintillation counting in analytical laboratories on Mururoa.

Samples were collected in clean low density polyethylene containers. Because radionuclides may be transported as both dissolved and non-dissolved (particulate and colloidal) species, at the end of each day's sampling the 450 nm filter paper was removed from the support and packaged in a sealed bottle for radiochemical analysis. Sampling logs were prepared for each well to record sample numbers, sampling chronology, Eh/pH calibration and field parameters (Eh, pH, temperature and pumping rate) as well as details of each day's sampling. Samples were sent to the MEL in Monaco, where they were kept refrigerated before analysis. Samples for ^{14}C, ^{36}Cl and ^{129}I analyses by accelerator mass spectrometry as well as for chemical analyses were shipped to ANSTO in Sydney.

6.6.4. Results of underground water sampling campaign

6.6.4.1 Cavity–chimney waters

The water samples from the Céto and Aristée cavity–chimney wells have, as expected, the highest concentrations of radionuclides of any of the wells sampled on Mururoa and Fangataufa (Table XLII) Tritium dominates the radionuclide activity concentrations; ^{90}Sr, ^{137}Cs, ^{36}Cl and ^{129}I were also detected, while ^{14}C was detected only in the Céto cavity–chimney. In filtered water samples, $^{239+240}Pu$ was found to be below the detection limit of 0.008 mBq/kg in Aristée and slightly above the detection limit in Céto (0.007 mBq/kg). The concentration of ^{241}Am (not shown in Table XLII) was measured in both cavity–chimneys but was also found to be very low: 0.06 mBq/kg in Aristée and 0.1 mBq/kg in Céto The measurements carried out in the sampling campaign confirm, in particular, the very low concentrations of $^{239+240}Pu$ in the waters of the cavity–chimneys reported by the French Liaison Office.

Figure 92 compares French measurements of ^{3}H, ^{90}Sr and ^{137}Cs in cavity–chimney water with those from the Study The measurements from the Study generally follow the time trend line evident in the French results (the ^{137}Cs activity in the Céto cavity–chimney was lower than expected and this could be due to the fact that the sampling point was at the entrance of the chimney).

The data for tritium indicate some dilution in the cavity–chimney water with time (even after allowing for decay) Using the Study model (Eqs (16) and (17)), it is possible to infer a Darcy velocity for the chimneys from the slope of the line of best fit on a semilogarithmic scale The slopes correspond to Darcy velocities of 1.5 m/a for Céto and 1 m/a for Aristée, in good agreement with the Study assumptions for regular tests. The French scientists have interpreted this trend as gradual

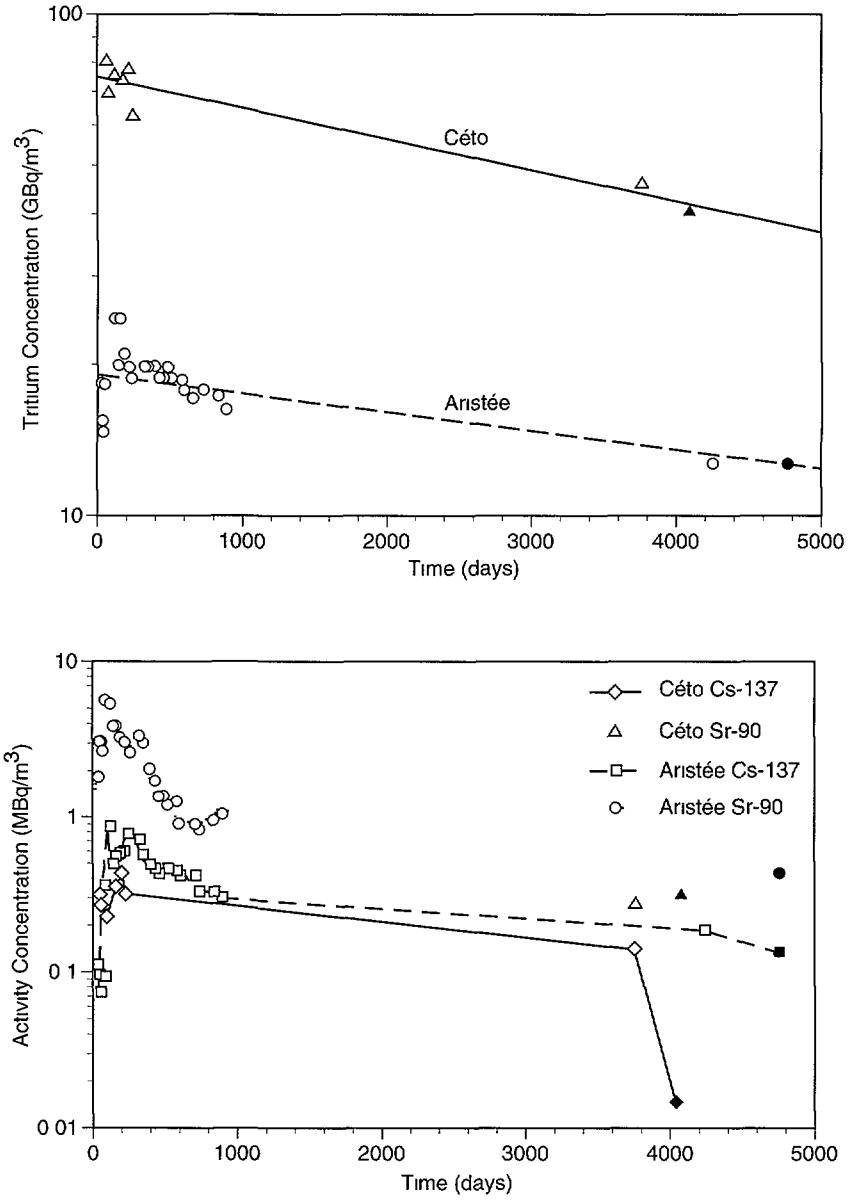


FIG. 92 Measured concentrations of radionuclides in Céto and Aristée cavity–chimneys corrected for decay back to time of test French data (from French Liaison Office Document No 8) are shown as open symbols and data from the Study as full symbols

incursion of cavity–chimney water into the fractured zone and not necessarily upward migration of water (French Liaison Office Document No. 8, ch. 3)

The data for ^{137}Cs and ^{90}Sr are more difficult to interpret because of scatter in the results attributable to complex circulation and sorption processes occurring during the first few hundred days following the explosion. However, the decrease in concentration with time for these radionuclides is probably due not to release from the cavity–chimney (the Study model predicts minimal release for sorbing radionuclides within the time frame of these measurements), but rather to the slow process of equilibration within the inner pores of the volcanic rock.

The cavity–chimney water concentrations can be used to estimate realistic K_d values, assuming no release of the radionuclide from the cavity–chimney. Table XLIII compares the calculated K_d values with the values used in the Study for transport modelling calculations. The calculated values for sorbing species (^{90}Sr, ^{137}Cs, $^{239+240}Pu$ and ^{241}Am) are all much higher than the values used in the Study modelling, indicating that the values chosen are indeed conservative. The very high K_d for plutonium, inferred from measurements of cavity–chimney water

TABLE XLIII. COMPARISON OF K_d VALUES (m^3/kg) CALCULATED FROM CAVITY–CHIMNEY CONCENTRATIONS WITH VALUES USED IN TRANSPORT MODELLING

Radionuclide	Céto	Aristée	Modelling value
^{3}H	0 0002	0 0002	0
^{90}Sr	0 07	0.14	0 008
^{137}Cs	4 9	0.8	0 3
$^{239+240}$ Pu (soluble)	4×10^5	$>1 \times 10^5$	0 5
$^{239+240}$ Pu (total[a])	1×10^4	5×10^3	0.5
^{36}Cl	0	0 003	0
^{129}I	0 0008	0 0004	0
^{241}Am (total[a])	3×10^3	4×10^3	0 05

[a] Based on total concentration including activity on filter paper (Table XLIV).

concentrations, is particularly worthy of note. The values of K_d for plutonium and americium in Table XLIII were based on the very conservative assumption that 5% of these actinides were present on the rubble. If only 0.1% were present, the K_d for ^{239}Pu and ^{241}Am would still be greater than 10 m^3/kg (10^4 L/kg).

The non-sorbing radionuclides (^{129}I, ^{36}Cl) have K_d values slightly above zero. For these radionuclides (as for ^{3}H), some dilution in cavity–chimney water concentration would be expected, so the assumption of $K_d = 0$ appears very reasonable.

6.6.4.2 *Waters from monitoring wells in carbonate formations*

The water samples from the monitoring wells contain, depending on their location, varying concentrations of radionuclides (Table XLII). The ^{3}H, ^{36}Cl and ^{129}I concentrations are depleted by at least three or four orders of magnitude in the monitoring wells (e.g. 10^6 mBq/kg for ^{3}H) relative to the cavity–chimney wells (e.g. 10^{10} mBq/kg for ^{3}H). The same is true for the ^{90}Sr and ^{137}Cs data, except for the wells in and around Area 1 where the corresponding decrease in ^{90}Sr and ^{137}Cs between the cavity–chimney wells (10^5 mBq/kg) and monitoring wells (10^4 mBq/kg) is only one order of magnitude or less Plutonium isotopes and ^{241}Am were not detected in any of the filtered waters produced from the monitoring wells.

In general, good agreement is found between samples collected and analysed by the CEA and equivalent samples analysed by the Study team. Tritium shows nearly a one to one correspondence between the two sample groups, while for ^{137}Cs there is reasonable agreement but some inconsistency for three samples (Tazard 14, Isurus 10 and Mitre 27) with very low ^{137}Cs concentrations (below 100 mBq/kg).

The activation product, ^{36}Cl, and the fission product, ^{129}I, both non-sorbing and easily dissolvable radionuclides, were found at rather low concentrations in the waters of the monitoring wells, except that no ^{36}Cl was detected in Géo 5, Mitre 27 or Isurus 10. This is consistent with the fact that these wells also have the lowest concentrations of tritium, another non-sorbing radionuclide.

6.6.4.3 *Analyses of solid residues*

In addition to the filtrate which passed through the 450 nm filter, the solid material found on the filter was analysed for radionuclides These solids were collected from about 40 to 100 L of water pumped through the filters in the course of the sampling activities.

The analyses (Table XLIV) show that plutonium isotopes and ^{241}Am are present in low but measurable quantities on the solids filtered from the waters of the two cavity–chimneys and from the monitoring well waters taken at Fangataufa (but not those taken at Mururoa) Activation and fission products (^{60}Co, ^{125}Sb, ^{137}Cs and ^{155}Eu) were also detected in the solids filtered from the cavity–chimney waters. Chemical analysis indicated that, in all cases, the solids were precipitates of iron oxide or hydroxide. It is well known that such precipitates are effective scavengers for many elements because of their large and highly reactive surfaces

The presence of plutonium and americium in solids filtered from the carbonate samples from Fangataufa was initially surprising since no measurable migration of these elements from the volcanics is predicted by the dual porosity model within the time frame of 10–20 years. A speculative interpretation of this finding is that plutonium- and americium-containing material may have entered the monitoring wells from Fangataufa lagoon before these wells were sealed. The isotopic compositions of the plutonium in the lagoon and on the solid material filtered from the waters of the monitoring wells are similar ($^{238}Pu/^{239+240}Pu$ = 0.38), which supports this hypothesis. Another interpretation, considered less likely, is that the actinides have migrated from the cavity–chimney as colloids, moving at a similar rate to the groundwater.

6.6.5. Radionuclide inventory in carbonates

The good agreement between the French data and Study results of underground water analysis is

TABLE XLIV. RADIONUCLIDES ON SOLIDS FILTERED FROM UNDERGROUND WATERS

	Cavity–chimney samples		Fangataufa karst samples	
	Aristée	Céto	Fuseau 30	Mitre 27
Solids concentration (mg/L)	0.85	6 6	44	7
Activity concentration (mBq/g solids)				
^{238}Pu	32	3 9	8 9	9.3
$^{239+240}Pu$	235	38	23.3	24 3
^{241}Am	44	17 2	0 54	1 2
^{60}Co	160	40	<1	<15
^{125}Sb	1750	80	<3	<30
^{137}Cs	1080	1030	<1	<15
^{155}Eu	270	<30	<2	<7
$^{238}Pu/^{239+240}Pu$	0 14	0 10	0.38	0.38

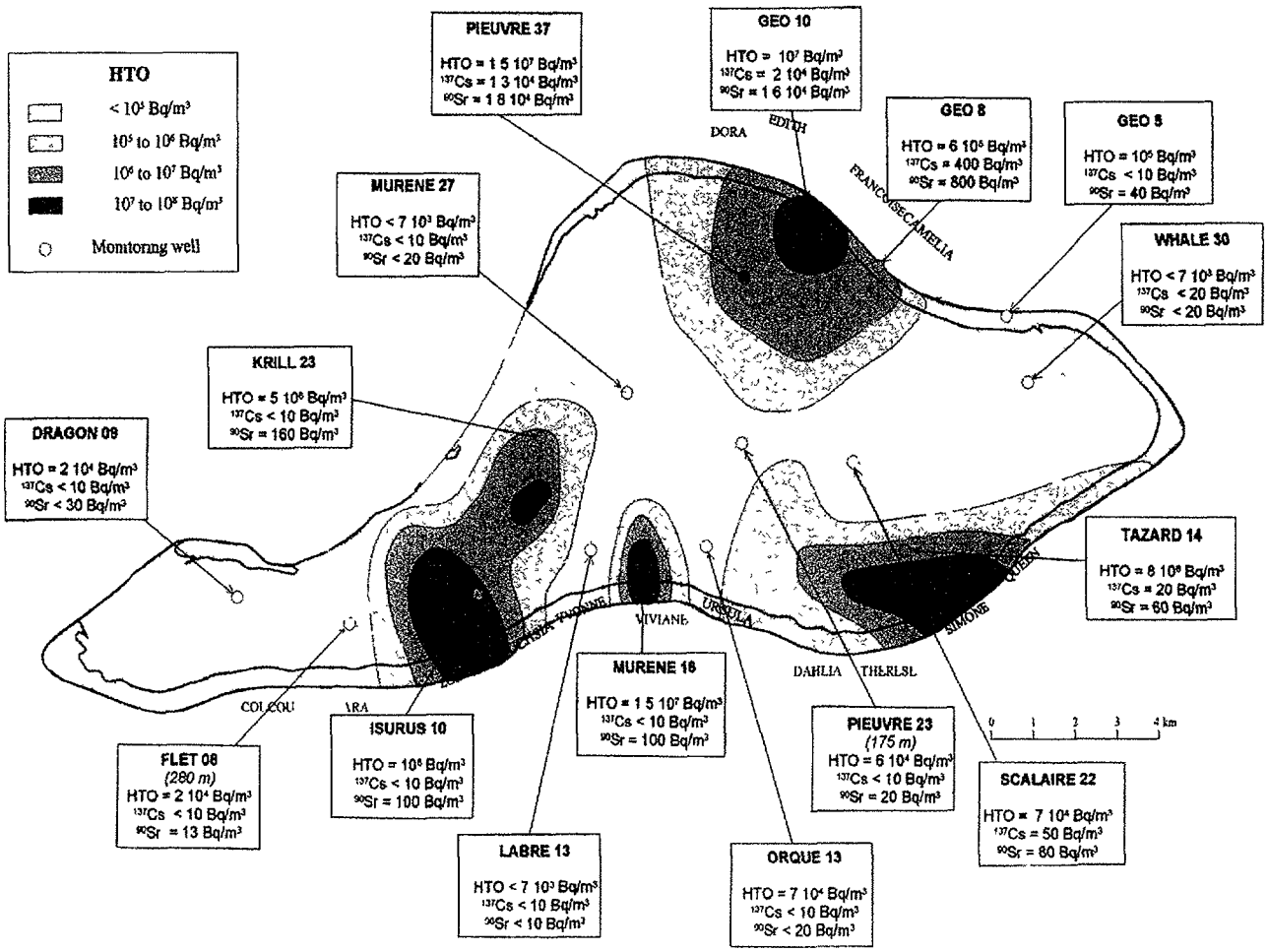


FIG 93. Tritium contours and concentrations of radionuclides in monitoring wells at Mururoa (From French Liaison Office Document No 9)

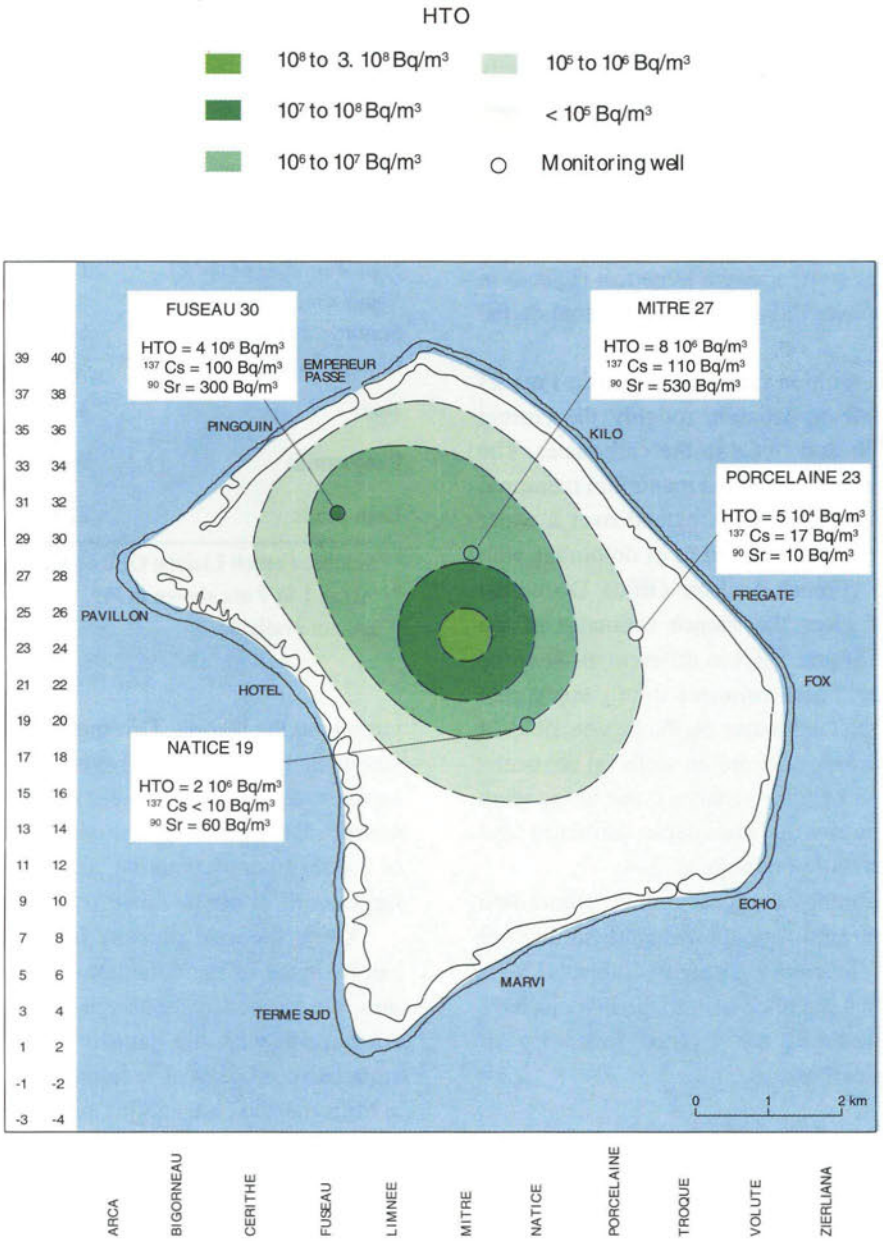


FIG. 94. Tritium contours and concentrations of radionuclides in monitoring wells at Fangataufa. (From French Liaison Office Document No. 9.)

confirmation of the validity of the more extensive French underground sampling data (French Liaison Office Document No. 9). The French Liaison Office has prepared maps for Mururoa and Fangataufa (Figs 93 and 94) which show the distribution of the maximum concentration of ^{3}H, ^{90}Sr and ^{137}Cs within monitoring wells in the carbonates during the period from 1994 to 1996. It should be noted that concentration gradients are sensitive to the placement of the monitoring wells; the French scientists emphasize that not all monitoring points used to construct the maps are presently available for sampling.

Figure 93 shows zones on Mururoa where radioactive material is spread in the carbonates. The sources of this material are, according to information provided by the French Liaison Office:

(a) Nuclear tests in Areas 1, 2 and 3 (Fig. 44) in the basalt whose chimneys reached the top of the volcanic cover (i.e. CRTV tests);

(b) Large yield underground tests (Nestor or Enée under the coral rim in Area 4 and Mégarée under the lagoon) whose volcanic cover did not sufficiently contain the radionuclides produced by these explosions.

Figure 94 shows the radionuclide distribution beneath Fangataufa. Here, the radioactive material in the carbonates originates from a single large test (Lycos) in which the volcanic cover did not sufficiently contain the radionuclides.

Using the concentration contours shown in Figs 93 and 94, it is possible to estimate roughly the current inventory of ^{3}H, ^{90}Sr and ^{137}Cs in the carbonates. The French assessment assumes that the maximum measured concentrations in the karst waters extend over a water thickness of 10 m, equivalent to 50 m of dolomites with a porosity of 20% (French Liaison Office Document No. 9). Table XLV gives the French estimates of the inventories of ^{3}H, ^{90}Sr and ^{137}Cs in different areas of the carbonate formations. These estimates strictly apply only to the inventory in the carbonates on the lagoon sides of the atolls since there are no sampling wells on the ocean side For the purpose of future analysis, the Study team accepts these inventories as reasonable estimates and probably accurate to within a factor of 2–4.

The estimated combined release rate of tritium into the two lagoons is currently about 6 TBq/a (Section 8) or about 0.1% of the inventory given in Table XLV. It follows, therefore, that the releases into the lagoons have not significantly reduced the overall inventory of radionuclides in the carbonates.

TABLE XLV. FRENCH ESTIMATES (1996) OF RADIONUCLIDE INVENTORY IN CARBONATE ZONES[a]

	^{3}H (TBq)	^{90}Sr (GBq)	^{137}Cs (GBq)
Mururoa			
North zone (Area 1)[b]	1100	1600	1100
Southeast zone (Area 2)	1300	30	na[c]
South zone (Area 3)	170	2	na
Southwest zone (Area 4)	1500	150	na
Lagoon (Areas 5–7)	130	70	na
Total	4200	1850	1100
Fangataufa	3000	250	80
Both atolls	7200	2100	1180

[a] Source French Liaison Office Document No 9
[b] Areas 1 to 7 are shown in Fig. 44
[c] na not available

6.6.6. Review and refinement of geosphere transport model

6 6.6.1. Release into carbonates

Figures 93 and 94 show that the tritium plume has dispersed to a far greater extent than is predicted by pure advective transport The tritium front has dispersed up to 4 km in 20 years (200 m/a), whereas the calculated pore velocities are of the order of 10 m/a. It is concluded, therefore, that dispersion (presumably through tide induced flow in the karsts) dominates over advection. An important consequence of this conclusion is that radionuclides released from tests along the rim are as likely to migrate towards the ocean as they are towards the lagoon. In further calculations, it will be assumed that 50% of radionuclides released from tests along the rim are dispersed towards the ocean while the other 50% flow inwards and upwards to the lagoon. For tests under the lagoon, it is assumed that 100% of the radionuclides migrate to the lagoon. This model, depicted in Fig. 95, is simplistic but it has the advantage that inventories in the lagoon-side and ocean-side zones determined in this manner cannot be underestimated by more than a factor of 2. Any other assumption could overestimate either the lagoon-side or ocean-side inventories by a greater factor.

Using the dual porosity transport model, estimates can be made of the cumulative release of radionuclides into the carbonates beneath each of Areas 1–7 for comparison with the data in Table XLV. Estimates of cumulative releases of radionuclides into the carbonates at Mururoa and Fangataufa can be made by integration of the release rate curves (Figs 80–82). The dual porosity model has also been used to predict the inventories in the carbonates beneath each of the Areas as a function of time. From a comparison of predicted and measured inventories, a number of preliminary conclusions can be drawn on the appropriateness of the parameters used in the dual porosity model:

— A Darcy velocity of 20 m/a appears reasonable for the CRTV tests.
— For Category 2 tests (those with inadequate cover), a Darcy velocity of 20 m/a is too high since the tritium inventories in the zones of carbonate overlying such tests are significantly overestimated. This was not unexpected because the volcanic cover, although defective, should provide some resistance to flow. Closer agreement with measured values was obtained by using a Darcy velocity of 5 m/a for the three Category 2 tests at Mururoa and 10 m/a for the Lycos test at Fangataufa. This is consistent with the

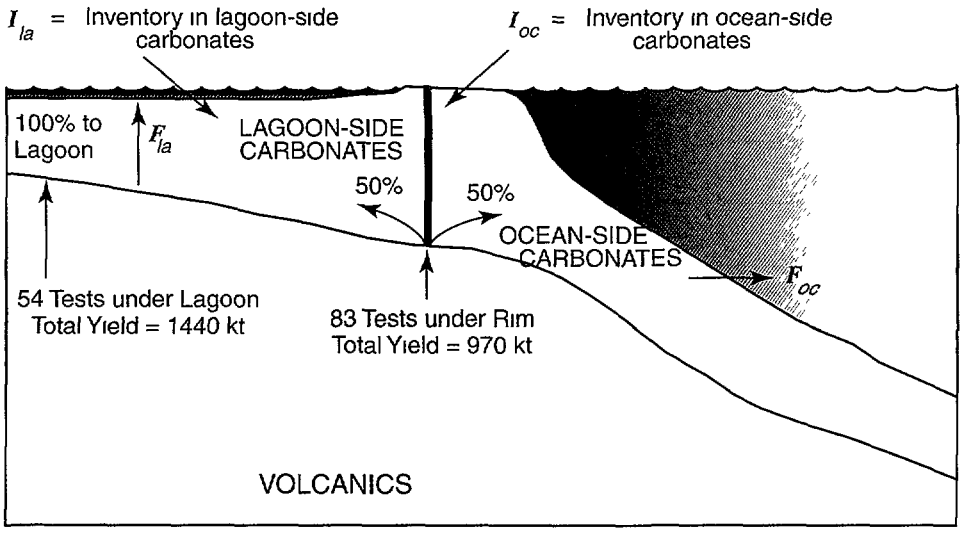


FIG 95 Model for release of radionuclides into carbonates, lagoon and ocean

French analysis, which indicates that Lycos is the 'leakiest' of the Category 2 tests (French Liaison Office Document No. 10).

— Table XLV shows that the north zone (Area 1) at Mururoa is the source of almost all the ^{137}Cs and ^{90}Sr. Moreover, the $^{3}H/^{137}Cs$ and $^{3}H/^{90}Sr$ ratios in this zone are much lower than in other zones. This is strong evidence that the three Category 4 safety trials (safety trials that went critical), all of which were carried out in Area 1, are the dominant source of ^{137}Cs and ^{90}Sr since tritium is not a component of safety trials. The dual porosity model, with a Darcy velocity of 2 m/a and standard K_d values for basalt, underestimates the measured inventory of ^{137}Cs and, to a lesser extent, ^{90}Sr from Category 4 trials. This is not unexpected because the basaltic sand used as packing around each trial extends out to a diameter of about 1.6 m, whereas the diameter of the cavity in a Category 4 trial (yield ≈ 0.1 kt) is estimated to be about 14 m In further calculations, it was decided to use a K_d of zero (no sorption) for these trials.

TABLE XLVI PREDICTED INVENTORY (1996) OF RADIONUCLIDES IN LAGOON-SIDE CARBONATE ZONES USING MODIFIED PARAMETERS

(Darcy velocity of 5 m/a for Category 2 tests on Mururoa and 10 m/a for the Lycos test on Fangataufa; K_d = 0 for ^{137}Cs and ^{90}Sr for Category 4 safety trials)

	^{3}H (TBq)	^{90}Sr (GBq)	^{137}Cs (GBq)
Mururoa			
North zone (Area 1)[a]	2 200	4 000	1 160
Southeast zone (Area 2)	1 400	2 000	240
South zone (Area 3)	360	500	60
Southwest zone (Area 4)	1 400	2 900	120
Lagoon (Areas 5–7)	3 100	2 100	90
Total	8 460	11 500	1 670
Fangataufa	3 000	4 300	140
Both atolls	11 500	15 800	1 800

[a] Areas 1 to 7 are shown in Fig 44

Table XLVI gives the predicted inventories for 1996 in the lagoon-side carbonate zones using the modified parameters. These predictions take account of the decay of each radionuclide; release into the lagoon is insignificant within this timescale (Section 6.6.5). The predicted inventories are greater than the French estimates based on actual measurements, indicating that conservative parameters have been used in the dual porosity model. The predicted ^{90}Sr inventory is much higher than the measured value, suggesting that the chosen K_d value of 0.008 m^3/kg (8 L/kg) is too low. Moreover, the predicted tritium release into Mururoa lagoon (which, in 1996, is dominated by a large number of regular tests) appears to be too high, suggesting that an average Darcy velocity of 1 m/a for regular tests is probably too conservative.

It is possible to adjust the model parameters further in order to get closer agreement between measured and predicted inventories. Table XLVII compares the predicted and estimated inventories by assuming a K_d for ^{90}Sr of 0.07 m^3/kg for all tests (except the Category 4 trials) and a Darcy velocity of 0.1 m/a for regular tests. The K_d of 0.07 m^3/kg is consistent with the value inferred

TABLE XLVII. COMPARISON OF FRENCH ESTIMATES (1996) OF INVENTORY OF RADIONUCLIDES IN CARBONATE ZONES WITH PREDICTIONS FROM THE STUDY FOR 1996 USING OPTIMIZED PARAMETERS
(Darcy velocity of 0.1 m/a for regular tests; K_d = 0 07 m^3/kg for ^{90}Sr for all tests except Category 4 safety trials)

	^3H (TBq)		^{90}Sr (GBq)		^{137}Cs (GBq)	
	The Study	French data	The Study	French data	The Study	French data
Mururoa						
North zone (Area 1)[a]	1500	1100	790	1600	1160	1100
Southeast zone (Area 2)	920	1300	270	30	240	
South zone (Area 3)	260	170	60	2	60	
Southwest zone (Area 4)	1100	1500	350	150	120	
Lagoon (Areas 5–7)	390	130	50	70	20	
Total	4170	4200	1520	1850	1600	1100
Fangataufa	2800	3000	500	250	140	80
Both atolls	6970	7200	2020	2100	1740	1180

[a] Areas 1 to 7 are shown in Fig 44

from the concentration in Céto cavity–chimney water (Table XLIII). The predicted inventories are within the range of probable uncertainties in French estimates based on actual measurements in the carbonates.

6.6.6.2. Release into lagoons and directly into ocean

As noted earlier, the mixing model is preferred over the single porosity model for modelling the release from the carbonates. If perfect mixing and no sorption are assumed within the karsts, the release rate to the lagoon (R_{la}) or ocean (R_{oc}) for each nuclide can be described by the simple first order equations.

$$R_{la} = F_{la} I_{la} \quad (22)$$

$$R_{oc} = F_{oc} I_{oc} \quad (23)$$

where F_{la} and F_{oc} are the fractional releases from the lagoon-side and ocean-side carbonates per unit time, respectively, and I_{la} and I_{oc} are the lagoon-side and ocean-side inventories of each radionuclide. These equations can be applied to both Mururoa and Fangataufa Atolls but direct release to the ocean at Fangataufa is assumed to be negligible because only two low yield rim tests were carried out there.

Estimates of I_{la} and I_{oc} were computed using the dual porosity model with the following parameters:

Darcy velocities	(m/a)
Category 1	1
Category 2	5; 10 for Lycos
Category 3	20
Categories 4, 5	2
Categories 6, 7	1

K_d *values in volcanics*	(m^3/kg)
^3H	0
^{90}Sr	0.008
^{137}Cs	0 3
^{239}Pu	0.5
^{90}Sr, ^{137}Cs (in carbonates)	0 for Category 4 tests only

These are the values used to calculate the data in Table XLVI. The values of K_d for ^{90}Sr and especially ^{239}Pu are almost certainly too low on the basis of underground analyses but are retained to preserve the conservative approach adopted throughout the Study

The values of F_{la} and F_{oc} depend on the volumes and flow rates within the carbonates; F_{la} is most accurately estimated from the inventory of tritium and the measured release rate to the lagoons as determined from the elevation in tritium concentration in the lagoons compared with the oceanic background. This effectively 'anchors' the predicted release rates for 1996 to the measured values in that year. It is, therefore, a realistic estimate for tritium release to the lagoons but is more conservative for sorbing radionuclides (such as those of plutonium, ^{137}Cs and ^{90}Sr).

The best estimate of the current tritium release rate from Mururoa lagoon based on the elevation in tritium concentrations above the oceanic background is 10 TBq/a (Fig. 110 in Section 8). Since the calculated inventory is 8460 TBq (Table XLVI), 0.12% of the predicted tritium inventory in the lagoon-side carbonates

was released to Mururoa lagoon in 1996. Hence F_{la} = 0.0012 a^{-1}, which is reasonably consistent with estimates based on volumes and predicted flow rates (Section 6 5 2).

F_{oc} is more difficult to estimate because it is not possible to measure release rates directly to the ocean at a depth of about 300 m. However, F_{oc} is almost certainly higher than F_{la} because of the large ratio of the surface area through which release may occur to the volume of the ocean-side carbonates, and because tidal effects are likely to be stronger near the flanks The lateral distance along the karsts to the ocean is not known precisely but is likely to be between 0.5 and 1 km. Taking into consideration the lateral spread of the front of the tritium plume inferred from concentration measurements under the lagoon, an average residence time on the ocean side of about 20 years seems reasonable. This is equivalent to F_{oc} = 0.05 a^{-1}.

Estimates of release rates from the geosphere were determined for each radionuclide by computing the release rates into each zone of the carbonates on the basis of the dual porosity model and then the cumulative inventory in each zone as a function of time (allowing for decay and release from the carbonates). F_{la} and F_{oc} can be varied as parameters but the chosen reference values were F_{la} = 0 0012 a^{-1} and F_{oc} = 0.05 a^{-1}.

Figures 96–99 show the predicted release rates to Mururoa and Fangataufa lagoons and directly to the ocean at Mururoa as a function of time for ^{3}H, ^{90}Sr, ^{137}Cs and ^{239}Pu. For tritium, the release rates to Mururoa lagoon are predicted to be relatively constant between 1980 and 2025, with the peak value occurring in about 2010. The peak release rate into Fangataufa lagoon is predicted to occur in 1999. The peak release rate of tritium directly into the ocean of 320 TBq/a is predicted to have occurred in 1981 (Fig 96)

The highest release rate of ^{90}Sr directly into the ocean (300 GBq/a) is predicted to have occurred in 1995 (Fig. 97). For Mururoa and Fangataufa lagoons, the peak release rates of ^{90}Sr are much lower and are predicted to occur in 2015 and 2030, respectively. The curves for ^{137}Cs (Fig. 98) are similar in shape to those for ^{90}Sr but the absolute values are reduced by an order of magnitude because of the higher K_d for ^{137}Cs.

An important conclusion from this modelling is that future release rates of ^{3}H, ^{90}Sr and ^{137}Cs are unlikely to be significantly higher than the current release rates.

The release curves for ^{239}Pu (Fig. 99) are more complex and extend to much longer times because of the long half-life (24 110 years). The predicted release rates from underground sources are very low in the short term (up to 100 years) In all cases, the peak release rates are predicted to occur from 5000 to 10 000 years in the future. The peak values of about 5 GBq/a are, however, less than the current release rates into the lagoons due to leaching of plutonium-bearing sediments

Comparison of the release rates into the lagoons using the single porosity (Figs 83–85) and mixing models shows that, as expected, the mixing model gives higher (i.e more conservative) values for sorbing radionuclides (^{90}Sr, ^{137}Cs and ^{239}Pu).

The release curves based on the mixing model (Figs 96–99) will be used as the source term for modelling of marine dispersion in Section 8. The effect of variation in model parameters, especially F_{la}, F_{oc} and the K_d values for ^{90}Sr and ^{239}Pu, is discussed in the Technical Report, Vol. 4.

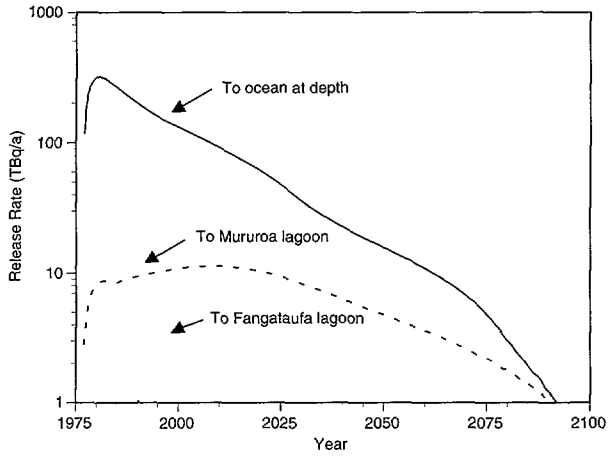


FIG 96 Predicted rates of ^{3}H release based on the mixing model

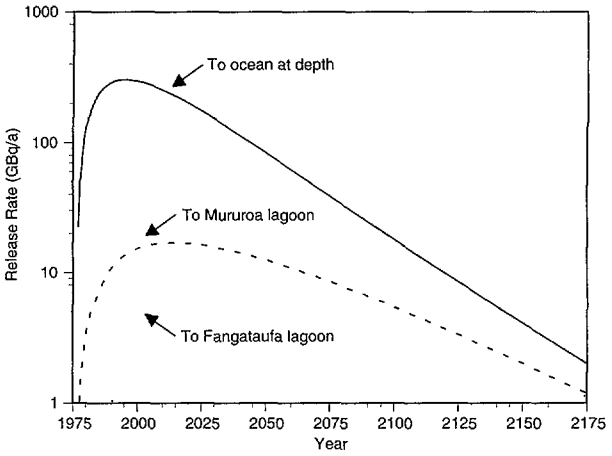


FIG 97 Predicted rates of ^{90}Sr release based on the mixing model

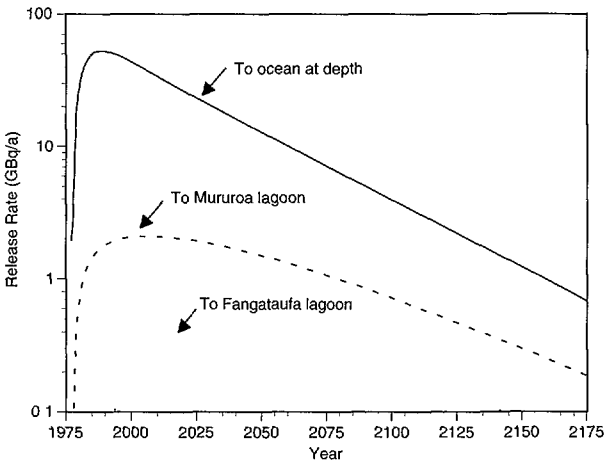


FIG. 98 Predicted rates of ^{137}Cs release based on the mixing model

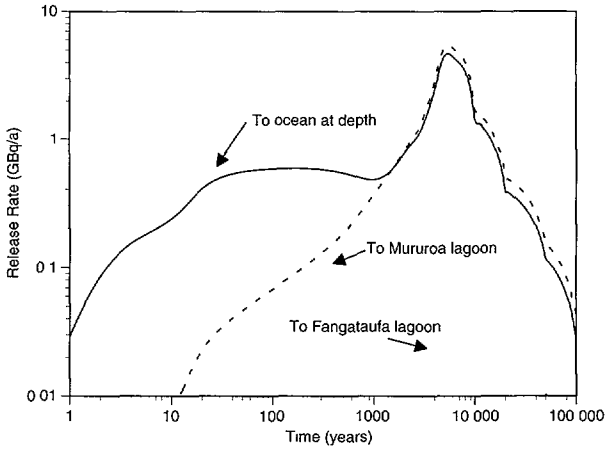


FIG 99 Predicted rates of ^{239}Pu release based on the mixing model. Year 1 is 1979

6.7. COMPARISON WITH FRENCH MODELLING RESULTS

The geosphere transport modelling carried out by the French scientists (French Liaison Office Document No 10) differs from that performed in the Study in several respects. The French assessment considers two cases, a 'realistic' scenario, where total confinement is assumed for all regular tests, and a 'pessimistic' scenario, where a major anomaly is assumed for all tests. In the Study, transport through the volcanics is modelled more rigorously in that a dual porosity model is used and regular tests are integrated into the overall transport model. The major limitation in the dual porosity model is the need to assume a constant flow velocity but this has been overcome by choosing conservative values for the Darcy velocities.

The French 'realistic' scenario is based on the estimated time dependent turnover rates for abnormal tests (CRTV tests and tests with inadequate cover) and for the safety trials that went critical to simulate the effect of cooling within the cavity–chimneys. Values for K_d also vary depending on circumstances but are typically in the range 0.002–0.20 m^3/kg for ^{90}Sr, 0.05–0.4 m^3/kg for ^{137}Cs and 10 m^3/kg for ^{239}Pu. The K_d values for ^{90}Sr and ^{137}Cs are similar to those used in the Study but the French authorities assume a much higher K_d (as estimated by French scientists and by the Study team) for ^{239}Pu, and also assume that plutonium and other actinides partition completely into the lava.

Table XLVIII compares the predicted peak inventories of ^{3}H, ^{90}Sr and ^{137}Cs as estimated by the Study with the French estimates. The year of the predicted peak is also shown. In general, the agreement is fairly good although the peak releases are predicted in the Study to occur later because of the delayed release from regular tests, which are not considered in the French 'realistic' scenario.

French scientists have used a complex model to describe transport from the carbonates either into the lagoons or directly into the ocean (French Liaison Office Document No. 10) As indicated previously, the effect of tides is simulated by introducing the concept of an apparent dispersion coefficient. Flow and dispersion are assumed to occur predominantly within a karst system in the lower carbonates. In the upper carbonates, a very low effective porosity is used (0.1%) to simulate rapid transport along preferred pathways into the lagoon. The model requires estimates of many parameters· apparent transverse and longitudinal dispersion coefficients, thickness of the karst layer, velocity in the karsts and effective porosity in the upper carbonates. Appropriate parameters are estimated from data on the dispersion of tritium in the carbonates (Figs 93 and 94). No sorption is assumed in the carbonates (as is done in the mixing model examined in the Study (Section 6.5.2.2)).

Compared with the Study, the French model predicts much smaller release rates of ^{3}H, ^{90}Sr and ^{137}Cs directly to the ocean. Because of the lack of pertinent data, it is not possible to determine which model is more realistic but the predictions of the Study are clearly more conservative. For release into the lagoons, the release rate versus time curves are fairly similar except that, in the French model, the maximum release rates have already occurred, whereas in the Study model they occur in the future owing to delayed releases from regular tests. The French estimates of release rates into the lagoon tend to be higher than the Study estimates in the past and present

TABLE XLVIII. COMPARISON OF ESTIMATES OF PEAK INVENTORIES (TBq) IN CARBONATES AND YEAR OF PEAK

	^{3}H (Year)	^{90}Sr (Year)	^{137}Cs (Year)
Mururoa			
The Study[a]	14 000 (1981)	16 (2004)	2 6 (1995)
French estimate	13 000 (1978)	17 (1983)	4.2 (1983)
Fangataufa			
The Study[a]	3 200 (1999)	10 (2029)	0 4 (2030)
French estimate	2 000 (1995)	1.4 (2000)	0 05 (2000)

[a] Lagoon-side plus ocean-side inventories

but lower in the future. However, in view of the differences in assumptions, the agreement can be considered reasonable.

The French assessment considers three scenarios for modelling of the long term (beyond 100 years), where transport of plutonium is the dominant consideration. In both the Study and the French assessment, the four safety trials in the carbonates that did not go critical are considered to be the major potential contributor to releases because the plutonium is in a more available form. In the French analysis, the peak releases of plutonium generally occur from 100 to 10 000 years in the future (depending on the parameters used in the model) but are generally lower than those attributable to leaching of lagoon sediments. The Study reached the same conclusion (Section 6.6).

6.8. SUMMARY

Underground nuclear testing has caused destabilization of the flanks of Mururoa Atoll in the form of submarine slope failures on the southern and northern rims. The latter are of some concern since slow movement (creep) continues even though testing has stopped. These movements are monitored continually by the French authorities. There is a possibility of a slide of carbonate rock as a result of these movements. Depending on the location of the slide, some radioactive material could be released to the ocean but this would be limited to material in the carbonate formations near the zone where shear failure occurred The release of radioactive material following a hypothetical massive slide is considered in Section 7.

Some areas along the Mururoa rim have suffered surface settlements of up to 2.2 m as the result of underground testing. However, the Study analysis indicates that these settlements are essentially near surface phenomena and are not an indication of preferred pathways for radionuclides. An assessment of the long term stability of the cement plug used to backfill each test shaft has also concluded that it is most unlikely that the plug will seriously degrade before radionuclides have decayed to insignificant levels.

The permeability of the underground rocks at Mururoa has been estimated from the temperature variation with depth using a numerical modelling program, FEFLOW The volcanic rocks in which the nuclear tests were carried out have a low pre-test permeability of 10^{-7} m/s or lower. The carbonate rocks that overlie the volcanic rocks have a much higher and more variable permeability (typically 10^{-4} m/s on a large scale). The average pre-test Darcy velocities of groundwater are estimated to be 2–5 mm/a in the volcanics and 0.5–2 m/a in the carbonate formations. Karsts at a number of levels in the lower carbonates are the major conduits for groundwater flow and mixing caused by tidal oscillations.

Nuclear testing results in a marked increase in permeability within about two to three cavity radii of the zero point The collapse of rock above the cavity results in a chimney of broken rock extending in height to about five cavity radii. Fracturing of rock is possible up to the elastic limit, which extends to about ten cavity radii. Estimates were made of the permeability of the surrounding rock after a nuclear test on the basis of French data on the rate of infiltration of water back into the cavity–chimneys. The infiltration rates are consistent with an increase in permeability above the chimney and/or in the surrounding rock (to about two to three cavity radii) of about one order of magnitude

After a nuclear explosion, groundwater flows upwards from a chimney owing to the buoyancy of the heated water Using FEFLOW, estimates were made of the Darcy velocities as a function of time for a number of typical test configurations The Darcy velocity is not sensitive to the yield of the test but depends mainly on the thickness and integrity of the volcanic rock above the

chimney. The velocities are highest for CRTV tests and tests with inadequate cover, where the overlying rock is more permeable. To simplify transport modelling calculations, a constant velocity was used even though the velocity will decrease with time as a result of cooling and advection To ensure that estimates were conservative, peak velocities were used rather than average velocities. On this basis, the vertical Darcy velocities were estimated to be 20 m/a for CRTV tests, 5–20 m/a for tests with inadequate cover and 1 m/a for regular tests.

A dual porosity model was used to estimate transport rates of radionuclides from the cavity–chimney to the carbonate formations. Calculations were carried out for 32 radionuclides but particular attention was focused on ^{3}H and the radionuclides of potential radiological significance: ^{90}Sr, ^{137}Cs and $^{239+240}Pu$. For the first 20 years, predicted release rates into the carbonates are dominated by the CRTV tests and tests with inadequate cover.

An underground water sampling campaign was undertaken to verify the results of more extensive measurements carried out by French scientists and to compare the predictions of concentrations of radionuclides in the cavity–chimney water with measured values. Samples of water were taken from within the cavity–chimney of two tests and at nine other locations within the carbonate formations. There was good agreement between the French data and Study results. The plutonium concentrations were found to be either very low or not detectable, even within the cavity–chimneys It is concluded that plutonium is effectively retained within the glassy lava formed as a result of the nuclear explosion.

From the underground water sampling results, estimates were made of the inventories of radionuclides within particular zones of the carbonate formations. Some minor adjustments were made to the parameters used in the dual porosity model on the basis of a comparison of predicted and measured inventories, but for the most part the predicted rates of release changed only slightly.

Radionuclides in the carbonate formations can be released to the biosphere either by groundwater flow upwards into the lagoons or by flow along the karstic layers into the ocean at a depth of about 300 m. Although the carbonate formations are quite permeable, they are also large water reservoirs and the average residence time is much longer than the half-life of some radionuclides, such as ^{3}H, ^{90}Sr and ^{137}Cs. Two models were considered to describe the release to the biosphere· a single porosity model and a mixing model. The mixing model was considered to be the more appropriate because it is consistent with the high degree of lateral mixing of tritium apparent from the underground sampling results. It is also very conservative for sorbing radionuclides such as ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ since no sorption of these radionuclides is assumed.

In the mixing model, the release rate to the lagoon or ocean is assumed to be proportional to the inventory in the carbonates. For transfer into the lagoon, the proportionality constant can be calculated from estimates of the current inventory of tritium in the carbonate formations and measurements of the elevated levels (relative to the background in the South Pacific Ocean) of tritium in the lagoon. This corresponds to a fractional release rate of about 0.12% of the inventory per year. For release into the ocean, the fractional release rate has been assumed to be about 5% per year.

Using the dual porosity model for transport through the volcanic formations and the mixing model for release from the carbonates, the inventories in the carbonates and release rates to the biosphere have been estimated for several hundred years for ^{3}H, ^{90}Sr and ^{137}Cs and for over 100 000 years for ^{239}Pu. The most important conclusion from these predictions is that the future release rates of ^{90}Sr and ^{137}Cs to the lagoons are unlikely to be significantly higher than current release rates The predicted maximum release rate into the ocean at depth has already occurred.

For ^{239}Pu, the peak release rates from underground sources are predicted to occur from 5000 to 10 000 years in the future but are expected to be lower than the current release rates into the lagoons, owing to the leaching of plutonium-bearing sediments.

The release rates to the lagoons and the ocean as predicted in this section are the input for modelling of marine dispersion of radionuclides (Section 8) and, ultimately, are the basis for the estimated doses associated with radionuclides released from the underground tests and trials (Section 9)

7. EFFECTS OF HYPOTHETICAL DISRUPTIVE EVENTS

In Section 6, estimates were made of the release rates of radionuclides from the underground cavity–chimneys on the basis of upward migration (by convection, diffusion and sorption processes) through fractured rock to either the lagoon or directly to the ocean Pathways which could accelerate this migration were also assessed, including the gradual degradation of the cement used to backfill the test boreholes. This section considers the effects of 'disruptive events' that could circumvent these migration pathways by effectively creating a short circuit which would allow radionuclides to enter the biosphere in greater amounts and/or within a shorter time period

7.1. FRENCH 'WORST CASE' APPROACH

The French Liaison Office (Document No. 4) has provided an assessment of what it considers the 'worst case' release of radionuclides from the underground tests. From measurements and calculations, the total activities of radionuclides in solution in all the cavity–chimneys were estimated. It was then assumed that all of this activity is released into the lagoons at a rate of 10% per month until the source becomes exhausted (approximately one year). The dose rates to a hypothetical group living on the atolls were then calculated on the basis of estimates of the Polynesian diet, assuming exclusive and continuous consumption of lagoon products. With the assumption that water in the lagoons is well mixed, with a residence time of one month, the estimated dose rate ranges from 0.08 mSv/a for Mururoa to 0.15 mSv/a for Fangataufa.

Although the French calculations enable assessments to be made of worst case releases from the cavity–chimneys to the lagoons, they are of limited use for two reasons. First, the calculations overestimate the dose rate from radionuclides in solution because there is no conceivable scenario which could result in such a rapid transfer of all radionuclides in solution from the cavity–chimneys into the lagoons. Second, no consideration is given to possible contributions to the dose from radionuclides in the solid phase, including the plutonium currently in the lagoon sediments

7.2. POSSIBLE DISRUPTIVE SCENARIOS

Seven scenarios are outlined below which could hypothetically lead to increased rates of release of radioactive material. A brief qualitative assessment of the probability and consequences of each scenario is also provided.

7.2.1. Further volcanic activity

Scenario. Reactivation of the volcano that formed Mururoa Atoll leads to major radiological consequences. According to this scenario, all the radioactive material underground would be brought to the surface in the form of molten lava and vapour for release to the atmosphere and deposition in the ocean and lagoon and on the land surface.

Assessment. As described in Section 2, the atolls of Mururoa and Fangataufa are extinct volcanoes that were formed about 11 million years ago from a hot spot in the Earth's interior. As a result of movement of the Pacific Plate in a northwesterly direction at a rate of about 1 km every 10 000 years, the 'hot spot' responsible for their formation is now 70 km southeast of Pitcairn (Bonati and Harrison 1976, Molnar and Stock 1987, Guille et al. 1995). Thus, it is inconceivable that the original hot spot could cause further eruptions at Mururoa and Fangataufa.

There are a number of other hot spots in the South Pacific Ocean (Fig. 9 in Section 2), but the movement of the Pacific Plate is such that none would be near Mururoa or Fangataufa Atoll within a time frame of 1 million years. Within that time, all of the major radionuclides (including ^{239}Pu) will have decayed.

7.2.2. Global warming

Scenario. Global warming raises the level of the Pacific Ocean, leading to slow submergence of the atolls. As the sea level rises, wave action during storms would erode the land, artificial structures and coral formations. It is hypothesized that the lagoons would eventually disappear under water and any release of radionuclides would occur directly to the ocean.

Assessment The highest points on the atolls are no more than 3 m above the mean low water level so any rise in sea level could have a major effect on the atolls. Recent estimates of sea level rise due to global warming by the year 2100 are in the range 15–95 cm (Intergovernmental Panel on Climate Change (IPCC) 1997). In the extreme event that the vast Antarctic and Greenland ice caps were to melt, the rise in sea level could continue at a rate of 3–5 mm/a for several thousand years (Henderson-Sellers and Blong 1989)

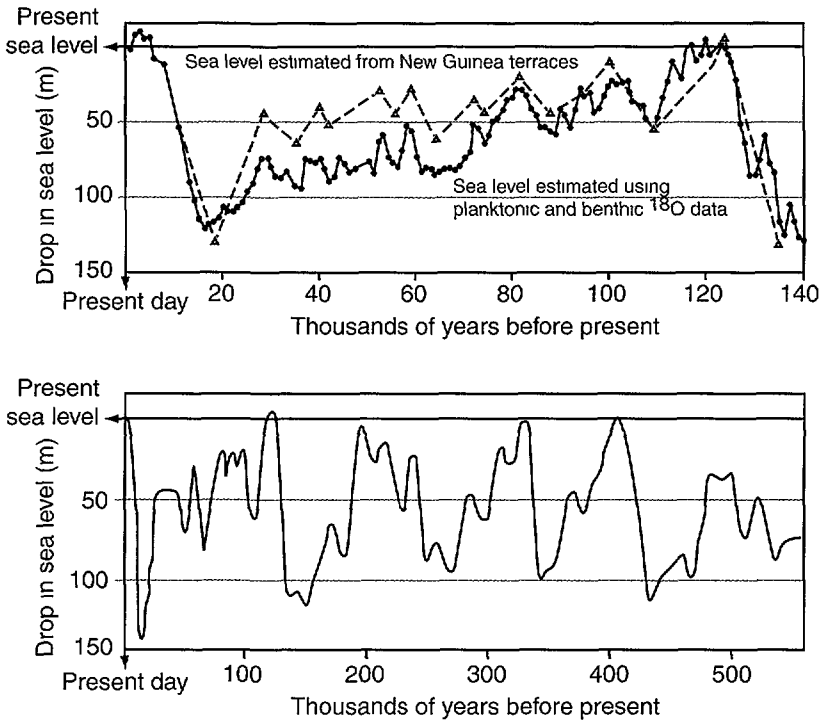


FIG. 100 Variation in sea level over the last 500 000 years (After Shackleton (1987) and Lalou et al (1988).)

Since coral grows best under 2–15 m of water, any rise in sea level would tend to increase the growth rate of coral near the shoreline. The historical record indicates that the accretion rates of coral reefs have been particularly high during periods of rising sea level. The expected rates of sea level rise due to global warming are well within the range of growth rates of healthy coral reefs. However, the responses of reefs to rising sea level are unlikely to preserve the present physical relationship between reef elevation and sea level, so that even rapidly accreting reefs may be less effective as wave barriers. As a consequence, sedimentation and erosion rates are likely to change, thus causing an impact on shoreline structures (Wilkinson and Buddemeier 1994). This scenario could lead to more rapid transfer of plutonium currently in the lagoons to the ocean.

The effects of sea level rise as described above will have no significant impact on the release of radionuclides from the cavity–chimneys However, the changes to shoreline structure are likely to make atolls less suitable for habitation, so that the existence of hypothetical groups on Mururoa, Fangataufa or nearby atolls would be less plausible.

Thus, while a rise of sea level due to global warming is possible within the next hundred years, it would have little impact on the radiation dose to humans.

7.2.3. Glaciation

Scenario. The sea level falls as a result of increasing glaciation. The lagoons dry up and the atolls become islands large enough to support a permanent population. The drying of the lagoons increases the number of pathways by which humans may be exposed to long lived radionuclides (particularly plutonium); possible pathways would include resuspension and inhalation of lagoon sediments, consumption of crops grown on land that was previously lagoon sediments, and drinking of contaminated groundwater from freshwater lenses under the atolls when the sea level has dropped by 100 m.

Assessment. Glaciation periods are generally attributed to periodic variations in the Earth's orbit around the Sun, as originally proposed by Milankovitch (1941). Three factors with varying periodicity have been identified (Dawson 1992): changes in orbital eccentricity (period 96 000 years), changes in the inclination of the Earth's axis of rotation (period 41 000 years) and 'wobbling' of the axis (period 22 000 years). The combined effects of these three processes result in the complex periodicity shown in Fig. 100.

On a geological timescale, ice ages are fairly frequent the last one began about 30 000 years ago and lasted 12 000 years. Thus, Mururoa and Fangataufa

Atolls have been subject to sea level changes resulting from many ice ages since their formation. The fall in sea level during the last ice age was about 120 m.

Ice age scenarios have been considered in the safety assessment of nuclear waste disposal (King et al. 1994, Aranyossy et al. 1994). French safety regulations for geological disposal (Direction de la sûreté des installations nucléaires (DSIN) 1991) require assessment of the impact of glaciation after 60 000 years leading to a sea level drop of 100 m and a major (Riss type) glaciation period after 160 000 years.

The next major ice age is unlikely to occur for at least 50 000 years. During this time, the major fission product radionuclides, ^{137}Cs and ^{90}Sr, will have completely decayed However, it is possible that the next ice age will occur before all the plutonium has decayed Accordingly, glaciation could result in some additional radiation dose which could be exacerbated by compounding scenarios, such as an earthquake or human intrusion.

7.2.4. Human intrusion

Scenario Drilling is conducted on the atolls This may be for the purpose of extracting water from boreholes, for identifying natural resources for commercialization, for confirmation of the radioactive inventory or for some other purpose. The drilling operation could lead to exposure of the drilling team and, if the drill holes were not backfilled, a pathway could be created for release to the environment.

Assessment. The geology of the atolls is well known and there does not appear to be any opportunity for economic recovery of minerals or other natural resources. The depth of the tests means that simple forms of human intrusion such as digging or shallow drilling are unlikely to lead to any significant release of radioactive material or exposure to radiation.

For the immediate future, this scenario is considered most unlikely. However, even if every effort were made to maintain records of the tests and even if warning signs were placed on the atolls, it is likely that, in the long term, records would eventually be lost. The effects of human intrusion would be greatest following a fall in sea level, when plutonium contaminated sediments could be present at or near the surfaces of what are now the lagoons.

It is also conceivable that drilling could be undertaken with knowledge of the presence of radioactive material underground. In this case, it is assumed that appropriate precautions would be taken and that the drill holes would be properly backfilled and the public protected from exposure to radioactive material.

7.2.5. Cyclones, tsunamis and storms

Scenario. The atolls are ravaged by extreme weather, which could include cyclones, tsunamis (large ocean waves caused by an underground earthquake) and/or major storms. Damage to the surface of the atolls could be extensive and could result in slides of coral and carbonate rock into the ocean, leading to development of additional pathways for the escape of radioactive material.

Assessment. Extreme weather events, including cyclones, are not infrequent in French Polynesia. The frequency of major cyclones coming close to the atolls is about one every ten years (Lachenaud 1986) However, during the El Niño year of 1982, five cyclones hit the Tuamotu Archipelago (Dupon 1986). If a cyclone were to directly hit a small atoll, such as Mururoa or Fangataufa, it could wipe out all inhabitants.

Although cyclones, tsunamis and storms can have a major effect on reef structures and human populations, it is difficult to envisage them having a major effect on the release of underground radioactive material The volcanic zone in which the tests were conducted will not be affected by weather no matter how extreme. It is feasible that extreme weather could affect the carbonate and coral regions, which contain some radioactive material at present and could contain more in the future owing to radionuclide migration. Extreme weather could also trigger a rock slide and hasten the transfer of plutonium in lagoon sediments into the ocean. The transport of sediments from the lagoons by storms is considered in Section 8.

7.2.6. Major earthquake

Scenarios. A number of scenarios are conceivable based on the effects of a major earthquake. One such scenario involves the fracturing of either Mururoa or Fangataufa Atoll through the backfilled boreholes and cavity–chimneys, with the consequent exposure of a significant fraction of the radioactive inventory to the marine environment. In another scenario, an earthquake is hypothesized to cause the side of the atoll to slough off into the ocean, accelerating the release of any radioactive material in the carbonate zone.

Assessment. French Polynesia is an area of very low seismic activity (Fairhurst et al. 1998). The occurrence of a major earthquake is highly unlikely but cannot be excluded. An earthquake will tend to propagate along natural or artificial fractures and, hence, is likely to enlarge any fractures caused by the testing The most likely effect of an earthquake would be to trigger a slide

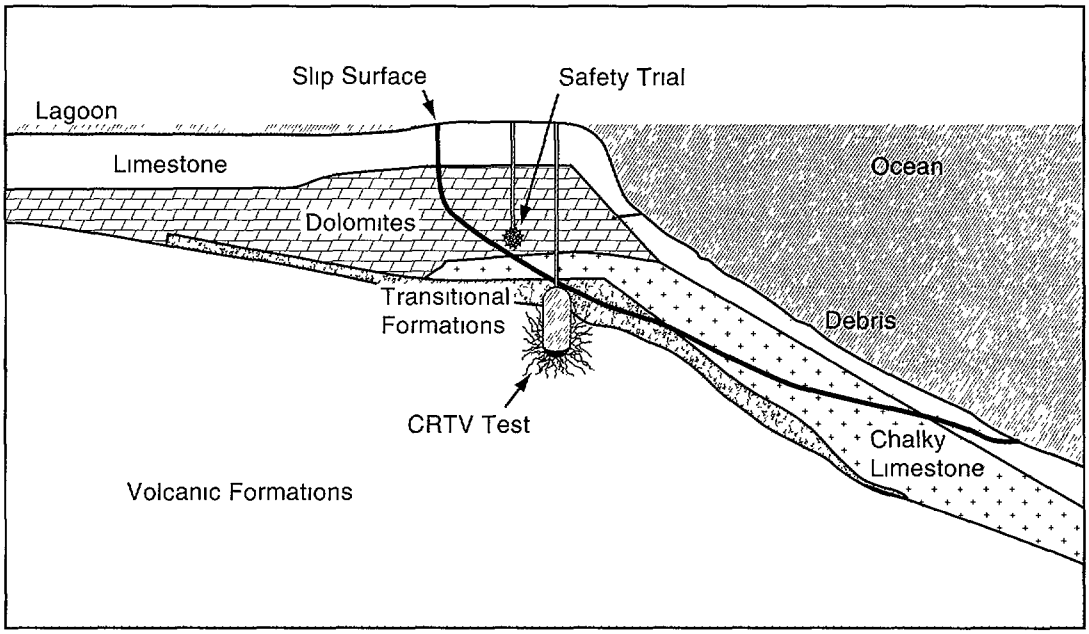


FIG. 101 Hypothetical slide of carbonate rock leading to release of radioactive material.

in the carbonate zone. The consequences of such a slide are assessed in Sections 7 2.7 and 7.3 1

7.2.7. Slide of carbonate rock

Scenario. Nuclear testing has caused some fissures within the carbonate zone of the atolls In this scenario, a large slide of coral and carbonate rock occurs either spontaneously or as a result of an earthquake or extreme weather The hypothesized slide is assumed to occur preferentially along zones weakened by the tests, thus leading to direct exposure of radionuclide bearing material to sea water

Assessment. The coral and carbonate rocks that form an atoll are relatively weak structures that are naturally susceptible to weathering processes The Tydée test in July 1979 triggered a number of rock slides with a total volume of 360 million cubic metres in the southwestern region of Mururoa (French Liaison Office Document No. 7). The report of the Cousteau Mission (Cousteau 1988) concluded that nuclear testing had accelerated the ageing of the coral crown and that the risk of further collapses in the south zone could not be excluded.

The possible effect of fissures, subsidence and other test induced damage on the integrity of Mururoa Atoll has been described in detail in Section 6 2.2.3. It was concluded that there was a risk of a slide in the carbonate zone of the atoll, especially in the north zone, where chalky carbonate rocks are present and where creep continues (French Liaison Office Document No. 7).

In order to release radioactive material, any rock slide would have to intersect areas where radionuclides are deposited. Since most of the radioactive material resides in the volcanic zone, a slide within the carbonate zone would expose only a small fraction of the radionuclides underground

7 3. CREDIBLE DISRUPTIVE EVENTS

On the basis of the preliminary assessments presented above, it is concluded that two of the scenarios are credible and could give rise to some increase in radiation exposure:

— Slide of carbonate rock
— Sea level fall due to glaciation.

Other scenarios either are not feasible or would result in increased radiation dose rates only if taken in combination with the more credible disruptive events mentioned here. The two credible scenarios are discussed below along with estimates of possible releases of radionuclides. The estimates of dose rates

associated with these postulated events are discussed in Section 9.

7.3.1. Rock slide

Figure 101[8] depicts a hypothetical major slide of coral and carbonate rock from the northern sector of Mururoa Atoll (Area 1) due to either an earthquake or extreme weather conditions. Area 1 was chosen because of its known structural weaknesses (Figure 58) and because it was the site of a number of safety trials and seven of the 12 CRTV tests where the chimney penetrated into the carbonate zone. It is assumed that the slide intersects the chimney of one CRTV test with a yield of 5 kt and the zone of one safety trial containing 3.7 kg of plutonium. It is further assumed that all the plutonium from the safety trial and radioactive material in the cavity–chimney water and rubble from the CRTV test are released instantaneously into the ocean. (Release from the lava will not be important in the short term because it is controlled by the slow rate of the leaching process.) This is a highly pessimistic scenario because of:

— The low probability of a slide extending to the base of the carbonate formations.
— The low probability of a slide intersecting both a CRTV test and a safety trial [9]
— The unlikelihood of instantaneous dissolution of radionuclides In reality, dissolution of plutonium oxide and hydroxide from a safety trial would not be instantaneous and it is highly likely that most of the plutonium would be retained on the solid phase, which would sink to the bottom of the ocean. Similarly, it is likely that only a small fraction of the ^{137}Cs and ^{90}Sr on the rubble from a CRTV test would be released immediately

The activities of radionuclides released in this scenario would depend on the time of the rock slide. Again, it is assumed pessimistically that this occurs in the near future so that the decay time between the test and the release is about thirty years. The calculated values (rounded upwards) for the release of key radionuclides under such conditions are given in Table XLIX It is assumed that this release will be into the surface layers of the ocean (Section 8).

TABLE XLIX. ASSUMED RADIONUCLIDE RELEASE (TBq) FROM A HYPOTHETICAL SLIDE OF CARBONATE THAT INTERSECTS A CRTV TEST CAVITY–CHIMNEY AND A SAFETY TRIAL CAVITY

Radionuclide	Release
^{3}H	1000
^{90}Sr	10
^{137}Cs	30
$^{239+240}Pu$	10

The concentrations at various locations in the South Pacific arising from such a rock slide are estimated in Section 8 and the dose implications are presented and discussed in Section 9.5 3.1

7.3.2. Glaciation

In this scenario, an ice age is assumed to begin 50 000 years in the future. Because of a large increase in size of the polar ice caps, it is assumed that this will lead to a worldwide drop in sea level of 100 m. Under such conditions, sea water will drain from the lagoons; in the case of Mururoa, the lagoon has a maximum depth of 55 m. It is further assumed that the emerged island (Mururoa, say) is inhabited and that crops are grown on land contaminated with plutonium. Although plutonium is being lost from Mururoa lagoon at a rate of about 0.03%/a as a result of natural leaching from the lagoon sediments and dispersion of fine sediment particles, the rate of loss has decreased rapidly over the last decade for reasons that are not fully understood (Sections 4.3.2.3 and 8 4) It is assumed, pessimistically for the purposes of this analysis, that no plutonium is lost from Mururoa lagoon over the next 50 000 years apart from that (approximately 75%) which will decay Therefore, there would be about 1.3 kg of plutonium distributed in finely divided carbonate sediments. It is likely that these sediments would be progressively covered owing to natural sedimentation processes.

Exposure to plutonium through inhalation of dust or through the food chain is considered the most probable pathway to humans under this scenario. The burial of

[8] Although Fig 101 is based on fig 30 of French Liaison Office Document No 7, the positions of the CRTV test and safety trial are hypothetical. The French Liaison Office has indicated that no safety trials were carried out in the region on the northern rim of Mururoa where slip zones have been identified

[9] The safety trials were carried out at depths of at least 280 m and outside the current area of instability, according to information provided by the French Liaison Office

plutonium by sedimentation processes will reduce the impact of this pathway. Other radionuclides either will have decayed to negligible levels or will present a far lower safety hazard than the plutonium.

Another possible exposure route during glaciation periods would be the drinking of plutonium contaminated water from boreholes drilled into the carbonate rock. During periods of sea level fall, freshwater lenses are known to form within the carbonate zone of atolls (indeed these are responsible for the dissolution processes that result in the formation of the karsts). The highest plutonium concentrations would be encountered in the vicinity of the cavities of the four safety trials without nuclear yield because, in these, no lava was formed in which the residual plutonium would be immobilized. Although the precise location of these cavities is not known to the Study team, the French Liaison Office has stated that all seven safety trials in the carbonates were conducted under the northern rim of Mururoa at depths greater than 280 m and within 300–500 m inland from the outer edge of the rim measured from an underwater cliff face at present 150 m deep The position of the boundary of the freshwater lens within the carbonates was calculated for sea level drops of 100 and 150 m (Technical Report, Vol. 4). It seemed likely that for a 150 m drop, the safety trial cavities could be within the fresh water. This appeared less likely for a 100 m drop, but for the purposes of this scenario it was assumed that potable water could be present in the vicinity of such a cavity.

The inventory of plutonium within the carbonates in 50 000 years' time may be estimated from the analysis of plutonium release rates from the carbonates presented in Section 6.6.6 From the predicted plutonium release rates shown in Fig. 99, and recalling the assumption that 0.12 and 5%, respectively, of the inventory in the lagoon-side and ocean-side carbonates are released each year, the total inventory of plutonium in the carbonates is estimated to be about 0.1 TBq; on the basis of this model, most of the plutonium from the safety trials would be released within 20 000 years The total volume of fresh water in the Mururoa carbonates is estimated to be 6×10^9 m^3 (Technical Report, Vol. 4). In this analysis, the plutonium was assumed to be transported through the karstic channels with $K_d = 0$. The average concentration of plutonium in the fresh water is therefore about 17 Bq/m^3.

The above estimate is based on parameters which were chosen to be conservative in the sense that release to the biosphere is maximized. For the glaciation scenario, assumptions that maximize retention of plutonium in the carbonates also need to be considered. In this case, the most conservative approach is to assume that all plutonium released to the carbonates is retained within the carbonates until it decays. Each safety trial contained 10 TBq, which will have decayed to 2.5 TBq in 50 000 years. Since there are seven such trials, the total plutonium inventory is 17.5 TBq (say, 20 TBq).

The cumulative plutonium release to the carbonates from nuclear tests in the volcanics can be estimated by integration of Fig. 82 (after subtracting the effects of the safety trials, which are responsible for the peak at about 6000 years). After allowing for decay, the cumulative amount of plutonium from these sources is estimated to be about 30 TBq. The maximum total inventory in the Mururoa carbonate formations after 50 000 years would therefore be about 50 TBq.

This inventory will only be retained within the carbonates if the K_d for plutonium is reasonably high. Assuming a K_d value of 0.5 m^3/kg (500 L/kg), a porosity in the carbonates of 0.3 and a carbonate density of 2200 kg/m^3, it can be readily shown (from Eq. (14) in Section 6) that only about 0.04% of the plutonium is in solution; the remainder is sorbed on the solid phases. Under these conditions, the average concentration of plutonium in solution is about 3 Bq/m^3 ($50 \times 10^{12} \times 4 \times 10^{-4}/(6 \times 10^9)$).

This average concentration would be the most appropriate value for calculations of dose if a large number of production wells were drilled into the carbonates. However, if a borehole were to be drilled into the region near one of the four safety trials that did not go critical, the concentration could be much higher The maximum concentration in the plume from such a safety trial cavity is the saturated solubility, which has been assumed to lie between 10^{-9}M and 10^{-7}M, or from 6×10^5 to 6×10^7 Bq/m^3 (Section 6.4.2.3). However, the volume of porous rock containing water at this concentration after 50 000 years is estimated to be only 200 m^3 per non-critical safety trial. With a porosity of 0.3, this represents a very small fraction of the total volume of fresh water in the carbonates of 6×10^9 m^3.

In order to encounter a concentration near the solubility limit, a borehole would have to be drilled some 300 m deep into the carbonates. This is considered unlikely since fresh water could be extracted at much shallower depths and the risk of striking saline water increases with depth Moreover, in the unlikely event that an open borehole was drilled into the region of a plume, any extracted water would be diluted by water from karstic zones flowing into the borehole (French Liaison Office Document No. 9). The extent of such dilution is a matter for conjecture but is probably large. At any rate, the dose received from drinking water at those concentrations should be assessed against the very low chance of its occurrence.

The dose rates that could be received by drinking water from boreholes sunk into the carbonate formations at Mururoa are calculated in Section 9.5.3.2. These calculations consider predicted average plutonium concentrations in the water as well as the probability of drinking water with much higher concentrations. The corresponding concentrations beneath Fangataufa Atoll would be much lower because of the small number of nuclear tests performed there and the absence of any safety trials.

8. TRANSPORT OF RESIDUAL RADIOACTIVE MATERIAL THROUGH THE MARINE ENVIRONMENT

8 1. INTRODUCTION

Section 4 summarized the concentrations and locations of residual radioactive material currently in Mururoa and Fangataufa Atolls, resulting largely from the French atmospheric tests and safety trials. Section 6 described the modelling of the transport of radionuclides from the underground tests and trials through the geosphere of the atolls, and the estimation of the release rates of radionuclides from the geosphere into the lagoons and directly into the ocean. In Section 7, possible disruptive events were discussed, and it was concluded that a slide of carbonate rock that could increase the release of radionuclides into the ocean was credible though extremely unlikely. Estimates of radionuclide releases were made for a highly pessimistic scenario in which the radioactive material from one safety trial and one CRTV test in the north zone of Mururoa Atoll was instantaneously released into the ocean by such a rock slide.

This section discusses the modelling of the transport of radionuclides through the marine environment after they are released from lagoon sediments or the geosphere, including mixing within the lagoons, discharge into the ocean and transport to the shores of neighbouring islands and distant continents. For the purposes of the modelling, the area around the source of radioactive material (i.e. the point at which radionuclides are released into the marine environment) was divided into three major zones:

(a) Near field (the lagoons),
(b) Regional field (broadly, the area of French Polynesia);
(c) Far field (the South Pacific beyond the regional field).

Figure 102 is a flow chart showing the tasks required to assess the radionuclide transport through the marine environment The methodology adopted in the Study can be summarized as follows:

(1) A model of the mixing of water in the lagoons was developed. This model was used to estimate the radionuclide concentrations in the lagoons for given releases from underground into the lagoons, and the flow rates of radionuclides from the lagoons into the surrounding ocean.
(2) The rates of release of radionuclides from the lagoon sediments were assessed, leading to estimates of the release rates of ^{3}H, ^{90}Sr, ^{137}Cs and plutonium from the lagoons to the ocean as a function of time.
(3) A model was developed to predict the movement of sediment between the lagoons and the ocean. Estimates were made of the amount of sediment, and the corresponding quantity of plutonium, leaving the lagoons annually under average weather conditions, or with a severe storm.
(4) Three compartment models were used to model dispersion of radionuclides in the regional field. These models cover different areas with different resolutions, and each has particular strengths and weaknesses. Taken together, they give an indication of the likely uncertainty in the dispersion estimates, and improve the robustness of the final conclusions.
(5) Transport and dispersion in the far field were assessed using a predictive model of world ocean circulation.

The outputs from these models are estimates of radionuclide concentrations in the ocean as a function of time and location. Section 9 describes how these concentrations were used to estimate doses to real and hypothetical people at various locations and times in the future.

8 2. RADIONUCLIDE INVENTORY IN LAGOONS

As discussed in Section 4, the radioactive materials currently in the lagoons are predominantly from atmospheric nuclear weapon tests in the late 1960s, specifically three barge tests at Mururoa and one at Fangataufa. The five atmospheric safety trials on Mururoa also contributed to the plutonium content of the sediments in Mururoa lagoon.

The radionuclides were mainly concentrated in sediments around the zero points of the tests ($^{239+240}Pu$ distributions are shown in Figs 41 and 42 in Section 4) and in a sandbank near the Colette motu of Mururoa where the safety trials were carried out Four main hot spots were identified in Mururoa lagoon, and one in Fangataufa lagoon.

Two of the Mururoa hot spots are at the zero points of the Aldébaran and Sirius barge tests, both in the Dindon area. The maximum concentrations of $^{239+240}Pu$

at the two spots — 40 and 20 kBq/kg dry weight, respectively — were observed at a depth of about 1 m. The highest concentrations of gamma emitting radionuclides were observed at the Sirius site: up to 5 kBq/kg ^{137}Cs, 4 kBq/kg ^{155}Eu and 2 kBq/kg ^{60}Co. At the Sirius site, high concentrations of plutonium isotopes, ^{241}Am and gamma emitters were found in sediment at depths of up to about 3 m. The third hot spot identified in Mururoa lagoon is in the Denise area, resulting from the Arcturus barge test, where the $^{239+240}$Pu concentrations observed were up to 20 kBq/kg.

The other hot spot in Mururoa lagoon is due to safety trials in the Colette area. Concentrations of up to 1 MBq/kg $^{239+240}$Pu, 70 kBq/kg ^{241}Am and 11 kBq/kg ^{238}Pu were measured in sediments collected from the Colette sandbank (Figs 32 and 33 in Section 4).

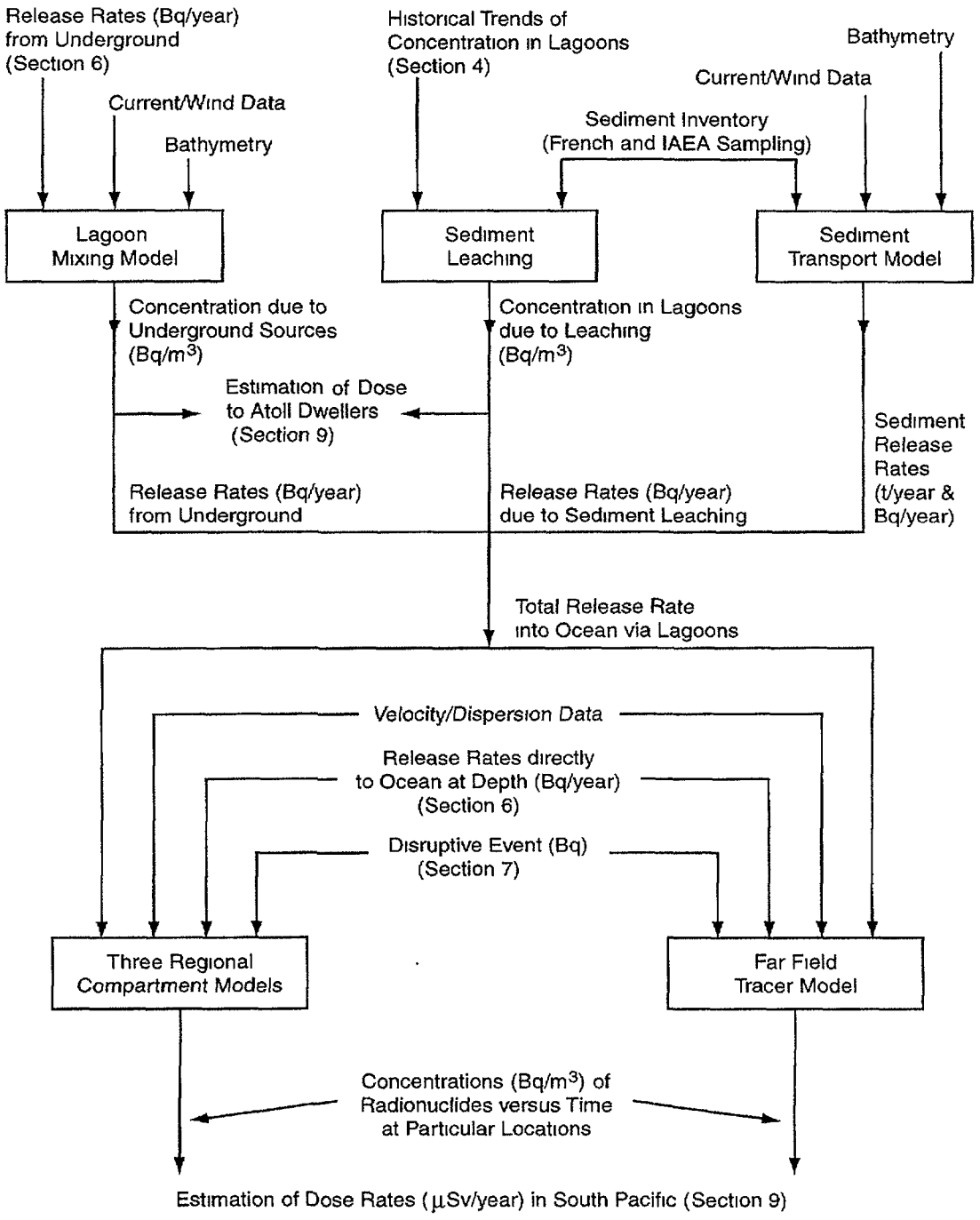


FIG 102. Assessment of radionuclide transport through the marine environment

TABLE L. RADIONUCLIDE INVENTORIES (GBq) IN LAGOONS IN 1996

Radionuclide	Mururoa		Fangataufa		Total
	Water	Sediment	Water	Sediment	
^{3}H	1 700		100		1 800
^{90}Sr	10	[a]	1.4	[a]	[a]
^{137}Cs	10	800	1 5	200	1 000
$^{238+239+240}Pu$	2	20 000	0 4	10 000	30 000
^{241}Am	0 02	800	0.005	400	1 200

[a] There was limited information available to provide reliable estimates, but ^{90}Sr inventories are considered to be one to two times the ^{137}Cs inventories on the basis of this information.

The concentrations of $^{239+240}Pu$ in the top 5 cm of Mururoa lagoon sediment vary from less than 20 Bq/kg in the southern part of the lagoon and about 50 Bq/kg in the central part to 6 kBq/kg at Denise, 17 kBq/kg at Dindon and 400 kBq/kg at Colette. Gamma emitters follow a similar pattern but their concentrations are at least an order of magnitude lower and they are virtually absent from the Colette sandbank Few data are available on the concentrations of ^{90}Sr in sediments, but information provided by the French Liaison Office (e.g Document No. 1) indicates that they are of the same order as (possibly a factor of 2 higher than) ^{137}Cs concentrations.

The main hot spot in Fangataufa lagoon is due to the Rigel barge test, performed in the Frégate area Plutonium concentrations of about 10 kBq/kg ($^{239+240}Pu$) were observed at depths of up to 1 m (^{241}Am, ^{137}Cs and ^{60}Co concentrations were about 400 Bq/kg). The concentrations of $^{239+240}Pu$ in the top 5 cm of sediment vary from about 10 Bq/kg in the northern part of the lagoon to 4 kBq/kg in the Frégate area.

Radionuclide concentrations in lagoon water are orders of magnitude lower than in sediment, and in the case of ^{137}Cs and ^{90}Sr, where the current levels are about 2 Bq/m^3, are generally close to global fallout levels in the open ocean For $^{239+240}Pu$, the concentration of the soluble phase in the lagoons is about 0.3 Bq/m^3, which is of the order of 100 times the global fallout levels in the open ocean. The highest concentrations observed in the Study's sampling campaign in 1996 were for ^{3}H (up to 800 Bq/m^3), clearly showing east–west and top–bottom gradients and suggesting leakage of ^{3}H from underground sources. A similar top–bottom gradient was also observed for ^{90}Sr, although it is not as conclusive as for ^{3}H.

Radionuclide inventories in water and sediments are given in Tables XIV and XV (Mururoa) and Tables XVII and XVIII (Fangataufa) of Section 4 and are summarized in Table L for those radionuclides which are of interest from a modelling point of view (^{3}H, ^{90}Sr, ^{137}Cs, $^{239+240}Pu$ and ^{241}Am). The inventories in water include contributions from the oceanic background, which constitute about 60 and 90% of the inventories of ^{90}Sr and ^{137}Cs, respectively. Inventories in Mururoa sediments are about twice those in Fangataufa sediments.

The total inventory of $^{238+239+240}Pu$ in both lagoons is estimated to be about 30 TBq, with about 2 TBq of ^{3}H and 1 TBq each of ^{241}Am and ^{137}Cs. These estimates are approximate because of the highly uneven distributions of radionuclides in the sediment and of sediment in the lagoons. It is clear from depth profiles (e.g. Fig. 34 in Section 4) that there will be significant amounts of radioactive material at depths greater than those for which concentrations have been measured. On the other hand, the lagoon bottoms are not uniformly covered by sediment: about 30% of the bottom of Mururoa lagoon and 50% of the bottom of Fangataufa lagoon consist of rock with little or no sediment cover. The estimates of radionuclide inventories given in Table L are probably within a factor of 3 of the real values.

8.3. NEAR FIELD MODELLING

8.3.1. Flow and mixing in the lagoons

A model of water flow and mixing in the lagoons is a prerequisite for the interpretation of results from sampling campaigns in the lagoons. A model is also needed to estimate radionuclide concentrations in the lagoons from estimates of release rates from underground, and to estimate radionuclide transfer rates from the lagoons into the ocean on the basis of lagoon concentration data.

The basic information required to model the lagoons is physical data on depth, tidal currents and wind velocities. This information was provided by the French Liaison Office (Document No 11 and supplementary data). Figure 103 shows bathymetric charts for Mururoa

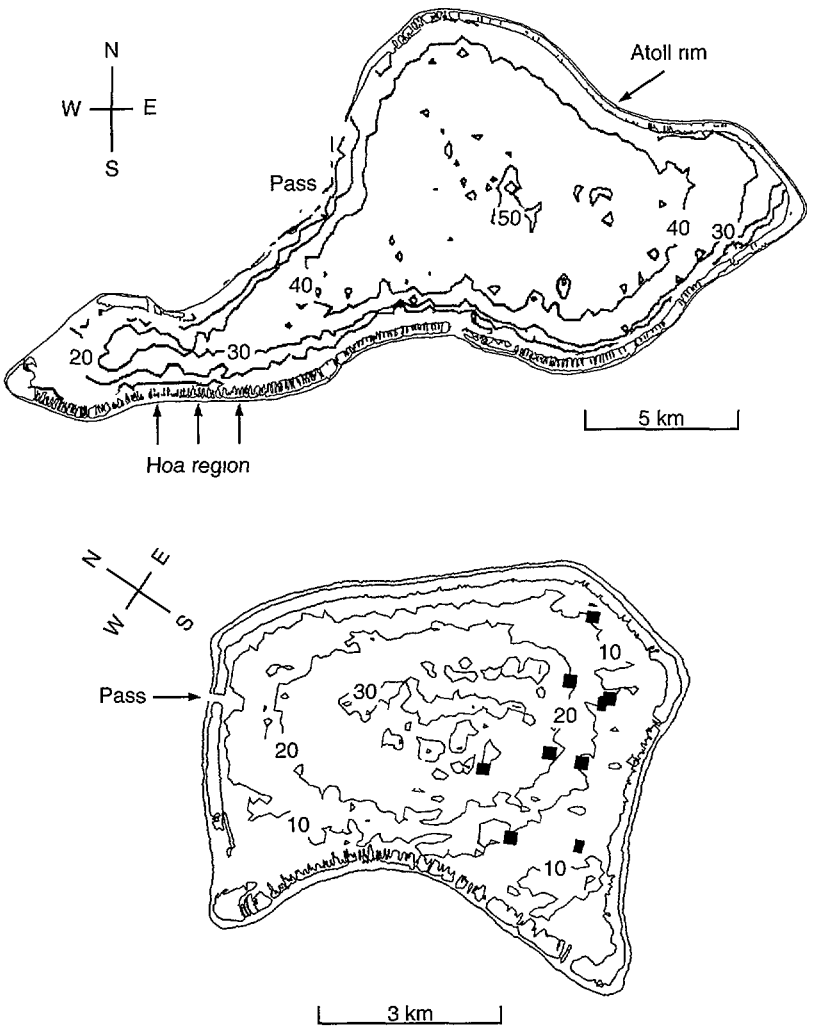


FIG. 103 Bathymetry of Mururoa and Fangataufa lagoons The isobath interval is 10 m For Fangataufa, the black rectangular areas represent large coral patches, which were considered as impermeable for purposes of numerical simulation.

and Fangataufa lagoons. Using these data, the volume and average depth of water in the lagoons can be calculated (Table LI). The average depth of Mururoa lagoon is about twice that of Fangataufa lagoon.

The pass in the rim of Mururoa Atoll is about 4 5 km wide and about 8 m deep on average. Because of this large entrance, there is only a small phase difference (about 5 min) between the tides in the ocean and those in the lagoon. Current velocities in the pass are less than 0.3 m/s. On average, the flood tides bring about 100 million cubic metres of water through the pass into the lagoon each day, while the ebb tides give a daily outflow of 150 million cubic metres (French Liaison Office Document No. 11). The difference between these flows — some 50 million cubic metres per day — is the inflow through the hoas on the southwestern rim (Fig. 103) during flood tides.

TABLE LI. CHARACTERISTICS OF LAGOONS

	Mururoa	Fangataufa
Volume (m^3)	$4\,7 \times 10^9$	$5\,5 \times 10^8$
Surface area (m^2)	$1\,4 \times 10^8$	$3\,6 \times 10^7$
Mean depth (m)	33	15

The Fangataufa pass is an artificial channel, 100 m wide with an average depth of 8 m. The tide in the lagoon is about 20 min behind that in the ocean owing to the low water exchange through the narrow pass. Only limited measurements have been made of the flow in the pass, but average currents are about 0.6 m/s. The daily outflows and inflows through the pass are estimated to be 42 million and 33 million cubic metres, respectively (French Liaison Office Document No. 11). The

estimated flow through the hoas is therefore 9 million cubic metres per day.

The wind plays a major role in circulation and mixing in the lagoons. The surface water moves in the direction of the wind, and as a result water accumulates on the windward coast, creating a slight difference in water level which causes flow in the opposite direction in the subsurface layers. The velocities at the bottom of the lagoon are very low and therefore difficult to measure (French Liaison Office Document No. 11).

8.3 1.1. Residence and turnover times

A simple model was developed by the Study team to determine the residence time of water in the lagoon (Tartinville et al. 1997) The model does this by representing the behaviour of a 'passive tracer' — a radionuclide which behaves in the same way as a small 'parcel' of water — and can therefore also be used to model the residence time of such radionuclides Of the radionuclides of interest in the Study, only tritium would be expected to behave strictly as a passive tracer, but the model may be assumed to provide an adequate representation of the behaviour of the dissolved fraction of the other radionuclides of interest.

It is assumed that the dilution in the Pacific Ocean is sufficiently strong that a tracer parcel reaching the pass effectively leaves the lagoon permanently. Thus, the tracer content of a lagoon depends on the rate at which the source of the tracer releases material into the lagoon and the rate at which the lagoon water is renewed. The rate of renewal may be characterized by:

— *Residence time·* for a given point in the lagoon, this is the time required by a water parcel, initially located at that point, to leave the lagoon through the pass; or
— *Turnover time (θ):* this is the average over the lagoon of the residence times.

Thus, the residence time is location dependent whereas the turnover time is not The turnover time is a key parameter in assessments of the exchange rate of water and suspended matter, and hence of dissolved and scavenged radionuclides, between the lagoons and the adjacent open ocean.

Using a simple zero dimensional model it can be shown (Deleersnijder et al. 1997) that, if a tracer enters the lagoon at a constant rate S, the mean equilibrium concentration of the tracer in the lagoon is given by:

$$\bar{c} = c_b + \frac{\theta S}{V} = c_b + \frac{\theta Q}{V} \qquad (24)$$

where c_b represents the background concentration of a given radionuclide (Bq/m^3), V is the volume of the lagoon (m^3) and Q (= S) is a constant, the tracer flux from the lagoon to the Pacific Ocean (Deleersnijder et al. 1997). The available field data do not allow the turnover time θ to be determined simply, so numerical simulations of the flow within the lagoons were needed.

These numerical simulations were carried out using a 3-D model (ASTR) developed at the Institut d'astronomie et de géophysique G. Lemaître of the Université catholique de Louvain, Louvain-la-Neuve, Belgium. The ASTR model consists of two components, a hydrodynamic module and a tracer module. The purpose of the hydrodynamic module is to compute the three components of the water velocity and the eddy diffusivity in each grid box, which are needed to simulate radionuclide transport.

For both atolls, the computational domain is restricted to the lagoon, implying that the pass appears as an open sea boundary. The atoll rims are assumed to be impermeable, except for one hoa region, 5 km in length, located in the southwestern part of the Mururoa rim.

The water circulation in the lagoons is generated by the oceanic tide, the wind stress and, in the case of Mururoa, the hoa inflow. These 'forcings' were implemented in the model as boundary conditions to the hydrodynamic equations. Tartinville et al (1997) conducted a sensitivity analysis which revealed that the surface wind stress in Mururoa lagoon is clearly the dominant forcing It was also shown that the hydrodynamic processes which are likely to have the largest influence on long term tracer transport are the horizontal velocity (averaged over depth and over a whole tidal cycle) and the shear diffusion (Bowden 1965). These considerations are also believed to hold true for Fangataufa.

To determine the residence time, a large number of tracer parcels were uniformly distributed in each lagoon at the start of the model simulation. As 'time' (as represented in the model) progressed, the trajectories of these parcels were constructed by means of a Lagrangian transport algorithm (Hunter et al 1993, Tartinville et al 1997). By determining the time at which each tracer parcel left the lagoon, the residence time was computed as a function of position. The turnover time was then calculated.

To assess the extent to which the turnover time depends on the variability of the flow forcings, a series of numerical simulations with different boundary conditions was carried out. For Mururoa lagoon, the turnover time varied from 44 d, for summer conditions with a southeasterly wind blowing at 8 m/s, to 164 d for winter conditions with an easterly wind at 5 m/s (Technical

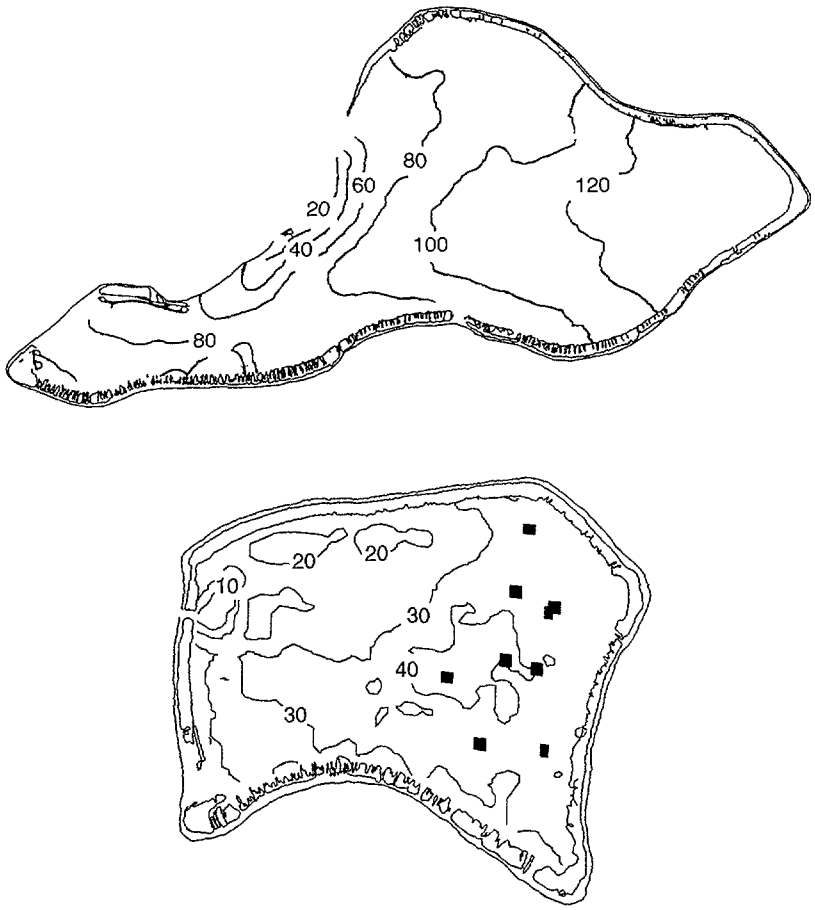


FIG 104. Average of the numerical simulations of the depth mean of the Mururoa and Fangataufa residence times. The contour interval is 20 d for Mururoa and 10 d for Fangataufa. For Fangataufa, the black rectangular areas represent large coral patches, which were considered as impermeable for purposes of numerical simulation

Report, Vol. 5). The turnover times for Mururoa and Fangataufa, averaged over a year, were estimated to be:

$$\theta_M = 98 \pm 37 \text{ d} \quad (25)$$

$$\theta_F = 33 \pm 12 \text{ d} \quad (26)$$

where the 'error' is derived from the standard deviation of the series of calculations of residence time.

The residence time depends only weakly on depth, because vertical diffusion is strong enough that the initial position of a tracer parcel within the water column is of little importance. Therefore, it is sufficient to calculate the depth averaged residence times; these are shown for both Mururoa and Fangataufa in Fig. 104. In broad terms, the shorter the residence time at a given point in the lagoon, the lower the concentration of a passive tracer at this location.

Equation (24) may be used to estimate the average concentration of a tracer in the lagoon if the relevant source is known or, given the mean lagoon concentration, to evaluate the tracer flux to the ocean. The uncertainty in the predictions of Eq. (24) stems from the variability of the turnover time and the error intrinsic in the simplified formulation. According to Eqs (25) and (26), the former induces a relative error of about 40%, while the uncertainty due to the latter is estimated, on the basis of Deleersnijder et al. (1997) and the 3-D tritium transport simulations described below, to be about 20%. Thus, the overall uncertainty affecting the predictions of Eqs (25) and (26) is of the order of 60%. Table LII summarizes the equations used for obtaining the lagoon concentration from a source releasing into the lagoon, and for obtaining the rate of activity release from the lagoon into the ocean on the basis of the concentrations in the lagoon

In developing their worst case scenario, the French scientists (French Liaison Office Document No. 4) calculated concentrations of radionuclides in the lagoon from the 'hydrological half-life', which was estimated to be about one month for both lagoons. Similarly, an average residence time of 23 d for Mururoa lagoon was

TABLE LII. EQUATIONS USED FOR COMPUTING MEAN LAGOON CONCENTRATIONS AND RADIONUCLIDE FLUXES TO THE PACIFIC OCEAN

	Mean lagoon concentration, $\bar{c}$ (Bq/m^3)	Flux to Pacific (= source), $Q = S$ (Bq/a)
Mururoa	$\bar{c} = c_b + (5.7 \pm 3.4) \times 10^{-11} S$	$Q = S = (1.8 \pm 1.1) \times 10^{10} (\bar{c} - c_b)$
Fangataufa	$\bar{c} = c_b + (1.6 \pm 1.0) \times 10^{-10} S$	$Q = S = (6.1 \pm 3.7) \times 10^{9} (\bar{c} - c_b)$

calculated from the ratio of the volume of the lagoon to the average daily inflow (Rougerie et al. 1984, French Liaison Office Document No. 11). Such calculations underestimate the true turnover time because, in most atoll lagoons, a significant fraction of the water that enters the lagoon during the rising tide remains in the vicinity of the pass and leaves with the next low tide (von Arx 1948). Figure 104 shows that the residence time near the pass is very much shorter than for locations further into the lagoon.

The hydrodynamics of Mururoa and Fangataufa lagoons depends — through the forcings applied at the sea surface, at the lagoon mouth and in the hoa region — on the regional meteorology and oceanography, the mean conditions and variability of which are governed ultimately by the Earth's climate. The sensitivity of the turnover time to the forcings suggests clearly that it may be altered significantly by changes in surface fluxes of momentum and in buoyancy due to climate change. Thus, over the next century, the turnover times might vary as a result of climate changes by a factor of about 2. The likelihood of much larger changes in the turnover times, e.g. by a factor of 10, is considered low, unless there is a significant rise in sea level.

8.3.1.2. Estimates of tritium release from underground sources into lagoons

As noted in Sections 4 and 6, there is clear evidence that tritium is being released from the carbonate zone into the water of the lagoons Tritium concentrations at various locations in the lagoons have been monitored systematically for the past decade (French Liaison Office Document No. 3), and independent measurements were carried out during the Study in 1996; the tritium concentrations in the lagoons are consistently above the average background in the South Pacific Ocean (assumed to be about 100 Bq/m^3).

Figure 105 shows a clear correlation between measured tritium concentration at various points in Mururoa lagoon and the estimated residence time at each point. The release rate of tritium into the lagoon can be estimated directly from the slope of the line to be 13 TBq/a.

Table LIII gives the estimated tritium release from underground sources as a function of time. In the calculations, the tritium concentration in incoming water (through the pass or the hoas) was assumed to be the background value, c_b = 100 Bq/m^3. The tritium source from Mururoa has been relatively constant over the last decade at about 20 TBq/a but appeared significantly lower (7 TBq/a) during the Study's survey in 1996. The reason for this lower value could be related to the somewhat rougher than normal weather conditions during the sampling campaign, the cessation of drilling activities in the lagoons (which involved airlifting of underground water containing high concentrations of tritium into the lagoons), and/or the sealing of monitoring wells and unused test boreholes (which could have provided a vertical pathway for transport of tritium from the karstic zones; Section 6.2.3.2).

The Study results for Fangataufa are also much lower than previous estimates, but it should be noted again that lagoon samples were taken under highly

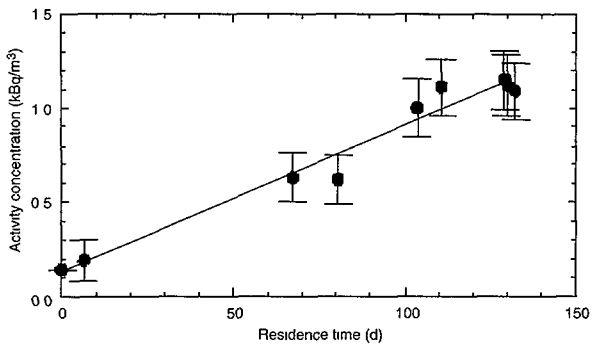


FIG 105. Measured tritium concentration in Mururoa lagoon in 1993 plotted against estimated residence time in the ASTR model. The release rate of tritium to the lagoon estimated from the slope of the line is 13 TBq/a

TABLE LIII. ESTIMATES OF TRITIUM FLUX (TBq/a) AT BOTTOM OF LAGOONS

Year	Mururoa[a]	Fangataufa[b]
1987	14 ± 3[c]	na[d]
1988	24 ± 5[c]	na
1989	25 ± 6[c]	na
1990	36 ± 8[c]	na
1991	23 ± 6[c]	2 4 ± 1.5[c]
1993	22 ± 4[c]	3 1 ± 1.8[c]
1996	7 ± 3[e]	0 68 ± 0.41[e]

[a] Estimates based on the ASTR (3-D) model

[b] Estimates based on the simple, zero dimensional model given in Table LII.

[c] Based on measurements of lagoon water concentrations from the French Liaison Office (Document No 3)

[d] na: not available

[e] Based on Study measurements of lagoon water concentrations

turbulent weather conditions, with water flowing over the lagoon rim at many locations

There is little knowledge of the spatial distribution of the upward flux at the lagoon bottom, so two hypotheses were investigated. The first represented the source by five point sources, located at the points on the lagoon bottom where there were local maxima of tritium activity concentration in the karstic horizons of the carbonates (Section 6). The strength of the point sources was assumed to be proportional to the amount of tritium contained in the corresponding karstic region (French Liaison Office Document No. 9) The second hypothesis tested was that of a uniform upward tritium flux from the lagoon bed.

For each hypothesis, the rate of release of tritium into the lagoon was estimated as the value that minimized the difference between the model results and the field measurements. With both hypotheses, the model predicted variations in tritium concentrations by as much as a factor of 3 between different locations (Fig 106), and the concentration fields predicted were rather similar. This suggests that it is mostly the hydrodynamics which determines the distribution of tritium activity concentration in the lagoon water, a consideration which is in agreement with the basic hypothesis underlying the zero dimensional approach. In all cases, the uniform bottom flux led to computed tritium activity concentrations (shown in Fig. 106) that were somewhat closer to the field data than those obtained with the point sources. The model predicts little variation of concentration with depth over the water column. However, variations in tritium concentration were observed in field measurements performed during the Study, with bottom concentrations always higher than those near the surface, although the differences were often small (Technical Report, Vol. 2, fig 11).

The determination of source terms for radionuclides other than tritium is complicated by other factors, such as sorption processes that could remove a particular radionuclide from the water column and the possible presence of the radionuclide in lagoon sediments as a result of atmospheric tests (Sections 8.2 and 8 4).

8.3.2. Transport of sediments from Mururoa lagoon into ocean

As indicated in Section 8.2, the sediments are effectively a source of radioactive material, mainly isotopes of plutonium, from the atmospheric tests (Table L). An

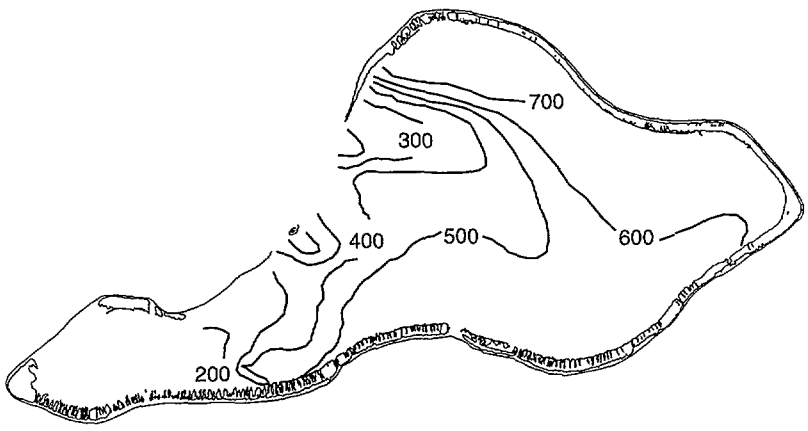


FIG 106 Depth averaged residual tritium activity concentration (Bq/m^3) in Mururoa lagoon simulated with a uniform bottom flux amounting to a total release rate of 10^{13} Bq/a.

understanding of the fate of these sediments is important to any assessment of their radiological impact.

In the Study, a 3-D hydrodynamic circulation model and a sediment transport model (Rajar and Cetina 1997) were used to estimate water and sediment fluxes from Mururoa lagoon to the open ocean. Stratification was not taken into account in the simulations Data on the bottom sediment grain size distribution were taken from Masse and Musa (1988). Two cases were simulated: normal and storm conditions.

8.3.2.1. Normal conditions: Effect of tides and trade winds

For the purposes of the analysis, 'normal' conditions are defined for Mururoa as a tide with an amplitude of 0.3 m and a period of 12.4 h, and an easterly trade wind of 8 m/s. The hydrodynamic simulation involved calculation of currents and heights of waves. The resulting velocity fields were very similar to the corresponding depth averaged fields given by Tartinville et al. (1997). The theoretical wave height increases from east to west and reaches a maximum value of nearly 1 m near the western coast of Mururoa lagoon.

Near the pass, the current velocities are of the order of 0.2 m/s. Most of the sediment resuspension is in the vicinity of the pass, although there is some in the shallow water along the southern coast. During the ebb tide, some sediment from the lagoon bottom is resuspended and transported out of the lagoon. The simulation results show that, during one tidal cycle, 110 t of sediment is washed out of the lagoon. This results in a rate of outwashing of sediments due to wind and tide of about 8×10^4 t/a (about 3 kg/s) over the whole cross-section of the pass.

This mass of 8×10^4 t of sediment corresponds to an erosion rate of 0.4 mm/a over the whole lagoon. This value is given only for illustrative purposes, because the erosion would not be uniformly distributed over the lagoon, and some sediments are also formed and deposited by various processes, including wave action on coral.

8.3.2.2 Storm conditions

The forcing conditions for the case of storm conditions were determined mainly from Lachenaud (1986) The 'maximum historically probable cyclone' in the region of Mururoa is defined as a northwesterly wind of 80 knots (150 km/h, or 42 m/s). The duration of maximum wind speed is estimated from the information on the travel velocity of the cyclone (15 knots, or 28 km/h) and the diameter of the cyclone centre (40 miles (~75 km), according to Lachenaud (1986)), which gives 2.7 h This has been increased to 4 h to take into account rough weather accompanying the passage of the cyclone.

The frequency of such cyclones is estimated from Lachenaud (1986) to be about one every ten years. Although the statistical data show a smaller frequency than this over the last 100 years, there were five cyclones in the first half of 1983 in the Tuamotu Archipelago (not all of them touching Mururoa). Gabrie and Salvat (1985) estimate the frequency in the region of Mururoa to be "four to eight per century".

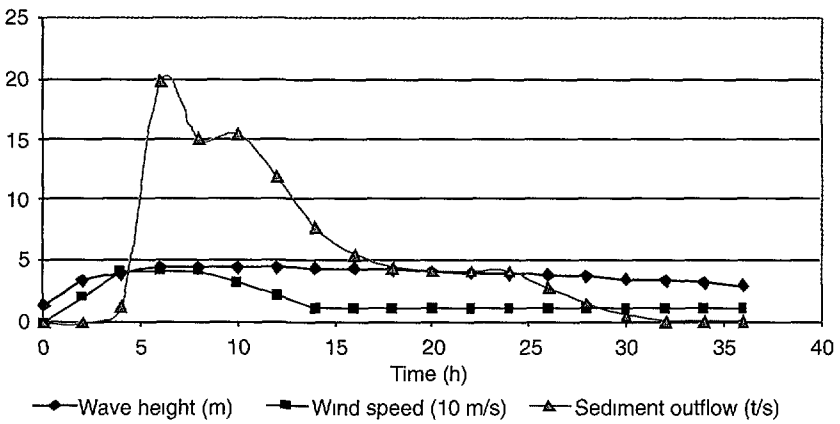


FIG 107 Mururoa lagoon· wave height, wind speed and sediment outflow through the pass storm case (wind speed 150 km/h)

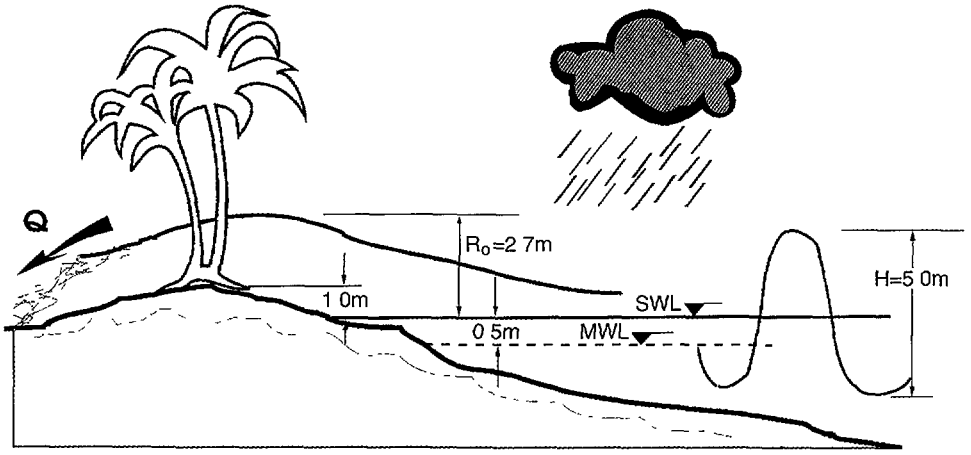


FIG 108 Parameters for computation of overflow over the rim of Mururoa Atoll

Flow through pass

The 3-D hydrodynamic simulation of a storm event predicted surface water velocities of about 1.3 m/s and maximum depth averaged velocities of the order of 40–50 cm/s, which agree approximately with the values given by Lachenaud (1986) Under these conditions, wave height in the ocean is about 10 m and in the central part of the lagoon is about 5 m. These values are used in the hydrodynamic and sediment transport simulations

The distribution of the ratio of bottom shear stress to critical shear stress shows that the resuspension of sediments will occur close to the pass and the southeastern rim. The final model results are shown in Fig. 107. Integrating the sediment discharge over the whole duration of the storm gives a mass of sediment washed out of the lagoon through the pass during one storm event of 7.2×10^5 t.

Flow over southeastern rim of atoll

For northwesterly winds of 150 km/h over Mururoa lagoon, the height of the waves along the southeastern and southern rim of the atoll was estimated to be 5 m (Lachenaud 1986). The height of the rim above the mean water level is between 1 and 3 m It is assumed that a cyclone would cause significant discharge of both water and sediment over the rim into the ocean This is confirmed by observations from similar atolls. Lachenaud (1986) describes observations on several atolls during cyclones, mostly with the "greatest part of the atoll submerged". A combination of observational data by Lachenaud (1986) and the empirical procedure of Sylvester (1974) was used to determine the water discharge. Another procedure (Van Rijn 1993) was used to determine the sediment concentration and the sediment outflow into the ocean.

Basic data and assumptions for the calculations are given in Fig. 108 The height of the rim above the mean water level (MWL) is taken to be 1.5 m. As the wind shear stress would cause a rise of about 0.5 m in the water level in the southeastern part of the lagoon, it is estimated that the average height of the rim over the storm water level (SWL) is only 1 m Using the data in Sylvester (1974), the wave run-up (the maximum height of the waves over the MWL) is estimated to be 3.5 m. As the atoll rim is about 300–400 m wide, it was estimated that the effective wave run-up (R_0 in Fig. 108) would be reduced to 2.7 m Taking account of the 0.5 m rise of the water level due to storm surge, the total rise of the water level above normal conditions is 3.2 m, which is in agreement with observations by Lachenaud (1986). For the parameter values given above, the water discharge over the rim was estimated to be 0.5 m^3/s per metre of the rim (Sylvester 1974). Over the rim length of 20 km, and for a storm duration of 6 h, 2.2×10^8 m^3 of water would flow over the rim.

For the conditions described, the suspended sediment load near the bottom of the lagoon would be about 50 kg/m^3. As high mixing is to be expected in storm conditions, it was assumed that the depth averaged sediment load would be about 60% of this, i.e. 30 kg/m^3. This implies a mass of 6.5×10^6 t of sediment washed out of the lagoon over the rim during one storm event. However, this outflow of sediment could only be realistic if the whole area of the shallow sea near the southeastern and southern rim, the beach and the nearby

TABLE LIV. SEDIMENT AND PLUTONIUM OUTFLOW FROM MURUROA LAGOON INTO OCEAN

	Wind–tide case		Storm case	
	Sediment (t/a)	$^{239+240}$Pu (Bq/a)	Sediment (t/storm)	$^{239+240}$Pu (Bq/storm)
Through pass	8×10^4	8×10^9	7.2×10^5	3.6×10^{11}
Over southeastern rim			3.2×10^6	3.3×10^{11}
Total	8×10^4	8×10^9	3.9×10^6	6.9×10^{11}

part of the atoll were all completely erodible. As there are parts of this region which are not erodible, or are only partly erodible (e.g. coral reefs and carbonates), it was arbitrarily estimated that only 50% of the calculated sediment mass would be washed out. Hence, the total mass of sediments washed over the rim during one storm event would be 3.2×10^6 t. This is approximately 4.5 times the mass which would be washed out of the lagoon through the pass during the same storm event.

A simple calculation shows that this would cause erosion of the beach to a depth of about 0.5 m, over the whole 20 km of the southeastern and southern rim and over a width of 300 m. In reality, the erosion would be concentrated along weaker, more erodible sections.

The total amount of sediment washed out of the lagoon during one storm (through the pass and over the rim) is estimated to be 4×10^6 t. This is equivalent to the erosion of a 20 mm thick layer over the whole lagoon. In reality, this erosion would be very non-uniformly distributed.

8.3.2.3. Outflow of plutonium

The average $^{239+240}$Pu concentration in the top 10 cm of the bottom sediment in Mururoa lagoon is estimated, on the basis of French data and results obtained from the Study, to be 500 Bq/kg. For the regions near the pass and in the vicinity of the southeastern rim, the concentration is estimated to be much lower, about 20 Bq/kg. In both of the cases considered — normal winds and tides, and storm conditions — the sediments are partly, but not entirely, mixed over the lagoon. It was therefore estimated that the concentration near the pass (wind–tide case) and in the vicinity of the southeastern rim (storm case) would be about 100 Bq/kg. Hence, the amount of radioactive material washed out through the pass by the permanent action of the trade winds and tides would be about 8 GBq/a, and the total outflow of plutonium during one storm event (through the pass and over the rim) is estimated to be about 0.7 TBq.

The estimated outflows of sediments and plutonium from Mururoa lagoon to the open ocean are summarized in Table LIV. The dominant release of plutonium will occur during storm conditions. Because the thickness of the sediment cover on the bottom of the lagoon and the topography of the atoll rim are not well known, and because a number of approximations have been used in these calculations, the estimates of the outflow of sediment and plutonium are considered to be accurate to within a factor of 3.

8.4. SOURCE TERM FUNCTIONS USED IN MODELLING

8.4.1. Concentrations within lagoons

It is necessary to estimate the concentrations of radionuclides in lagoon waters at Mururoa and Fangataufa as a function of time so that the dose rates to potential atoll dwellers, via the marine food chain, can be calculated. The radionuclide concentrations in the lagoons are attributable to three sources:

(a) Underground sources
(b) Sediments in the lagoons
(c) Global fallout in the ocean.

The underground sources were estimated in Section 6.

The contributions due to the global fallout in the ocean and to leaching from the sediments have been decreasing over the past 20 years owing to decay and other processes. This is apparent from the French measurements of the concentrations of ^{137}Cs and plutonium, which have been decreasing with an apparent half-life of 7–14 years (Figs 38 and 39 in Section 4). The decrease in leaching with time, which has also been observed at Bikini Atoll (IAEA 1998), is attributed to a combination of physical and chemical processes: slow burial of old sediments under new deposits, leaching of radionuclides from more accessible sites on sediment grains, redistribution of radionuclides onto different solid phases through sorption and desorption and, possibly,

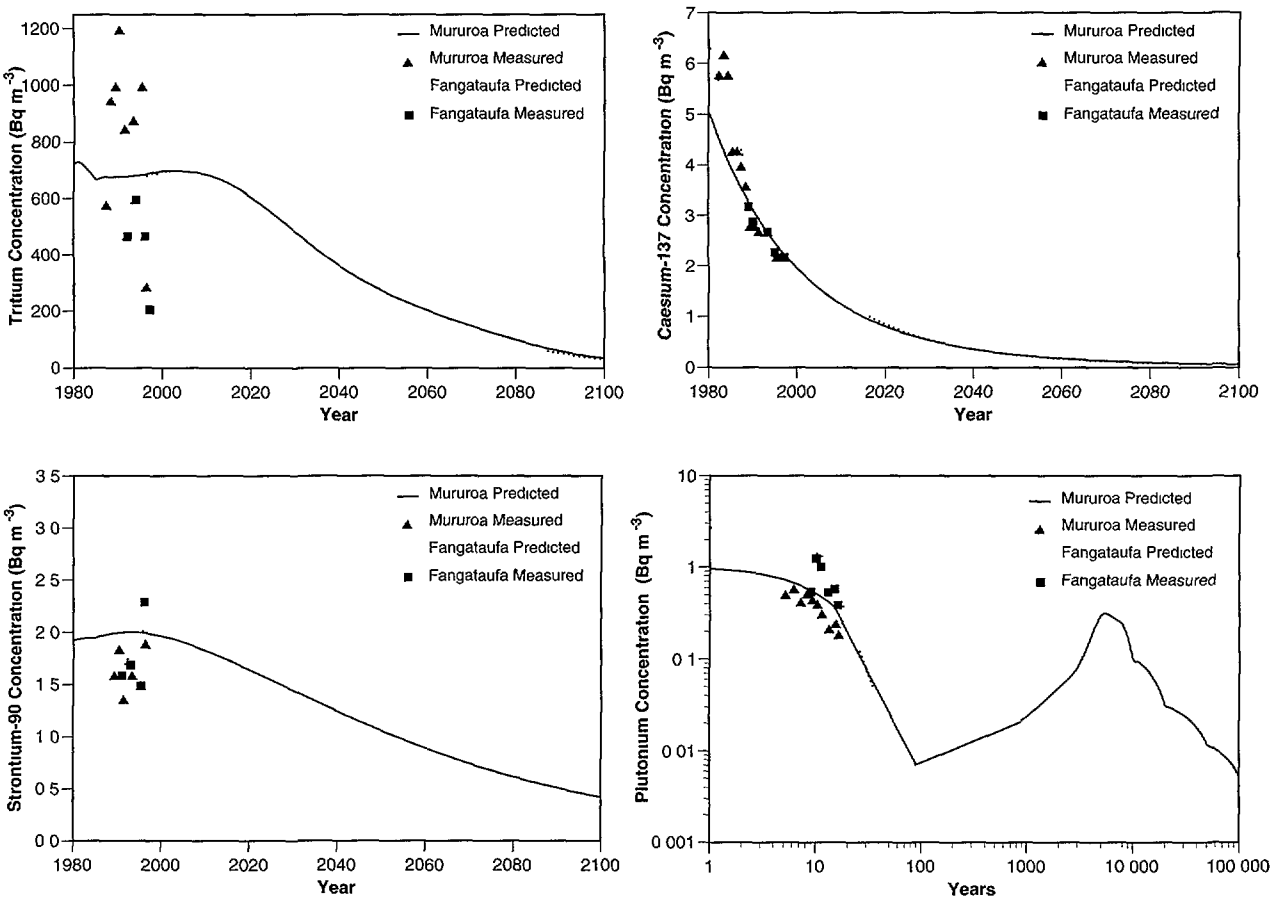


FIG 109 Measured and predicted concentrations of ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ in Mururoa and Fangataufa lagoons Year 1 is 1980 for both atolls

differences in the chemical form of particular radionuclides (especially plutonium).

For tritium, there is no contribution from the sediments. The underground source terms were obtained from Fig. 96 (Section 6) and converted to concentrations using the equations in Table LII. The present oceanic background was assumed to be 100 Bq/m^3.

For ^{137}Cs, the current release from underground sources is small relative to the global fallout levels in the ocean and to leaching of sediments. The oceanic background concentration was estimated to be 1.9 Bq/m^3 and was extrapolated backwards and forwards in time by assuming an effective half-life of 15 years based on the data in French Liaison Office Document No 3. The slight elevation above the oceanic background was attributed to leaching from sediments. The concentration in the lagoon due to leaching was assumed to have an effective half-life of ten years. The predicted release rates in the future take account of underground sources but these are not sufficient to compensate for the general decline due to the reduction in contributions from global fallout and sediment leaching (Fig. 109).

For plutonium, leaching of lagoon sediments is currently the only significant source. On the basis of the data in Fig. 40 (Section 4), it is estimated that the effective half-life for leaching is about ten years. The oceanic background is very low (about 0.003 Bq/m^3) and assumed constant with time. Underground sources are expected to make a contribution in the future, as indicated in Fig. 99 (Section 6).

Although there is considerable scatter in the data, it appears that the concentrations of ^{90}Sr in the lagoons have not declined over the past decade, indeed there is a possibility that they are increasing (Fig. 37 in Section 4). This is in marked contrast to the corresponding data for ^{137}Cs and plutonium (Figs 38 and 39). This increase in ^{90}Sr concentrations can be explained entirely by the underground source term if a conservative (i.e. low) K_d value (0.008 m^3/kg) is used in the modelling. It is also possible that the current concentrations could be explained by a higher K_d value together with some contribution from sediment leaching. Unfortunately, there is very little information on ^{90}Sr levels in sediments; the values obtained in the Study are mostly below

TABLE LV. ESTIMATED RELEASE RATES (GBq/a) OF SELECTED RADIONUCLIDES FROM MURUROA AND FANGATAUFA LAGOONS IN 1996

Radionuclide	Mururoa	Fangataufa	Total
^{3}H	5100	600	5700
^{90}Sr	18	9	27
^{137}Cs	6	5	11
$^{238+239+240}Pu$	6	5	11

detection limits. Late in the Study, the French Liaison Office provided limited data from 1984 on core samples taken from the Dindon area and recent results of French measurements of ^{90}Sr in replicate samples of sediment cores from the barge test areas taken during the Study's sampling campaign These indicated that the activities of ^{90}Sr were comparable to, but slightly higher than, those of ^{137}Cs.

Notwithstanding this late information, no contribution to ^{90}Sr levels in the lagoon waters from sediment leaching has been assumed for the purposes of the Study. This is a conservative approach as regards future concentrations in the lagoon. The oceanic background has been estimated to be 1.2 Bq/m^3 and, in the absence of adequate measured time trend data, is assumed to have a physical half-life of 30 years.

The predicted concentrations of the four key radionuclides in the Mururoa and Fangataufa lagoons are shown in Fig. 109. Experimental measurements from French and Study sampling campaigns are also shown for comparison. A number of important conclusions can be drawn from these graphs:

(1) The concentrations of ^{137}Cs and plutonium in lagoon waters are unlikely to exceed present levels at any time in the future.

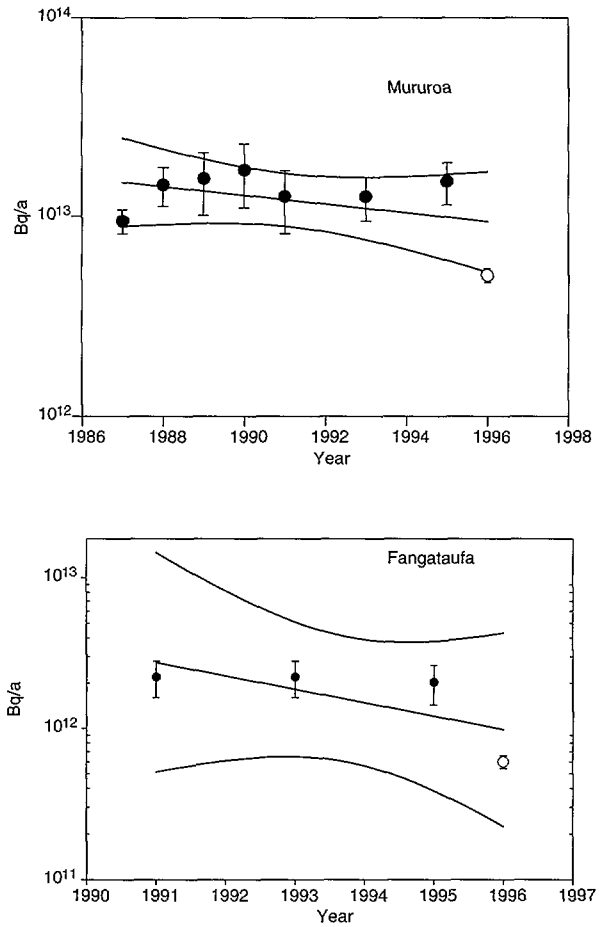


FIG 110 Trend in ^{3}H release rates from Mururoa and Fangataufa lagoons.

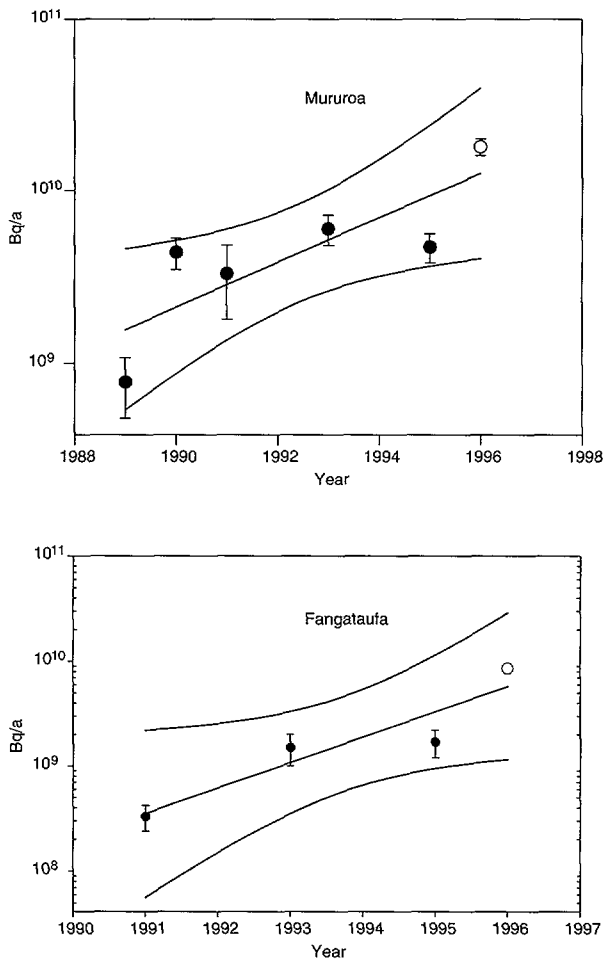


FIG 111 Trend in ^{90}Sr release rates from Mururoa and Fangataufa lagoons

(2) The concentrations of ^{90}Sr could rise marginally above current levels (especially in Fangataufa lagoon) but only for a few decades
(3) The concentrations of tritium in the lagoons may remain fairly constant for the next few decades before declining slowly.
(4) It is valid to use current data for estimating maximum dose rates to hypothetical populations of atoll dwellers in the future.
(5) Of the four key radionuclides studied, only the concentration of plutonium is markedly above oceanic background levels.
(6) The concentrations of artificial radionuclides in the lagoons are generally much lower than those of naturally occurring radionuclides in the open ocean, typical values of which are 12 000 Bq/m^3 for ^{40}K and 80 Bq/m^3 for uranium isotopes (French Liaison Office Document No. 3).

8.4.2. Releases via lagoons and directly to ocean

The best estimates of release rates of radionuclides (as of 1996) from Mururoa and Fangataufa lagoons into the surrounding ocean, as determined in the Study, are shown in Table LV. Estimated total release rates of ^{3}H, ^{90}Sr, ^{137}Cs and total $^{239+240}Pu$ (both dissolved and particulate fractions) from both lagoons in past years are presented in Figs 110–113 with 95% confidence intervals.

The total time dependent source terms (from both the surface and underground sources) for use in modelling the dispersion in the regional and far field oceans are shown in Fig. 114. These source terms are the sum of the underground releases as determined in Section 6 and, for releases via the lagoons, any contributions from sediment leaching. No attempt has been made to distinguish Mururoa and Fangataufa as separate sources since, on an

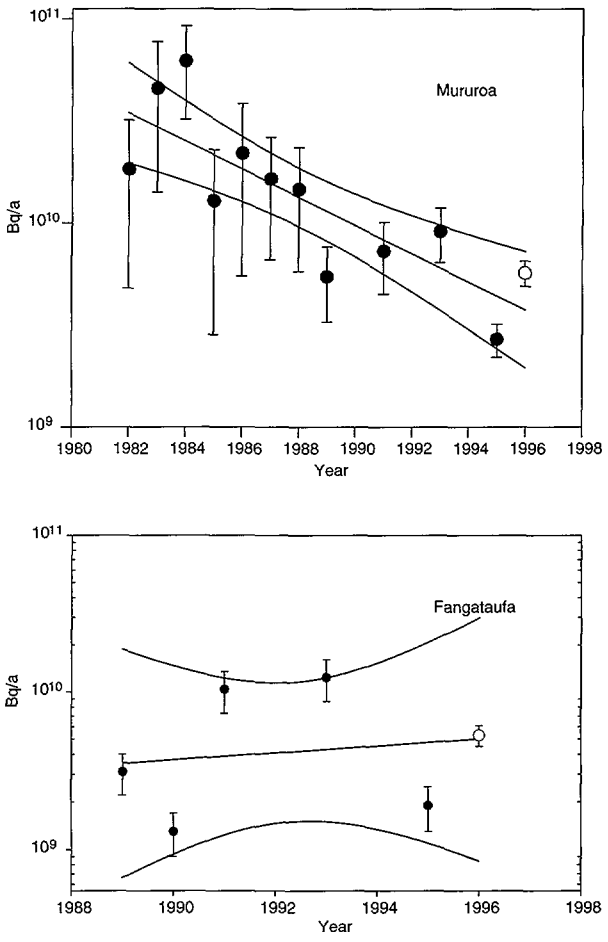


FIG. 112. Trend in ^{137}Cs release rates from Mururoa and Fangataufa lagoons

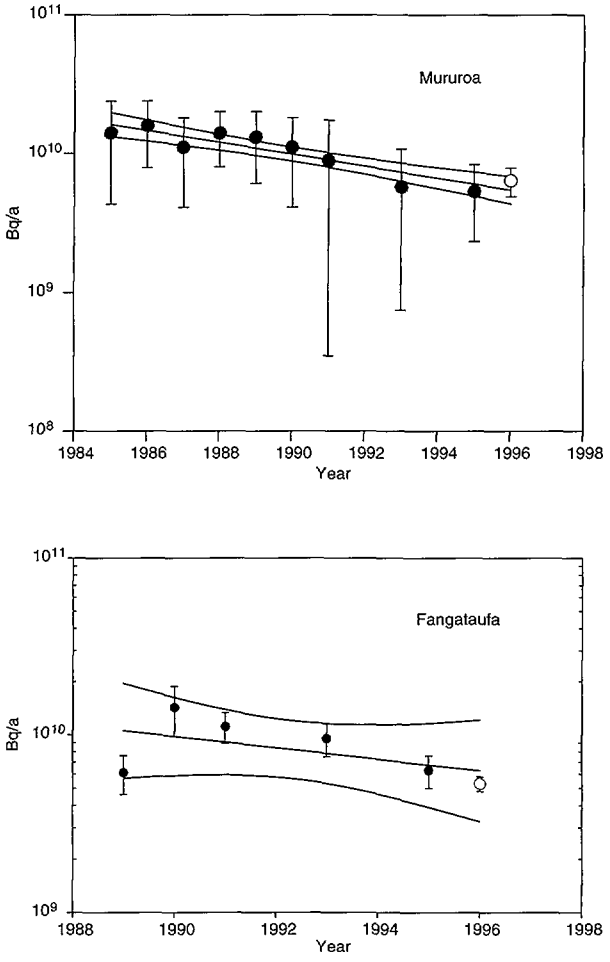


FIG 113 Trend in total $^{239+240}Pu$ (dissolved and particulate) release rates from Mururoa and Fangataufa lagoons

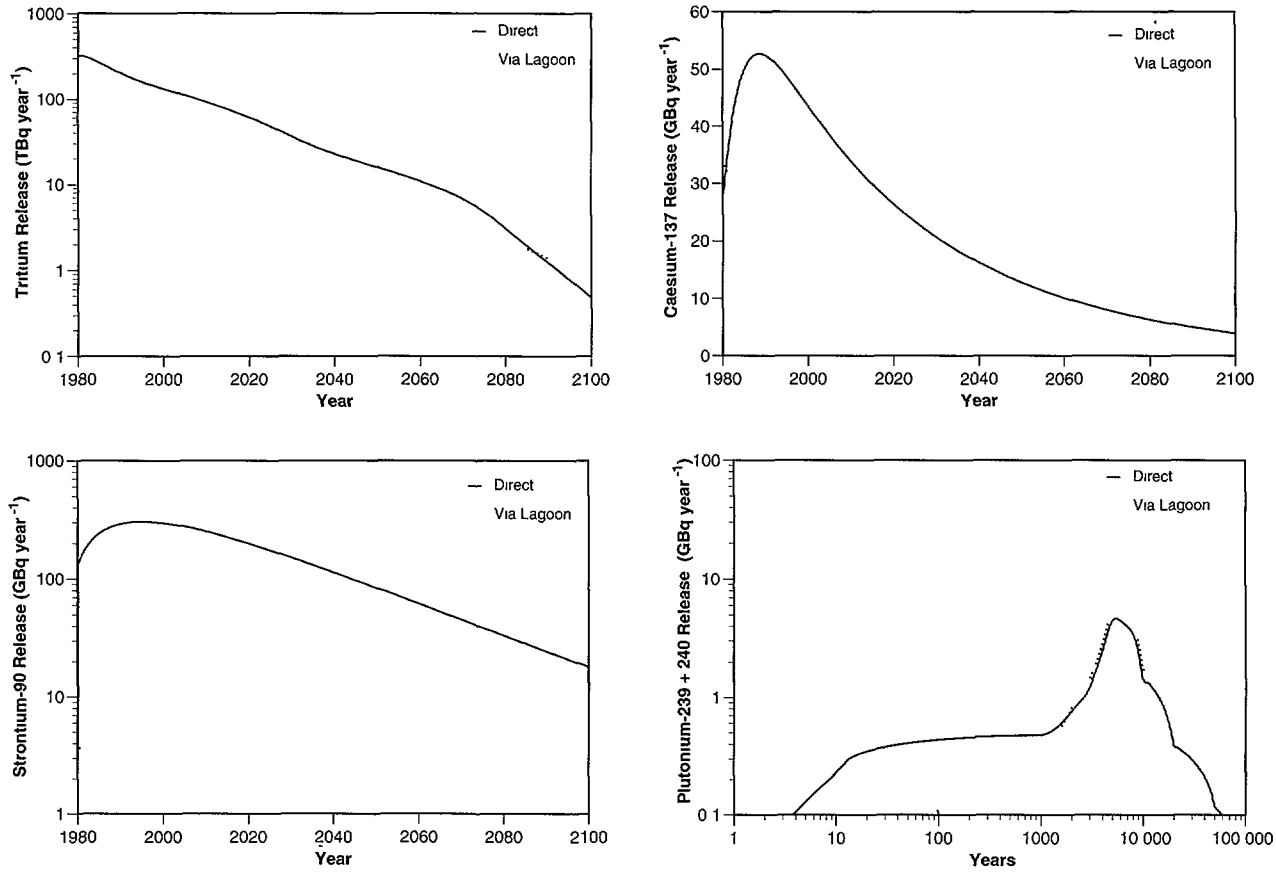


FIG. 114. Predicted time dependent release rates of ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ to the biosphere Year 1 is 1980.

oceanic scale, they are so close together as to be indistinguishable. The releases via the lagoons are considered to be surface releases; releases direct to the ocean are assumed to occur at a depth of 400 m Figure 114 shows that the total release rates of ^{3}H, ^{90}Sr and ^{137}Cs will decrease with time, with the dominant contribution from underground sources coming from releases directly into the ocean.

On the other hand, in the case of ^{239}Pu, which will migrate extremely slowly from underground, the dominant source is the lagoon sediment, and for a few decades the release rates will decrease with a half-life of about ten years. The contributions of ^{238}Pu and ^{240}Pu to the total plutonium release rate are about 25 and 11%, respectively; however, because of their shorter half-lives (87.74 years for ^{238}Pu and 6563 years for ^{240}Pu), ^{239}Pu (with a half-life of 24 110 years) is the dominant plutonium isotope on timescales of the order of 10 000 years. On the basis of the geological modelling, the contribution from underground sources of plutonium is expected to become dominant after about 100 years, reaching a peak release rate of about 10 GBq/a (5 GBq/a from the lagoons and 5 GBq/a direct) around A.D. 8000.

These time dependent source term functions were finalized late in the Study and were used with the Equidistant Grid Compartment Model and the Intermediate Range Compartment Model (MELPAC) described in Section 8.5.3. The South Pacific Compartment Model and the Far Field Model (in some simulations) used an earlier source term function whose maximum values differed slightly from those in the final functions (Technical Report, Vol. 5). However, the differences in predicted maximum concentrations between the two source functions are within the uncertainties of the models used for marine radioactivity dispersion calculation.

In the case of a storm event (Section 8.3.2.3), the total release from the two atolls together is estimated to be about 1 TBq $^{239+240}Pu$ per ten-yearly storm, predominantly in particulate form. This is about 3% of the total plutonium inventory (Table L). It is expected that this

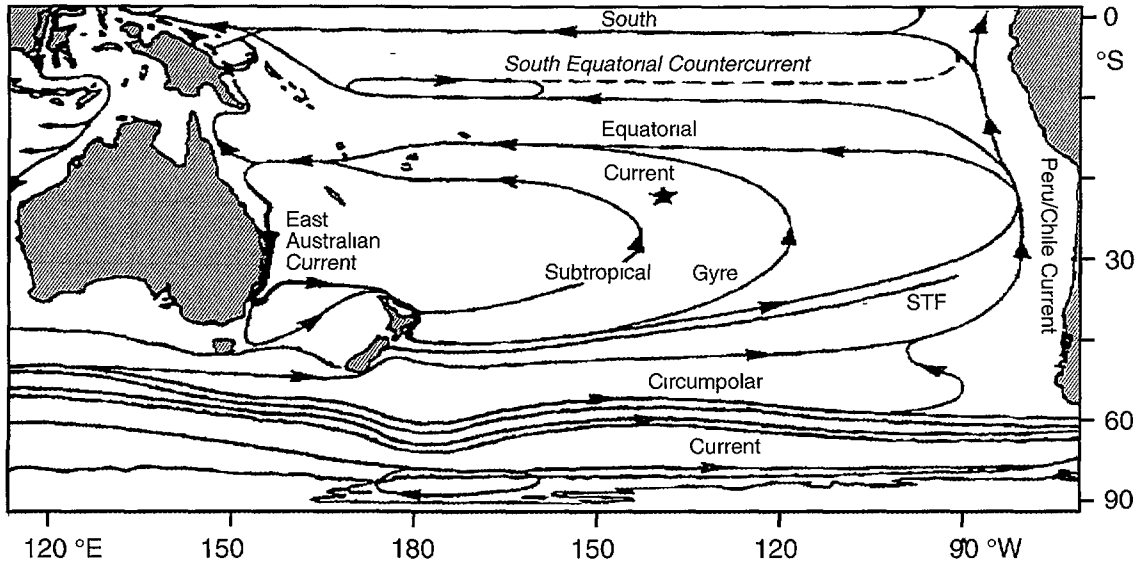


FIG. 115 Surface currents of the Pacific Ocean The star indicates the location of Mururoa and Fangataufa The ragged lines represent fronts STF: Subtropical Front, associated with the South Pacific Current (Tomczak and Godfrey 1994)

potential source term will decrease with time as the plutonium-bearing sediments are progressively buried by fresh sediment, but good estimates of the present sedimentation rates in the lagoons are not available. Values of about 2 mm/a (Mururoa) and 1 mm/a (Fangataufa) are expected in undisturbed areas of the lagoons. The sediment removed by storm events is estimated to average about 2 mm/a (Section 8.3.2 2), and therefore the total thickness of sediments is likely to remain in balance, i.e. the rate of sediment outflow will be matched by new sediment production Hence, the depth of water in the lagoons is expected to remain constant in the medium term (hundreds to thousands of years). During this period, the plutonium content of the surface sediments will be gradually depleted by a combination of dilution, burial and removal processes. For modelling purposes it was assumed, somewhat arbitrarily, that the plutonium inventory in surface sediments would decrease with an effective half-life of ten years (the same as the leaching source term), therefore, the total release of plutonium over the next 100 years from the expected ten cyclones would be a few terabecquerels.

In the case of the assumed disruptive event, i.e. a carbonate rock slide with an instantaneous release of radionuclides to the marine environment from underground sources, the estimated releases are those given in Table XLIX.

8 5. DISPERSION IN OCEAN: REGIONAL AND FAR FIELD MODELLING

8.5.1. General circulation in upper 500 m of South Pacific Ocean

The circulation of the upper ocean is generally determined by the wind. The oceans of the subtropical areas of the world are dominated by the trade winds, which blow from east to west and, in combination with the westerlies of the temperate region, produce an anticyclonic circulation pattern in each ocean basin, the 'subtropical gyres'

Winds in the subtropical South Pacific Ocean are generally light, and the wind generated mixed layer rarely exceeds 50 m in depth. Water movement in the upper mixed layer is more variable than in the large scale subtropical gyre circulation and follows the wind patterns on synoptic timescales (i.e. timescales of a few days, long enough to be representative of the normal range of conditions)

Wind patterns on seasonal and synoptic scales are determined by the large scale atmospheric pressure distribution, which produces two convergence regions over the Pacific Ocean. The Intertropical Convergence Zone (ITCZ) is located at about 5° N and is strongest during the northern summer. The South Pacific Convergence Zone (SPCZ) stretches from the western

equatorial Pacific Ocean southeastward towards Mururoa and Fangataufa, where it produces two anticyclonic circulation cells around the Kermadec Islands and Easter Island. During the southern summer, the trough is strong, keeping Mururoa and Fangataufa in the easterly airstream of the trade winds. During winter, the anticyclones move north and the SPCZ becomes the centre of frequent intrusions of cold air brought in from storm systems of the westerlies.

Figure 115 shows the predominant ocean currents in the South Pacific Ocean. The subtropical gyre consists of the northward flowing Peru/Chile Current in the east, the westward flowing South Equatorial Current in the north, the southward flowing East Australian Current in the west and the eastward flowing South Pacific Current in the south. This current system extends to at least 1000 m depth, but the axis of the gyre shifts gradually southwards as depth increases. At the surface, the boundary between the South Equatorial and South Pacific Currents is found north of 30° S, whereas at depths of 1000–1500 m it is located near 40° S (Reid 1986). This suggests that, at the 500 m depth level, the separation zone between westward flow in the north and eastward flow in the south is located somewhere in the vicinity of 35° S.

Within the South Equatorial Current is a band of weak eastward flow near 8° S, known as the South Equatorial Countercurrent. This water movement is more persistent in the western South Pacific than in the east, where it is often suppressed by westward flow. Mururoa and Fangataufa are situated on the southern edge of the South Equatorial Current near 22° S Material carried by currents past the atolls will therefore drift mainly to the west towards Australia, enter the East Australian Current and eventually turn east with the South Pacific Current. Owing to the proximity of the atolls to the gyre centre, current velocities in their vicinity are relatively small, closer to 0 1 m/s than the typical velocities of 0.2–0.3 m/s found in the centre of the South Equatorial Current.

The Polynesian region is an important ventilation region for thermocline water masses of the South Pacific Ocean.[10] High evaporation and low rainfall produce a net freshwater loss to the atmosphere, increasing the salinity of the upper few hundred metres of the ocean to 36 parts per 1000 or more. At the surface, the high salinity region coincides with the region of largest freshwater loss. Below the surface mixed layer, there is no mechanism to concentrate the salt content of the water, and the salinity maximum observed at depth must be the result of convective mixing. The details of the evaporation driven convection are not known, but observations suggest that the water column around Mururoa and Fangataufa may, at least occasionally, become homogeneous from the surface to a depth of several hundred metres as a result of convection Any material introduced into the upper few hundred metres of the water column would then be uniformly distributed over that depth range.

The description presented above is based on the assumption that the current system of the South Pacific Ocean does not change. If the world climate changes, this will bring about a change in wind and precipitation conditions, which in turn will produce changes in the oceanic current patterns. All global climate models indicate that changes in sea surface temperature and current systems in the South Pacific Ocean will be relatively minor. The largest impact would probably come from a change in cyclone frequency and an expanded area of cyclone occurrence. As discussed in Section 7.2 2, sea level rise, in conjunction with cyclones, is likely to increase the damage to surface and near surface structures, including coral formations.

8.5.2. Seasonal flow paths in the vicinity of Mururoa and Fangataufa

Tomczak and Herzfeld (in press) modelled the seasonal flow paths of a passive tracer starting at Mururoa. The advantage of their model is that it simulates surface flow due to the seasonally varying winds; the disadvantage is that dispersion is not considered However, the authors argue that, close to the source, dispersion is of lesser importance and that pathways of highest concentrations will be found along the trajectories.

The trajectories fall into two groups. Subsurface water movement is westward and exhibits little seasonal variability. At 155° W, some 1700 km from the source, the lateral spread produced by changes in the current field is less than 200 km. The surface trajectories show much more seasonal variability, passing anywhere between 136° and 148° W at 26° S latitude. Four patterns can be distinguished. During early winter (June–August), material released at the surface near Mururoa is carried westward before turning southward near 146° W. During summer (October–February), the current carries surface material in a direction just west of

[10] The thermocline denotes an ocean layer where the water temperature changes rapidly with depth In many cases other environmental parameters, such as salinity and nutrient concentrations, may undergo pronounced vertical changes within this layer as well Also, the vertical profile of radionuclide concentrations exhibits, in general, striking differences above and below the thermocline (French Liaison Office Document No 3).

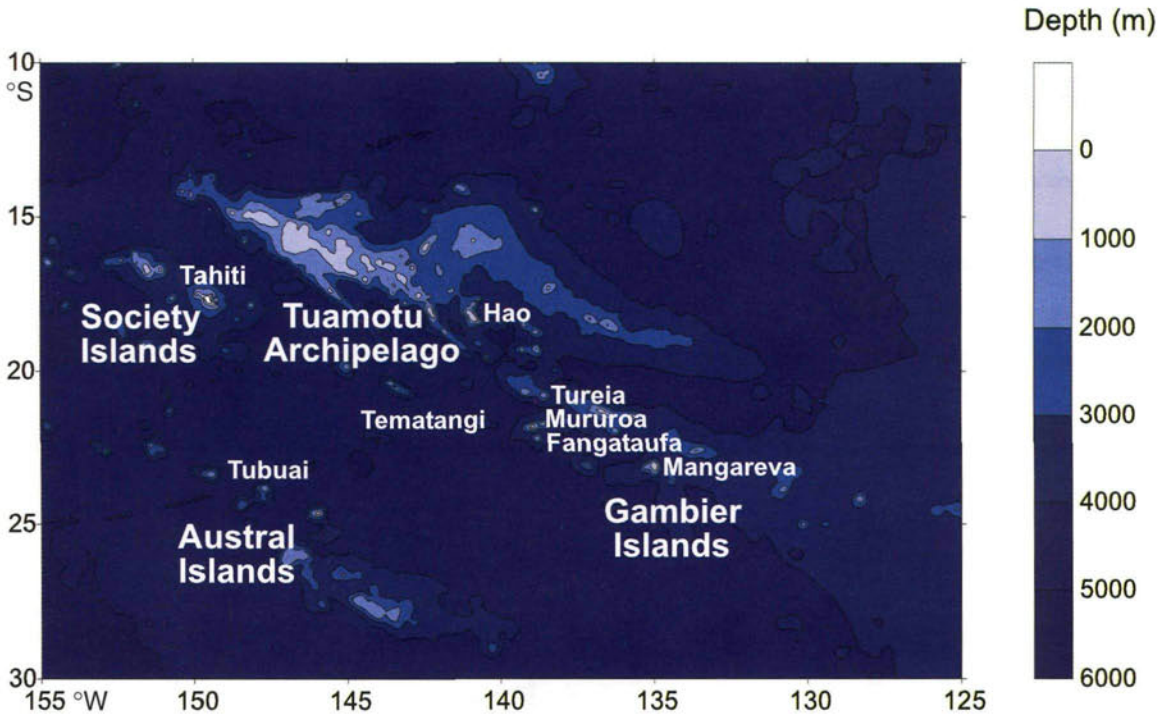


FIG. 116. Area of South Pacific Ocean assessed by the Equidistant Grid Compartment Model.

south. Material released in early autumn (March–April) is initially carried southward but is then trapped in the centre of the anticyclonic surface movement that is characteristic of the winter months. Finally, material released in either May or September is carried southward first but soon encounters transitional conditions between summer and winter and leaves the model region in the south about halfway between the summer and winter locations.

The model is a pure circulation model, which neglects mixing, and therefore cannot be used to determine concentrations of radionuclides. Nevertheless, the model and its results are of interest in the Study and are discussed in more detail in the Technical Report, Vol. 5.

8.5.3. Compartment models

The prediction of concentrations of radionuclides in the South Pacific Ocean relies on mathematical models of dispersion in the ocean. The spatial and temporal resolution requirements vary considerably, from the area of the nearest inhabitants (about 130 km from Mururoa) to the whole of the South Pacific Ocean, and over a wide range of timescales (up to 10 000 years). Several types of model are necessary to cover these space and time domains. Furthermore, basing the assessment on a number of different models adds to the robustness of the final conclusions and improves the credibility of the final results. In addition, the range of predicted outcomes from the different models can be used to provide a measure of the uncertainties.

Compartment models are widely used in assessments of radiological impacts, as well as in many other fields. In essence, the region of interest is divided into a number of compartments or boxes, and material can be transferred from one compartment to adjacent compartments on the basis of transfer coefficients derived from current and eddy diffusion data. Compartment models are especially useful for assessments over longer timescales and they can be easily linked to other models representing, for example, the sediments or transfer of radioactivity to biota. The spatial resolution of such models is determined by the number and size of the compartments, and a balance must be struck between spatial definition and the availability of data for the model and the computer time needed to run the calculations.

The main advantages of compartment models are as follows:

— It is possible to cover long timescales (up to thousands of years).
— The computational time is generally not excessive.
— The models can easily deal with particle reactive (i.e. sorbing) radionuclides.
— Detailed submodels for sediment and biota uptake can be simply accommodated.

TABLE LVI. PARAMETERS USED FOR EQUIDISTANT GRID COMPARTMENT MODEL

Parameter	Value	Reference
Eddy diffusion coefficient	100 m^2/s	Wadachi (1987)
Depth of thermocline	400 m	French Liaison Office Document No 11
Amount of suspended solids in sea water	1×10^{-4} kg/m^3	European Commission (1994)
Sedimentation rate of suspended solids	1×10^{-2} $kg \cdot m^{-2}$ a^{-1}	European Commission (1994)
Distribution coefficient between sea water and suspended solids	2×10^2 L/kg for Sr 2×10^3 L/kg for Cs 1×10^5 L/kg for Pu	IAEA (1985)

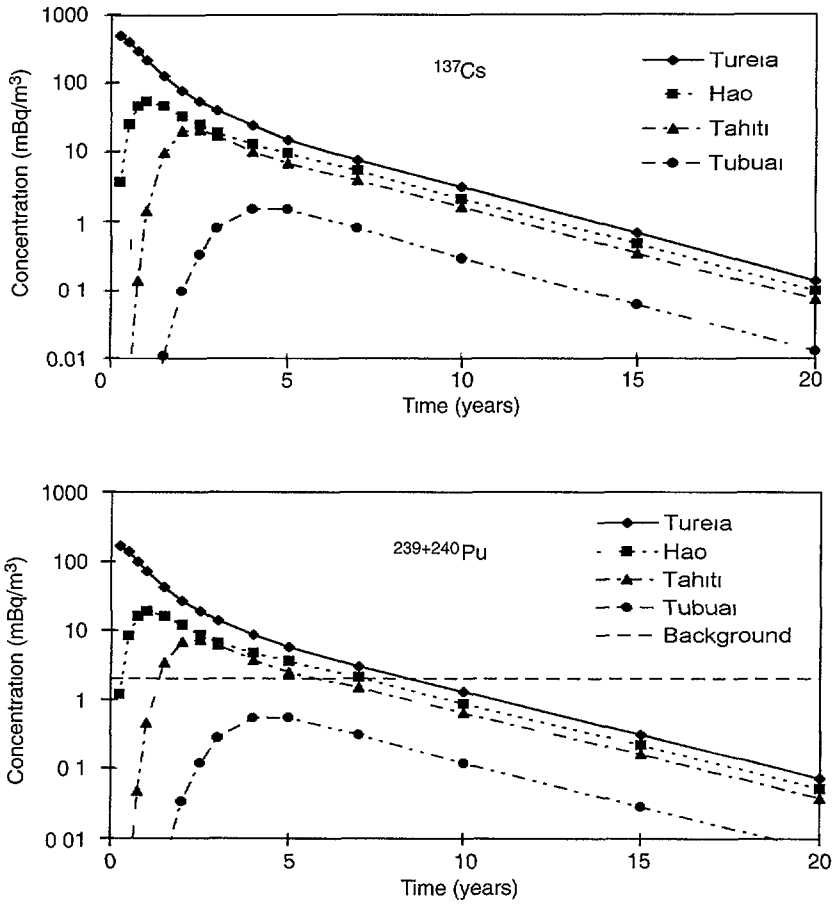


FIG 117 Predicted concentrations of ^{137}Cs and $^{239+240}Pu$ above background levels around islands of French Polynesia resulting from a hypothetical slide of carbonate rock The present background concentrations in the surface layer are 2–3 Bq/m^3 for ^{137}Cs and 1–4 mBq/m^3 for $^{239+240}Pu$

The main disadvantages of compartment models are as follows:

— A high degree of spatial averaging is implicit in their design, thus, within a compartment, no concentration gradient can be created.

— Concentration gradients can only be resolved in the model by increasing the number of boxes in the region of the expected gradient.

In the Study, three compartment models were used, each with its own particular advantages and disadvantages.

8 5.3.1. Equidistant Grid Compartment Model

The Equidistant Grid Compartment Model used in the Study was originally developed for regional scale modelling of discharges from a nuclear fuel reprocessing plant in Japan (Togawa 1996). For the Study, it was adapted to represent a region of interest defined to extend from 10 to 30° S and from 125 to 155° W (an area roughly 2200 km by 3100 km). Figure 116 shows the area, which is centred on Mururoa and Fangataufa Atolls and includes the Tuamotu Archipelago, the Society Islands, the Austral Islands and the Gambier Islands. For modelling purposes, radionuclides which leave this area were assumed not to return.

The model domain is divided into compartments of 1° latitude by 1° longitude (approximately 110 km × 110 km), giving a total of 600 compartments. The radionuclide concentration in each compartment is calculated using a simple model, in which the effect of the thermocline is taken into account. It was assumed that the concentration is uniform throughout the water column from the surface to the depth of the thermocline, and that radionuclides can be transferred below the thermocline only by sedimentation.

The ocean current data of Masumoto and Yamagata (1996) were used. This database has a resolution of 0.5° in both latitude and longitude, with 20 layers from the ocean surface to the bottom A total of 12 data sets are available, each of which contains monthly-averaged water velocities at all grid points. For the Study, yearly average values were calculated for each 1° × 1° compartment and for a layer from the surface to the thermocline.

Table LVI shows the model parameters, which were assumed to be constant over the entire domain. The bathymetry data were provided by Hamburg University. The volume, vertical cross-section and average depth for each compartment were calculated by linear interpolation of the depth data. Transfer of radionuclides between compartments was estimated by summing the components due to the ocean current and eddy diffusion. The continuity of the calculated current data was checked, and a water mass balance was confirmed to be preserved in all compartments.

Results

The model simulations presented here cover the three source term scenarios discussed in Section 8.4.2: the disruptive event (instantaneous release), the normal time dependent release (Fig 114) and the ten-yearly storm. It was assumed that all radionuclides are released from Mururoa Atoll into a layer from 0 to 450 m deep, where a uniform concentration with depth was expected

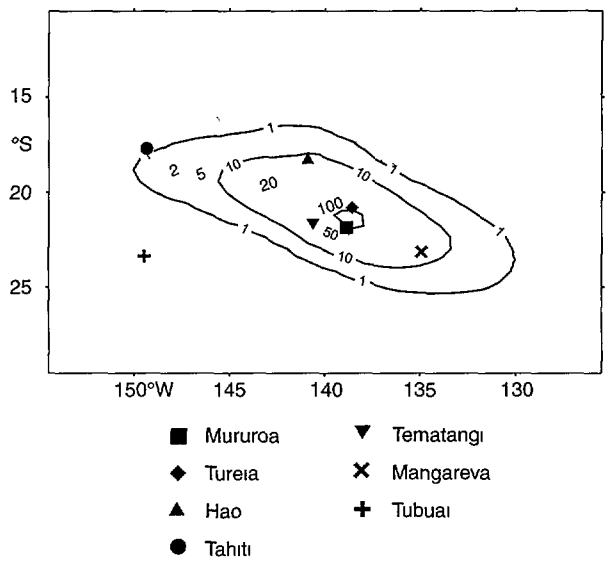


FIG 118 Elevation in concentration of $^{239+240}Pu$ in surface water (mBq/m^3) one year after a disruptive event

Disruptive event scenario

Predicted increases in concentrations of ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ in the ocean for periods of 20 years were estimated following the instantaneous release of the radionuclides listed in Table XLIX due to a rock slide in the carbonate zone. Figure 117 shows the time dependent concentrations of ^{137}Cs and $^{239+240}Pu$ above background levels in the surface water near four inhabited islands: Tureia, Hao, Tahiti and Tubuai. In general, the longer the distance, the lower is the peak concentration and the later it occurs; however, depending on the direction of the currents, there will be occasions when peaks may reach closer islands later than those farther away (the distances are approximately 130 km to Tureia, 460 km to Hao, 1100 km to Tubuai and 1200 km to Tahiti).

With the exception of $^{239+240}Pu$, predicted increases in levels are smaller than the present background levels for surface waters in the South Pacific Ocean, which are about 100 Bq/m^3 for ^{3}H, 1 Bq/m^3 for ^{90}Sr, 2 Bq/m^3 for ^{137}Cs and 3 mBq/m^3 for $^{239+240}Pu$ (French Liaison Office Document No. 3). Figure 118 shows the spatial distribution of elevations in $^{239+240}Pu$ concentration in surface water in the region of Mururoa and Fangataufa Atolls one year after a disruptive event.

Time dependent release scenario

Seawater concentrations of ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ resulting from the time dependent releases

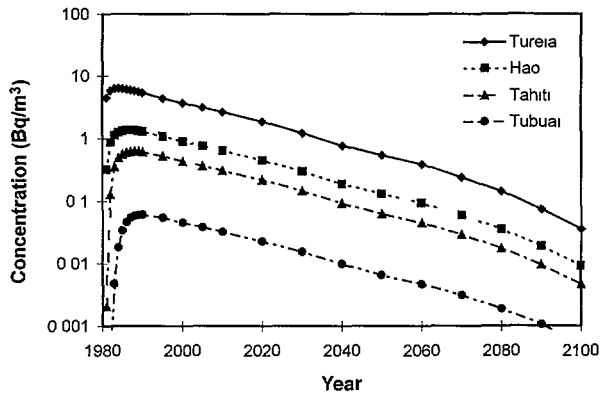


FIG. 119 Elevation in concentration of ^{3}H near inhabited islands for a time dependent release from the lagoons and geosphere

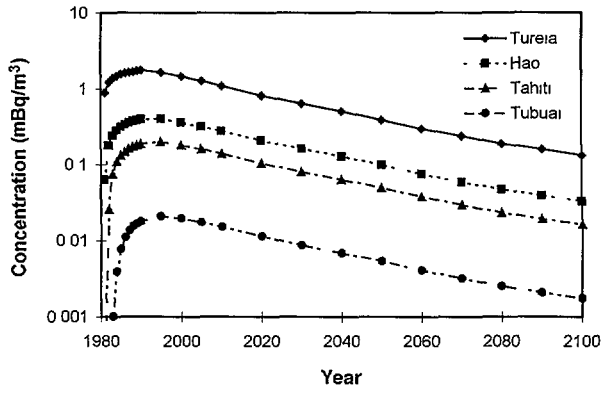


FIG 120 Elevation in concentration of ^{137}Cs near inhabited islands for a time dependent release from the lagoons and geosphere

shown in Fig. 114 were estimated. The calculations were made for a period of 100 years for ^{3}H, ^{137}Cs and ^{90}Sr and 100 000 years for ^{239}Pu. Figure 119 shows the time dependent elevation in concentration of ^{3}H in surface water near inhabited islands; the peak value is 6 Bq/m^3 at Tureia. The corresponding ^{137}Cs peak value (Fig. 120) is 2 mBq/m^3, a similar curve was obtained for ^{90}Sr, with a peak value of about 8 mBq/m^3. The ^{239}Pu curve (Fig. 121) shows two peaks (e.g 0 8 and 0.3 mBq/m^3 for Tureia), reflecting, respectively, the contributions from plutonium presently in the lagoons and the predicted future releases from underground sources. All of the elevations in concentrations are well below the background levels in the South Pacific Ocean.

Storm scenario

Time dependent concentrations of $^{239+240}Pu$ in the ocean for a period of 100 years were estimated for periodic instantaneous releases, simulating a severe storm event every ten years. Figure 122 shows the time dependent elevations in concentrations of $^{239+240}Pu$ in surface sea water near the three inhabited islands Tureia, Tahiti and Tubuai The elevations in concentrations have a peak every ten years at each location In this case also, the peak reaches Tubuai after Tahiti, which is slightly farther away. The first peak at Tureia is 10 mBq/m^3, and the size of the peaks decreases with time with an apparent half-life of about ten years. Only the first three peaks at Tureia are comparable with the present background level

In the case of a storm event, plutonium would be released to the open ocean mostly in particulate form and would probably be removed rapidly from the water

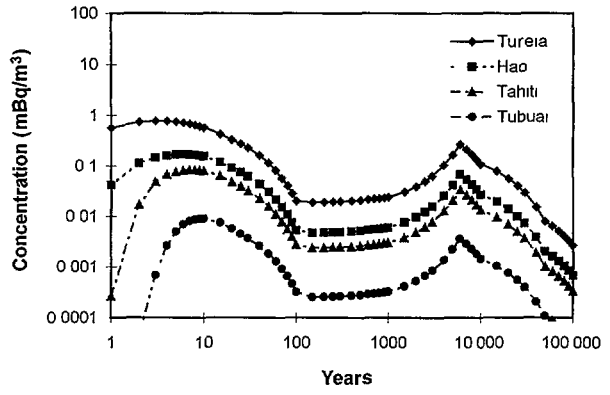


FIG 121. Elevation in concentration of $^{239+240}Pu$ near inhabited islands for a time dependent release from the lagoons and geosphere Year 1 is 1980.

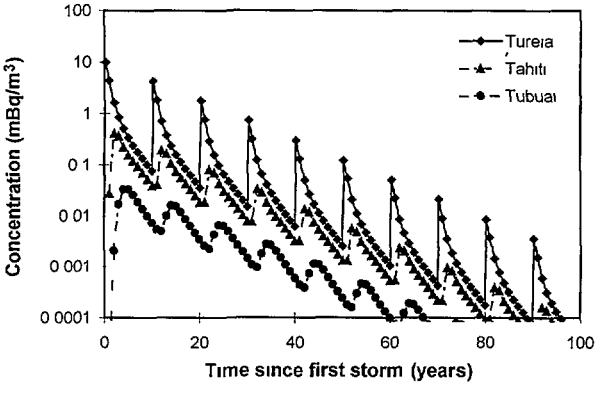


FIG 122 Simulation of elevation in concentration of $^{239+240}Pu$ in surface sea water near inhabited islands after severe storm events occurring once every ten years.

column. The Equidistant Grid Compartment Model does not take this into account and assumes a constant rate of sedimentation, as given in Table LVI. The calculations, therefore, give a conservative estimate of the elevation in plutonium concentration at the selected islands.

8.5.3.2. Intermediate Range Compartment Model

MELPAC was developed to simulate the dispersion of radionuclides released from Mururoa and Fangataufa over a long period (up to thousands of years) and on an intermediate spatial scale covering the area between 15° and 30° S and between 160° and 130° W (approximately 1700 km by 3000 km). The model domain, shown in Fig. 123, includes the Tuamotu, Cook, Society, Gambier and Austral archipelagos.

The model has 88 water and 20 sediment compartments. Exchanges of water between the model compartments were calculated from monthly 'snapshots' of velocity fields produced by a numerical model covering the Pacific and Indian Oceans (Masumoto and Yamagata 1996). A simple sedimentation model accounts for the removal of radionuclides from the water column into the bottom sediments (Technical Report, Vol 5).

The main features of the model are as follows:

(a) *High resolution in the area of the sources and the nearest inhabited islands:* A spatial resolution of 0.5° × 0.5° (about 55 km × 51 km) in the region 20.5–22.5° S, 140–138° W (Fig. 123) was chosen to represent the concentration gradients near the source more accurately. This high resolution area also includes Tureia, the closest inhabited atoll. Outside this region, the resolution is 5° × 5°.

(b) *Vertical structure resolving oceanographically distinct layers and vertical dispersion of radionuclides released at various depths:* This vertical structure makes it possible to distinguish releases to the ocean through the passes of the atolls from releases through the karstic layer.

(c) *Time variable flow fields:* From the Masumoto and Yamagata data set, water fluxes and exchange coefficients between compartments were calculated for each month of the year. The model uses the resulting 12 sets of coefficients sequentially, thus simulating the yearly variation in the water circulation patterns and volume flows, which controls dispersion at the scale covered by MELPAC.

MELPAC reproduces accurately the flow pattern predicted by the Masumoto and Yamagata model, and

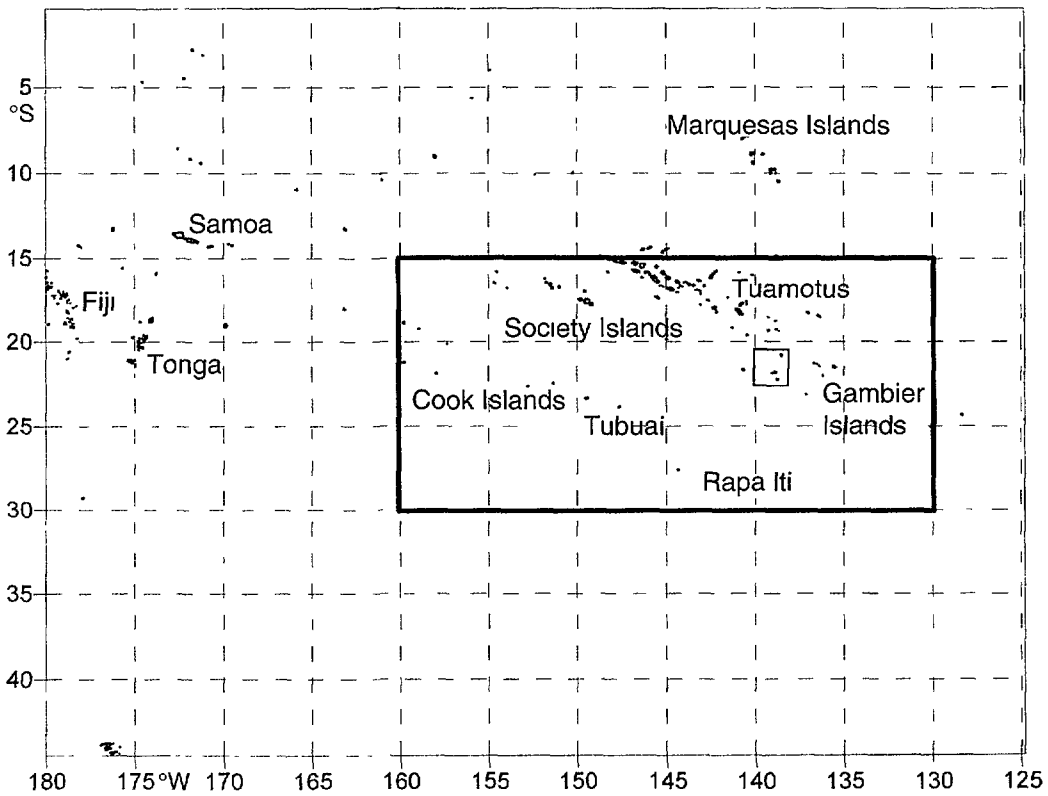


FIG 123 Model boundaries for MELPAC

TABLE LVII. MAXIMUM ELEVATIONS IN CONCENTRATIONS (Bq/m^3) IN 0–450 m DEPTH LAYER AND YEAR OF OCCURRENCE (IN PARENTHESES) FOR RADIONUCLIDE RELEASE FOLLOWING HYPOTHETICAL SLIDE OF CARBONATE ROCK: PREDICTIONS BY MELPAC
(year 0 is time of release)

Location	^{3}H	^{90}Sr	^{137}Cs	^{239}Pu
Tureia	6 (1)	0.06 (1)	0.2 (1)	0.05 (1)
Tematangi	0.4 (2)	0 004 (2)	0.01 (2)	0 004 (2)
Gambier Islands	0.9 (1)	0 009 (1)	0.03 (1)	0 008 (1)
Hao	0.1 (3)	0.001 (3)	0.004 (3)	0 001 (3)
Rapa Iti	0 04 (1)	0 0004 (1)	0 001 (1)	0 0003 (1)
Tubuai	0 07 (3)	0 0007 (3)	0 002 (3)	0 0007 (3)
Tahiti	0.1 (3)	0 0012 (4)	0 003 (4)	0 001 (4)
Cook Islands	0 02 (6)	0 0002 (7)	0 0007 (7)	0.0002 (7)

TABLE LVIII. MAXIMUM ELEVATIONS IN CONCENTRATIONS (Bq/m^3) IN 0–450 m DEPTH LAYER AND YEAR OF OCCURRENCE (IN PARENTHESES) FOR TIME DEPENDENT RADIONUCLIDE RELEASE: PREDICTIONS BY MELPAC
(year 0 is time when release starts)

Location	^{3}H	^{90}Sr	^{137}Cs	^{239}Pu
Tureia	2 (5)	0 002 (21)	0 000 5 (11)	0 000 2 (5)
Tematangi	0.4 (7)	0 000 6 (22)	0 000 1 (12)	0 000 05 (6)
Gambier Islands	0.7 (7)	0.001 (22)	0.000 2 (12)	0 000 08 (6)
Hao	0 2 (8)	0.000 2 (23)	0.000 05 (13)	0 000 02 (7)
Rapa Iti	0 04 (7)	0 000 06 (23)	0.000 01 (13)	0.000 004 (6)
Tubuai	0 1 (9)	0 000 2 (23)	0 000 03 (14)	0.000 01 (8)
Tahiti	0 1 (9)	0 000 2 (24)	0 000 04 (14)	0 000 02 (9)
Cook Islands	0.02 (12)	0 000 03 (32)	0.000 006 (20)	0 000 002 (11)

achieves mass balance to within 1%. The basic flow information built into the model allows a time resolution for predictions of one month. The monthly sequence of transfer coefficients is repeated for each year, so there is no variation between years in the model. Tests of the sensitivity of the predictions of the model to the exchange rates between its South Pacific and World Ocean compartments showed that uncertainty in these rates would not affect significantly model predictions for the locations of interest.

Results

For any given source term, the model predicts the time evolution of radionuclide concentrations in each of its compartments In order to allow comparison with predictions of other models, the reported concentrations are generally averaged annually and over depth from the surface to 450 m. All results reported below correspond to releases of radionuclides from the atolls into the 10 m surface layer of ocean water Calculations were carried out for Tureia, Tematangi, the Gambier Islands, Hao, Rapa Iti, Tubuai, Tahiti and the Cook Islands. The simulations were run for timescales of 100 years following instantaneous release or the beginning of continuous release for ^{3}H, ^{90}Sr and ^{137}Cs, and of 10 000 years for ^{239}Pu.

Disruptive event scenario

Predicted maximum increases in concentrations following a disruptive event, averaged over a water column depth of 0–450 m, are shown in Table LVII, together with the year of occurrence. The time trends in the averaged concentrations for the whole water column (0–450 m) are very similar for all radionuclides, the differences being mainly due to the differences in half-life. The effect of scavenging of radionuclides by suspended particulates and their removal from the water column through sedimentation is weak because of the low suspended solids load and sedimentation rate used

(Table LVI). Nevertheless, adsorption onto suspended solids and the settling of these solids (sedimentation) represent the main mechanism of depletion of the inventory of dissolved ^{239}Pu.

The predicted elevations in concentrations at Tureia are, with the exception of ^{239}Pu, below the present background levels.

Time dependent release scenario

The maximum elevation in concentrations of ^{3}H, ^{90}Sr, ^{137}Cs and ^{239}Pu in the depth interval 0–450 m and the year in which the maximum is attained (year zero being the start of the release given as 1980) are presented for selected locations in Table LVIII. The resulting maximum elevations in concentrations in water are very low, several orders of magnitude below the present background levels.

For a 10 000 year simulation of the time dependent release of ^{239}Pu a secondary maximum in the concentration of dissolved ^{239}Pu is predicted to occur at about A.D. 8000 in the surface waters around Tureia, the nearest inhabited location. This secondary maximum is three times lower than the first maximum given in Table LVIII, which itself is about one order of magnitude below the present day background concentrations measured in the region.

Storm scenario

One storm event would result in ^{239}Pu concentrations in water one order of magnitude less than those given in Table LVII.

8.5 3.3. South Pacific Compartment Model

The South Pacific Compartment Model was designed to bridge any gap between finely resolved intermediate field and far field models. The model spans the South Pacific Ocean, with a domain from 0° to 90° S and approximately from 160° E to 70° W (the Australian coast to the South American coast), although not all areas are equally well resolved. Two main sources of data were used to define the model the monthly snapshots of circulation fields produced by Masumoto and Yamagata (1996) and the yearly circulation field of the World Ocean Circulation Model (OGCM) (Section 8.5.4). The South Pacific Compartment Model has coarser resolution than the intermediate scale models, but covers a larger domain. Near the source, it is more finely resolved than the OGCM, but in the far field it is more coarsely defined. However, it is possible to run the model to simulate long timescales. Thus, the model functions at the interface between the intermediate and far fields and, because it makes use of two independent sources of circulation field information, can be used to provide a check on the agreement between the intermediate scale model results at the more distant locations and the far field model results at those same locations.

For this model, Mururoa and Fangataufa are treated as one source, located in a single compartment of dimensions 1° × 1°. The source compartment is nested within a series of compartments, which allows resolution of some of the nearby inhabited islands of interest (within the area 20–25° S, 140–133° W). The model structure also allows the development of a concentration gradient over this spatial scale. In total, there are seven water compartments in this region, of typical dimensions 3° × 3°. Outside this region, a further 15 water compartments are defined, spanning 0–40° S and 160–120° W. These compartments represent large areas and so introduce a high degree of spatial averaging at this scale. Separate compartments are included for Tahiti, Tubuai and Rapa Iti. Beyond these boundaries, the model is extended by a further series of four very large scale compartments to encompass the South Pacific basin. The model also has vertical structure, the water column being divided into three layers: 0–50, 50–500 and below 500 m

Exchanges of water between the model compartments were calculated using the monthly data from Masumoto and Yamagata (1996), who used 0.5° resolution, and yearly data from the OGCM at 3.5° resolution. The fine scale results were used to calculate exchanges of water in the region 20–25° S, 140–125° W, while the OGCM results were used for all other compartments. As in all models, there is a compromise between a highly detailed structure and the computer time required to run simulations. As such, the South Pacific Compartment Model has a number of limitations, including the use of only three depth layers. However, the model still allows distinction between a surface release and release at depth (from the karstic layer) The surface layer (0–50 m) does not differentiate between the wind field circulation in the top surface layer and the geostrophic circulation below. Data availability also constrained the resolution of the vertical layers (the first layer of the OGCM is 50 m, compared with 10 m in the Masumoto and Yamagata model). The flows are based on annual average velocity fields, so if there is seasonal variation, the model cannot reproduce it. Owing to the spatial resolution, concentration gradients cannot develop over large distances. The model has not been interfaced with a sediment model, and therefore was not used to predict plutonium concentrations.

Despite these limitations, the model provides predictions for ^{3}H, ^{90}Sr and ^{137}Cs concentrations, which could

TABLE LIX. MAXIMUM ELEVATIONS IN CONCENTRATIONS (Bq/m^3) AVERAGED OVER 0–50 m DEPTH LAYER AND YEAR OF OCCURRENCE (IN PARENTHESES) FOR RADIONUCLIDE RELEASE FOLLOWING HYPOTHETICAL SLIDE OF CARBONATE ROCK: PREDICTIONS BY SOUTH PACIFIC COMPARTMENT MODEL
(year 0 is time of release)

Location	^{137}Cs	^{90}Sr
Tureia	2 9 (5)	1 (5)
Tematangi	4.7 (3)	1 5 (3)
Hao	0.2 (4)	0 07 (4)
Rapa Iti	0 5 (5)	0.1 (5)
Tubuai	0 7 (4)	0.2 (4)
Tahiti	0 1 (6)	0 04 (6)

TABLE LX. MAXIMUM ELEVATIONS IN CONCENTRATIONS AVERAGED OVER 0–50 m DEPTH LAYER FOR TIME DEPENDENT RADIONUCLIDE RELEASE: PREDICTIONS BY SOUTH PACIFIC COMPARTMENT MODEL

Location	^{3}H (Bq/m^3)	^{90}Sr (mBq/m^3)	^{137}Cs (mBq/m^3)
Tureia	4.6	1 7	0 6
Tematangi	5 7	1 8	0.7
Hao	0 4	0 1	0.05
Rapa Iti	0 8	0.3	0.1
Tubuai	1 1	0.4	0 1
Tahiti	0 2	0 1	0 04

be used in dose assessment, particularly for people living on the atolls who consume large amounts of seafood.

Results

Disruptive event scenario

Table LIX shows the maximum elevations in concentrations of ^{137}Cs and ^{90}Sr in ocean water (averaged over the top 50 m) at six locations following the postulated slide of carbonate rock. Of these locations, Tureia is the only one where the concentration estimates are based on the relatively high resolution model of Masumoto and Yamagata (1996); for the other sites the lower resolution Hamburg model (Section 8.5.4) was used The variation of concentrations with time is discussed in the Technical Report, Vol. 5.

The South Pacific Compartment Model predicts the highest elevated concentrations at Tematangi, 180 km west of Mururoa; predicted elevations in concentrations are slightly above the current background levels for ^{137}Cs at both Tematangi and Tureia. All other results are below the current background levels.

Time dependent release scenario

Table LX shows the maximum elevations in concentrations of ^{3}H, ^{90}Sr and ^{137}Cs in ocean water (averaged over the top 50 m) for six regional locations due to the continuous time dependent releases shown in Fig. 114. All elevations in concentrations are well below current background levels and would not be measurable in the environment.

8.5.4. Far Field Model

The Far Field Model ('Hamburg model') consists of a predictive World Ocean Circulation Model (OGCM) and a tracer dispersion model, both developed at the Max Planck Institute for Meteorology, Hamburg, to study global climate change. It is similar to the large scale model described in French Liaison Office Document No. 11. The model has a resolution of 3.5° × 3.5° and the ocean depth is divided into 22 layers. Tracer dispersion is simulated by means of a Lagrangian transport model, which uses the 3-D OGCM data as input. The tracer dispersion model requires a transformation of the model flow data from the Eulerian OGCM grid to the Lagrangian co-ordinates of the tracer.[11] The horizontal and vertical spreading of the tracer due to circulation and fine scale mixing is treated by means of Lagrangian particle tracking combined with a Monte Carlo method The dispersion of the tracer is determined by a slowly varying part of the velocity field (the advection) and a quickly varying part (the eddy diffusion) The model is forced by standard boundary conditions, such as climatological wind stress (Hellermann and Rosenstein 1983), air temperature from the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987) with a relaxation time of two months, and annual means of sea surface salinity (Levitus 1982). It has been recently used to study the dispersion of dissolved and particulate matter in the world ocean over long timescales (Maier-Reimer 1993, Segschneider 1996).

[11] The ocean currents are calculated at defined grid points in a fixed co-ordinate system (Eulerian co-ordinate system) The movement of a tracer in the marine environment is presented in a co-ordinate system moving with the tracer itself (Lagrangian co-ordinate system)

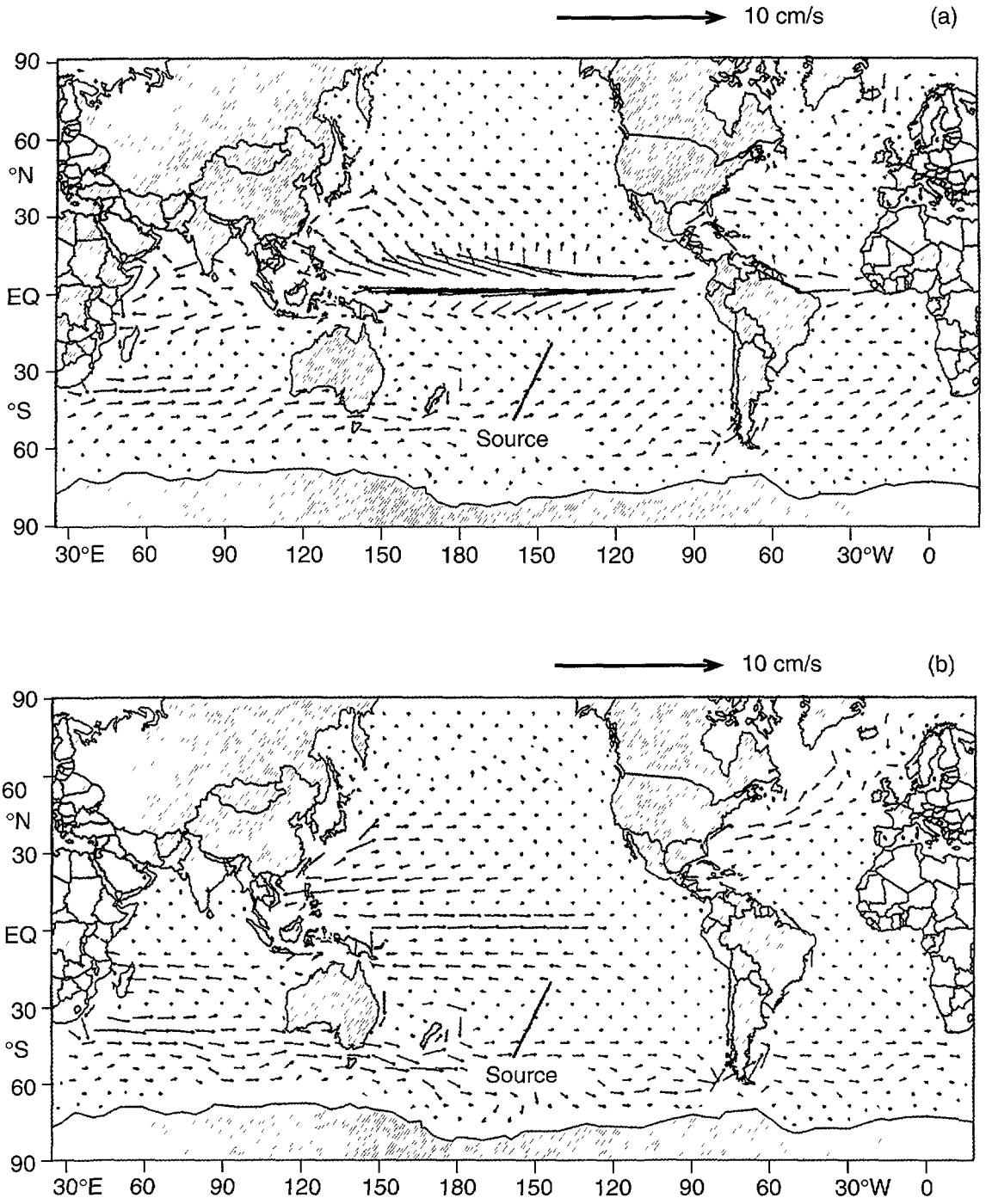


FIG 124 Mean current vector field of the World Ocean Circulation Model (a) in the surface layer (0–50 m) and (b) at 350–450 m depth

World Ocean Circulation Model

Figure 124 shows the annual mean velocity of the simulated world ocean currents in the surface layer (0–50 m depth) and in the intermediate layer (350–450 m depth). The model circulation in the surface layer agrees with the known large scale major flow currents described in Section 8 5 1 and with results from the French model (French Liaison Office Document No 11). The general agreement also holds for the subsurface circulation at around 400 m depth. The French dispersion simulations in the ocean are confined, however, to the South Pacific from 5° to 40° S and do not extend beyond ten years In the Study, the model domain was expanded to allow consideration of longer times and distances from the source

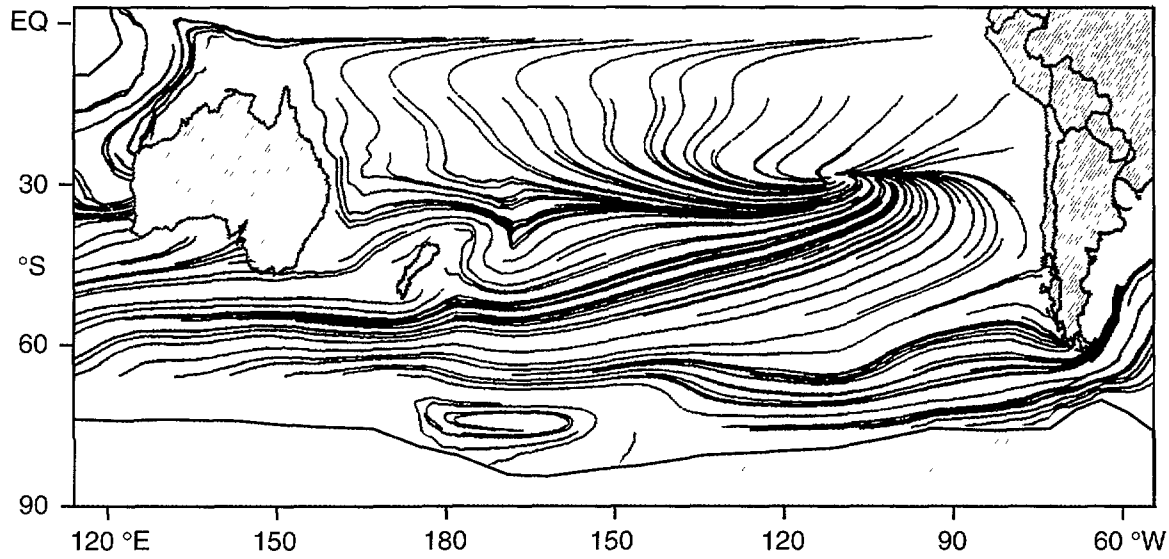


FIG 125 Three dimensional trajectories of the ocean circulation (ignoring depth variations) starting at the same time within the surface layer (0–50 m) (simulation period ten years) The western end of each trajectory corresponds to t = *0.*

Figure 125 shows 3-D trajectories of virtual water parcels or Lagrangian tracers, which flow with the mean circulation. All model particles start within the surface layer at the same time and move in three dimensions over a period of ten years. Over 300 years an individual parcel starting in the surface layer in the vicinity of Mururoa and Fangataufa would move several times back and forth across the South Pacific with the mean circulation, and would eventually end in the South Atlantic. During this period the particle would undergo considerable vertical displacement owing to sinking and ascending motions in the ocean.

A striking feature of the model results is the convergence of the trajectories around the region 30° S, 110° W, near Easter Island This behaviour causes a long-term trapping of water bodies or tracers in the surface layer within the convergence. This means that radioactive material released at Mururoa which reaches the region around Easter Island by means of the circulation tends to concentrate in this part of the South Pacific Ocean (regional concentration maximum). In the French analysis (French Liaison Office Document No. 11) the same feature is described as an anticlockwise rotating ocean gyre in which "the residence time of the water trapped can be several years".

Results

Disruptive event scenario

Figure 126 shows the tritium concentration field for the disruptive event scenario (Section 7.3.1) involving a release at depth (400 m). The maximum elevation in concentrations due to the disruptive event is about 10 Bq/m^3 after five years halfway towards Australia, and about 1 Bq/m^3 off the coast of Australia five years later. These compare with the background tritium level of 50–100 Bq/m^3 at 400 m.

The plume for other radionuclides (^{90}Sr, ^{137}Cs and $^{239+240}$Pu) will be similar to that for tritium, except that the concentrations will be lower and approximately (after a simple correction to take account of the different half-lives) in proportion to their relative concentrations in the source term (^{3}H.^{137}Cs.^{90}Sr:$^{239+240}$Pu = 100 3:1:1, Table XLIX).

The peak concentrations predicted for the hypothetical disruptive event are generally higher than those for the time dependent continuous release. In particular, the concentration of plutonium, close to the source, is predicted to be about 100 mBq/m^3, which is well above background levels (1–4 mBq/m^3) However, the concentration quickly returns to background levels within a few years. As noted earlier, very conservative assumptions are adopted in determining the plutonium source term for the disruptive event (Section 7.3.1).

Time dependent release scenario

The Far Field Model was used to determine the variation in radionuclide concentrations with time from a time dependent continuous release both at the surface (as from the lagoons) and at a depth of 400 m (as for a release from a deep karstic zone) using the source terms shown in Fig 114

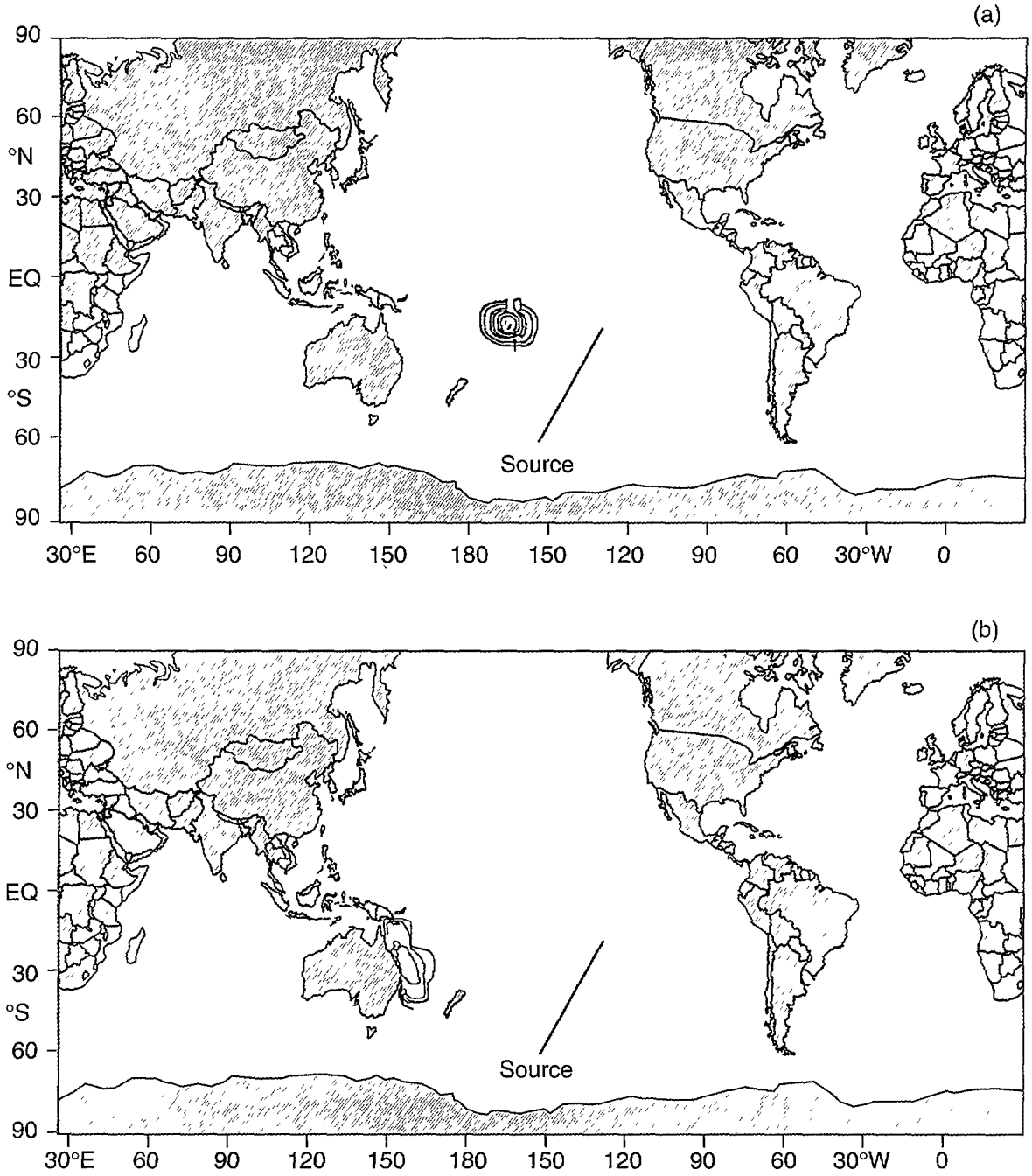


FIG 126. Elevation in concentration of ^3H after a hypothetical slide of carbonate rock (instantaneous release) at a depth of 400 m (a) after five years and (b) after ten years. Maximum after five years. 10 Bq/m^3, after ten years (off the coast of Australia) 1 Bq/m^3 Isolines in (a) 1, 10, 100, 250, 500, 750, 1000; isolines in (b) 1, 10, 100 (units of 10^{-2} Bq/m^3).

For a surface release, the calculated concentration is the average concentration over a surface layer 50 m deep. Plutonium (initially from leaching of lagoon sediments) is the most important source of radioactivity. The dispersion of plutonium was modelled at 5, 10, 30 and 50 years after the beginning of the release, assumed for the purposes of this assessment to begin in 1996, i.e. when the plutonium source term is about 10 GBq/a. Five years after the release starts, the surface plume is moving in an easterly direction with the maximum elevation in activity concentration (0.2 mBq/m^3) predicted to occur in the immediate vicinity of Mururoa and Fangataufa. After ten years (Fig. 127), the plume has widened in the surface layer, mainly in an easterly direction. After 30 years (Fig. 128), maximum elevations in activity concentrations (about 0.2 mBq/m^3) occur in the surface layer

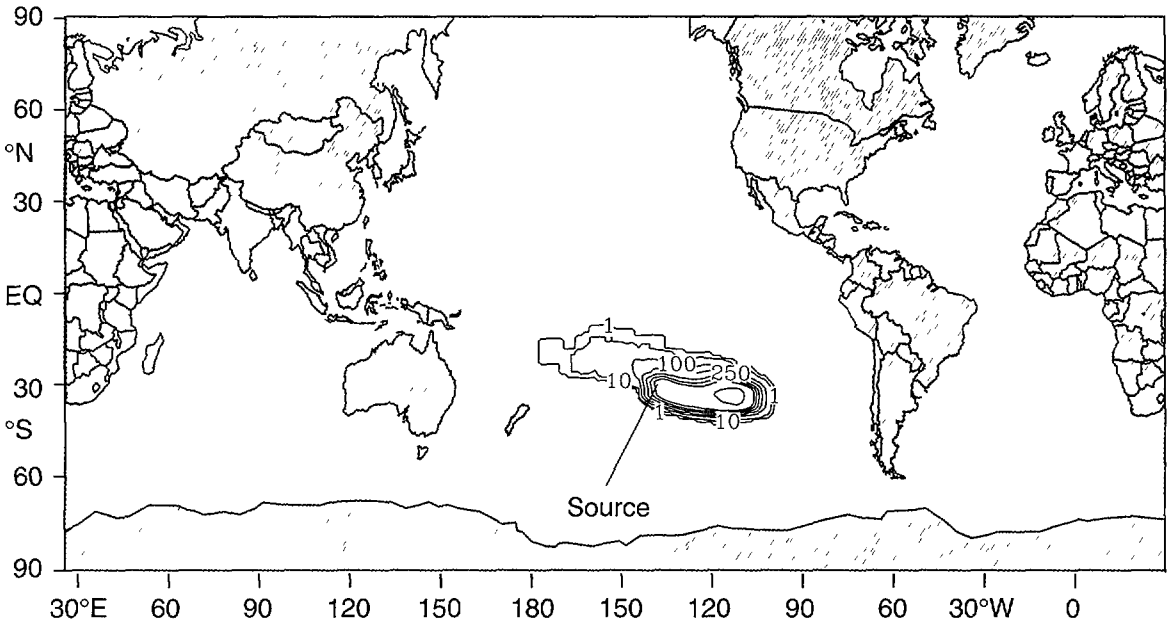


FIG 127. Elevation in activity concentration ten years after the start of a time dependent continuous release of plutonium in the surface layer. Isolines: 1, 10, 100, 250, 500, 750, 1000, 2000 (units of 10^{-7} Bq/m^3) The present background concentration in the surface layer is 1–4 mBq/m^3

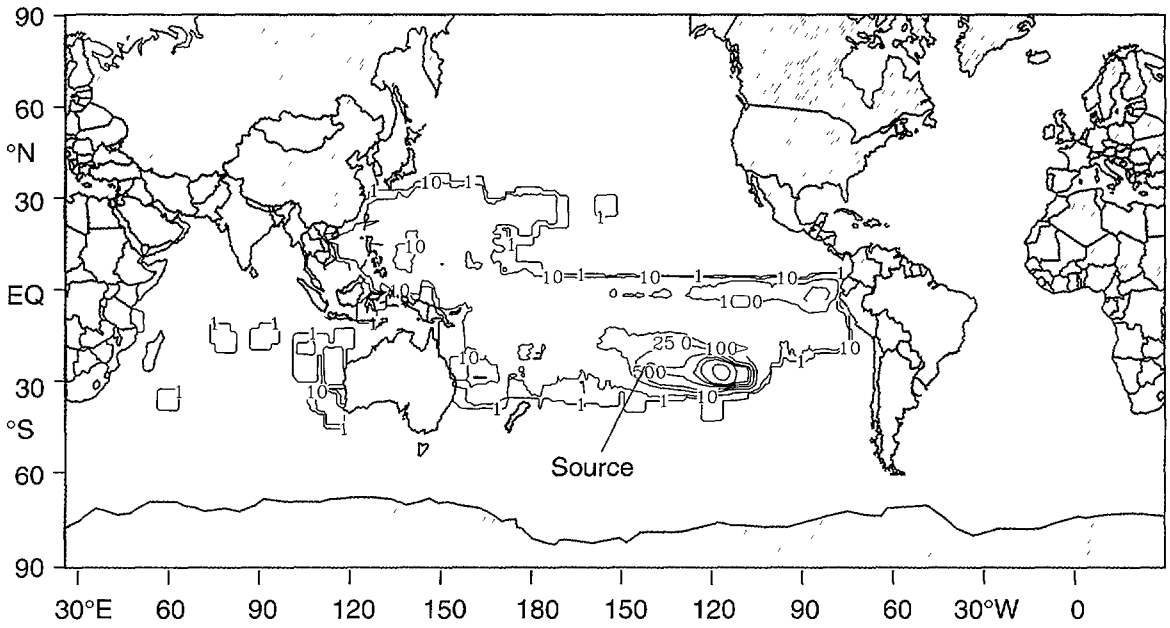


FIG. 128 Elevation in activity concentration 30 years after the start of a time dependent continuous release of plutonium in the surface layer Isolines. 1, 10, 100, 250, 500, 750, 1000, 2000 (units of 10^{-7} Bq/m^3) The present background concentration in the surface layer is 1–4 mBq/m^3

around Easter Island. After 50 years, the elevation around Easter Island is about 0 1 mBq/m^3 in the surface layer; elsewhere it is negligible. For longer times (up to 1000 years), the concentrations in the region gradually decline because of the decrease in the source term. From these calculations, it can be concluded that the maximum elevation in concentrations in the region from a continuous release at the surface will be an order of magnitude lower than the oceanic background (1–4 mBq/m^3) attributable to global fallout from atmospheric tests.

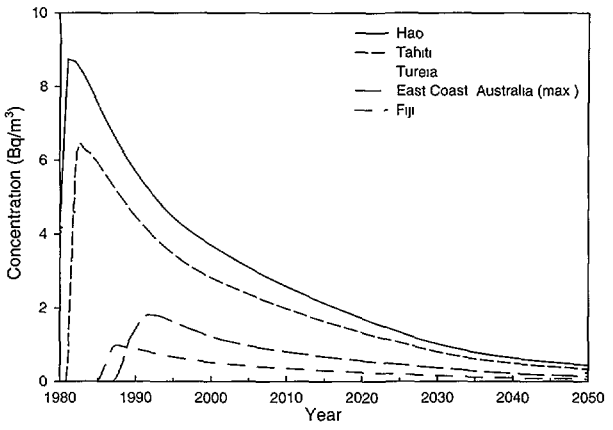


FIG 129 Elevation in concentration of ^{3}H in ocean water at 400 m at various South Pacific locations for a time dependent release at 400 m from Mururoa Atoll beginning in 1980.

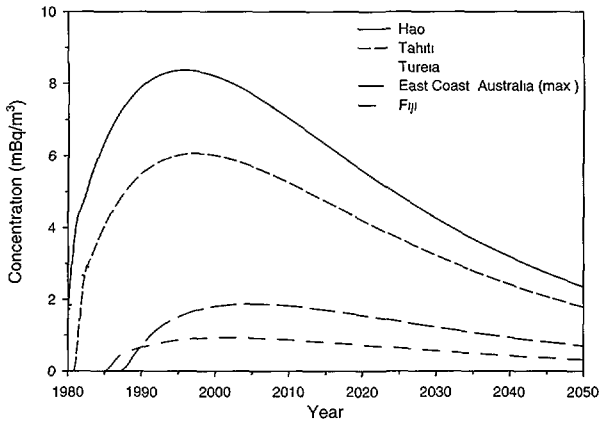


FIG 130. Elevation in concentration of ^{90}Sr in ocean water at 400 m at various South Pacific locations for a time dependent release at 400 m from Mururoa Atoll beginning in 1980

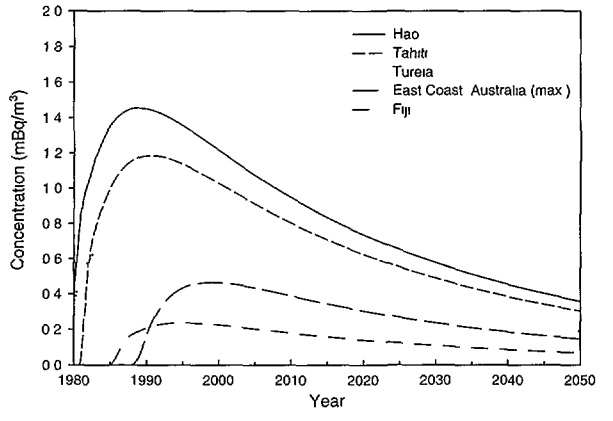


FIG. 131. Elevation in concentration of ^{137}Cs in ocean water at 400 m at various South Pacific locations for a time dependent release at 400 m from Mururoa Atoll beginning in 1980.

The results for surface releases of the other key radionuclides (^{3}H, ^{90}Sr and ^{137}Cs) are given in the Technical Report, Vol. 5. Predicted elevations in concentrations decrease below the oceanic background at short distances from the atolls. In general, these results are similar to those obtained using the Equidistant Grid Compartment Model and MELPAC (after allowing for the fact that concentrations were averaged over different depths)

For releases at 400 m depth, concentrations were averaged over a layer extending from 350 to 450 m below the surface The release rates of ^{3}H, ^{90}Sr and ^{137}Cs are initially higher than at the surface, whereas the release rate of plutonium is much lower (Fig 114) The simulation at 400 m depth follows a similar scenario to that described in French Liaison Office Document No 11. This release is assumed to arise from highly permeable karstic channels. Within the stratified thermocline layer in the ocean between 100 and 500 m, the subsurface flow and mixing (vertical and horizontal) are relatively weak, and therefore a radioactive injection into this layer spreads and dilutes more slowly than the same release into the surface layer.

Figures 129–131 show the elevations in concentrations of ^{3}H, ^{90}Sr and ^{137}Cs at five locations (Hao, Tahiti, Tureia, the east coast of Australia and Fiji) for a period of 70 years from 1980. According to the model, the peak elevation in tritium concentration has (in 1998) already occurred at all locations (Fig. 129). Because of the predominantly westward current flow at depth, the peak tritium concentrations at Hao (9 Bq/m^3) and Tahiti (6 Bq/m^3) are actually higher than that at Tureia (5 Bq/m^3) even though Tureia is closer to the source. The background concentration of tritium decreases with depth in the open ocean from about 100 Bq/m^3 at the surface to 6 Bq/m^3 at 1000 m (Section 4.3.2 3). In the Study's survey in 1996, the measured concentration of tritium in the ocean westward of the atolls was about 60 Bq/m^3 at depths of 400 and 600 m. It is possible that this short plateau observed in the tritium profile could be due to releases of tritium at depth from the atolls (Technical Report, Vol. 2).

For release of ^{90}Sr at depth (Fig. 130), broad peaks in the elevation in concentration are predicted to occur, depending on location, from about 1996 to 2005 The peak elevation in concentration (at Hao) is about 8 mBq/m^3. This is to be compared with the measured concentration of about 700 mBq/m^3 at 400 m westward of the atolls (Technical Report, Vol. 2), attributable predominantly to the oceanic background

Because the ^{137}Cs source term is significantly lower than that of ^{90}Sr, the predicted concentrations are even lower, with peak values below 2 mBq/m^3 at all

TABLE LXI. COMPARISON OF RESOLUTIONS USED IN OCEAN DISPERSION MODELS

Model	Circulation model	Horizontal resolution (km)	Depth layer to which concentrations refer (m)	Release depth (m)
Equidistant Grid Compartment Model (Section 8 5.3 1)	Masumoto and Yamagata	110 × 110	0–450	Top layer
Intermediate Range Compartment Model (MELPAC) (Section 8 5 3 2)	Masumoto and Yamagata	Inner: 55 × 55 Outer: 557 × 557	0–10 10–450	Top layer
South Pacific Compartment Model (Section 8 5 3 3)	Masumoto and Yamagata Hamburg	Inner 110 × 110 Outer variable	0–50 0–50	Top layer Top layer
Far Field Model (Section 8 5.4)	Hamburg	357 × 357	0–50 350–450	Top layer 400
French model (French Liaison Office Document No 11)	Université de Paris (LODYC)	200 × 200	Surface In thermocline	5 364

locations (Fig. 131). These elevations in concentrations are well below the oceanic background in the South Pacific of about 1 Bq/m^3 at a depth of 400 m (Technical Report, Vol. 2, and French Liaison Office Document No. 3).

For plutonium, the initial release at depth is not significant but, using conservative assumptions, the release rate is predicted to rise to 5 GBq/a after about 5000 years (Fig. 114). This release may be modelled by assuming a constant source since the release rate changes very slowly with time over periods of hundreds of years Assuming a constant release of 5 GBq/a (the maximum release rate, predicted to occur between about 5000 and 6000 years), the plutonium concentration at locations of interest in the South Pacific Ocean would reach a quasi-constant level within about 40 years. For release at depth, the concentrations are approximately 0.2 mBq/m^3 at Hao, 0 1 mBq/m^3 at Tahiti, 0.1 mBq/m^3 at Tureia and 0.03 mBq/m^3 at Fiji. These are all at least an order of magnitude below current background levels of global fallout plutonium in the South Pacific Ocean.

In summary, the Far Field Model predicts that releases at the surface and at depth will result in markedly different dispersion patterns. Releases from the lagoons will be dispersed to a greater extent, with the peak concentrations tending to move slowly in a southeasterly direction. On the other hand, releases at depth will move predominantly westward with lesser dispersion, reaching the Australian continent in about ten years but at concentrations which would be undetectable above the background due to global fallout.

8.6. COMPARISON OF MODEL RESULTS

Table LXI compares the three compartment models and one Lagrangian tracer model that have been used to investigate the dispersion in the regional field and far field. Two large scale circulation models serve as input for the simulations: that of Masumoto and Yamagata (1996), which is used in all three compartment models, and the OGCM, which is used in the South Pacific Compartment Model and the Far Field Model. Each of the three regional models has a different domain and structure. In the Equidistant Grid Compartment Model, dispersion is treated in only one layer extending down to the thermocline (lower boundary: 450 m). The horizontal resolution is 1° × 1° (approximately 110 km × 110 km).

MELPAC considers two ocean layers: the top 10 m and a lower layer down to 450 m. In the immediate vicinity of Mururoa the compartments have the same horizontal resolution as the circulation input model (0 5° × 0.5°). This model is best at predicting concentrations at Tureia and other nearby atolls or islands Outside the inner area, all other sites of interest are located within 5° × 5° compartments. To model the outer area, the data from ten neighbouring horizontal grid cells of the circulation model have been averaged. Thus, for example, there are two or three regional grid cells between Mururoa and Tubuai in the southwest and Tahiti in the northwest.

The South Pacific Compartment Model uses both circulation models, taking advantage of the fine resolution model of Masumoto and Yamagata in the interior of the model domain to simulate the spread from Mururoa to Tureia. Outside this region the compartments are divided in regions increasing in size with distance from

TABLE LXII. MAXIMUM ELEVATIONS IN CONCENTRATIONS (Bq/m^3) FOR RADIONUCLIDE RELEASE FOLLOWING HYPOTHETICAL SLIDE OF CARBONATE ROCK

Depth range over which concentration was averaged (m)	Radionuclide	Tureia	Tematangi	Hao	Rapa Iti	Tubuai	Tahiti
			Equidistant Grid Compartment Model				
0–450	^{3}H	10	5	1		0 04	0 6
	^{90}Sr	0.1	0 05	0.01		0 0005	0.006
	^{137}Cs	0.4	0.2	0.05		0 002	0 02
	Pu	0.1	0.05	0.01		0 0005	0.006
			Intermediate Range Compartment Model				
0–450	^{3}H	6	0.4	0.1	0 04	0 07	0.1
	^{90}Sr	0.06	0 004	0.001	0 0004	0 0007	0.001
	^{137}Cs	0.2	0.01	0.004	0.001	0 002	0 003
	Pu	0 05	0.004	0 001	0.0003	0.0007	0 001
			South Pacific Compartment Model				
0–50	^{90}Sr	1.0	1 5	0.07	0 1	0 2	0.04
	^{137}Cs	2.9	4.7	0.2	0.5	0 7	0 1
			Far Field Model				
350–450	^{3}H	20		34			25
	^{90}Sr	0.2		0.3			0 2
	^{137}Cs	0.6		1			0 8
	Pu	0.2		0.3			0 2

Mururoa. The next size class of the regional model compartments corresponds to the resolution of the Hamburg model (3 5° × 3.5°). For the outermost region, the flow data of several Hamburg model compartments have been averaged.

The French model (French Liaison Office Document No. 11) is a large scale circulation model, developed through collaboration with the Laboratoire d'océanographie dynamique et de climatologie (LODYC), Université de Paris. It is similar in structure to the Hamburg model, with a resolution intermediate between that of the Hamburg model and those of the regional models used in the Study Only 'instantaneous' releases (in which all soluble activity in the cavity–chimneys is released within a year; see Section 7) corresponding to the worst case scenario were considered. Release was either to the surface layer or in the thermocline at a depth of 364 m

Table LXII compares the results of the different models for the disruptive release scenario. The only direct comparison is between the Equidistant Grid Compartment Model and MELPAC over the range 0–450 m. Here the models generally agree to within a factor of 10, although they predict different dilutions at different locations (owing to differences in the position and size of the respective compartments) The predicted elevations in concentrations in the South Pacific Compartment Model are much higher because of the assumption that mixing occurs only in the top 50 m. The scenario underlying the hypothetical disruptive event — a large slide of carbonate rock — would obviously introduce enormous mixing over the entire water column, so averaging over the whole 450 m depth would seem appropriate.

The Hamburg model assumed instantaneous release at a depth of 400 m and concentrations are averaged over the range 350–450 m. This results in higher concentrations at these depths than release at the surface and a markedly different dispersion pattern, as discussed in Section 8.5 4. The concentrations thus obtained can be considered an upper limit.

TABLE LXIII. MAXIMUM ELEVATIONS IN CONCENTRATIONS (Bq/m^3) FOR TIME DEPENDENT RADIONUCLIDE RELEASE

(concentrations have been rounded)

Depth range over which concentration was averaged (m)	Radionuclide	Tureia	Tematangi	Hao	Rapa Iti	Tubuai	Tahiti
			Equidistant Grid Compartment Model				
0–450	^{3}H	6	4	1		0 06	0.6
	^{90}Sr	8×10^{-3}	5×10^{-3}	2×10^{-3}		1×10^{-4}	9×10^{-4}
	^{137}Cs	2×10^{-3}	1×10^{-3}	4×10^{-4}		2×10^{-5}	2×10^{-4}
	Pu	8×10^{-4}	5×10^{-4}	2×10^{-4}		9×10^{-6}	8×10^{-5}
			Intermediate Range Compartment Model				
0–450	^{3}H	2	4×10^{-1}	2×10^{-1}	4×10^{-2}	1×10^{-1}	1×10^{-1}
	^{90}Sr	3×10^{-3}	6×10^{-4}	2×10^{-4}	7×10^{-5}	2×10^{-4}	2×10^{-4}
	^{137}Cs	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	3×10^{-5}	4×10^{-5}
	Pu	2×10^{-4}	5×10^{-5}	2×10^{-5}	4×10^{-6}	1×10^{-5}	2×10^{-5}
			South Pacific Compartment Model				
0–50	^{3}H	5	6	0.4	0.8	1	0 2
	^{90}Sr	2×10^{-3}	2×10^{-3}	1×10^{-4}	3×10^{-4}	4×10^{-4}	1×10^{-4}
	^{137}Cs	7×10^{-4}	7×10^{-4}	5×10^{-5}	1×10^{-4}	2×10^{-4}	4×10^{-5}
			Far Field Model				
350–450	^{3}H	5		9			7
	^{90}Sr	5×10^{-3}		8×10^{-3}			6×10^{-3}
	^{137}Cs	1×10^{-3}		1×10^{-3}			1×10^{-3}
	Pu[a]	1×10^{-4}		2×10^{-4}			1×10^{-4}

[a] For peak release at depth of 5 GBq/a (at 6000 years).

The French results are difficult to compare with the results obtained in the Study because the source term is different and concentrations are not reported as a function of specific location (French Liaison Office Document No. 11). Concentration contours are shown in the South Pacific Ocean for 1, 3, 6 and 9 years after release either at the surface or at depth. Concentrations are normalized to an initial concentration of 1 Bq/m^3 (after homogenization at the injection grid). The contour patterns are similar to those obtained using the Hamburg model; the peak concentration in the plume moves to the southeast for a surface release and to the west for a release at 364 m.

Table LXIII shows the maximum elevations in concentrations estimated by the various models for the time dependent release The three regional models predict concentrations which, in general, agree to within an order of magnitude as far as the results can be compared The models also determine the times at which the peak concentrations occur. For ^{3}H, ^{90}Sr and ^{137}Cs, these times are essentially identical for the Equidistant Grid Compartment Model and MELPAC and occur slightly later in the South Pacific Compartment Model.

Table LXIII also shows the elevations in concentrations (at 350–450 m depth) predicted by the Hamburg model for a time dependent release from the karstic layer. The higher ^{3}H concentrations predicted by the Hamburg model in the subsurface layer at Hao and Tahiti are largely due to the less intense dispersion regime at depth. The reason why the simulated concentrations at Hao and Tahiti are higher than that at Tureia is related to the subsurface flow. Although Tureia is much closer to Mururoa than the other islands, it is not in the 'mainstream' of the radioactive release, which propagates with the flow towards the west at subsurface depth. As a consequence, the simulated concentrations are higher at Hao (about 460 km from Mururoa) and Tahiti (about

TABLE LXIV. COMPARISON OF ESTIMATED MAXIMUM ELEVATIONS IN RADIONUCLIDE CONCENTRATIONS AT TUREIA WITH CURRENT BACKGROUND LEVELS (Bq/m^3)

(model results apply to average over 0–450 m depth range and are rounded to nearest factor of 10)

Radionuclide	Disruptive event	Time dependent release	Typical regional background at surface
^{3}H	10	10	100–200
^{90}Sr	0 1	0.01	1–2
^{137}Cs	1	0.001	2–3
$^{239+240}$Pu	0.1	0.001	0 001–0.004

1200 km away) than at Tureia (about 130 km north of Mururoa).

8.7. MAIN RESULTS

(a) The estimated turnover time of the lagoon waters is 98 ± 37 d for Mururoa and 33 ± 12 d for Fangataufa

(b) The transfer of particulate (sediment-bound) $^{239+240}$Pu from Mururoa lagoon into the South Pacific Ocean is estimated to be:
- With mean winds and tides: 8 GBq/a
- In the event of an extreme storm. 0.7 TBq (per storm).

The frequency of an extreme storm is estimated to be one every ten years. The source term due to storms is expected to decrease with time, owing to depletion of plutonium-bearing sediments and gradual burial of these sediments. The source term due to plutonium from a storm is an order of magnitude below that released by the hypothetical disruptive event.

(c) Two main release scenarios were modelled:
- A disruptive event: a slide of carbonate rock, releasing activity from the carbonate zone corresponding to the inventory from one safety trial and one CRTV test;
- A time dependent source arising from the migration of material from the underground cavity–chimneys and the leaching of sediments in the lagoon

Most of the simulations assumed release to the surface layers, but some calculations were carried out assuming that the source was located at depth (400 m), simulating release from the karstic layers. For these scenarios, maximum elevations in concentrations were estimated for the lagoons and for islands and atolls in the South Pacific Ocean. The predicted concentrations at the closest inhabited atoll (Tureia) are compared in Table LXIV with current background concentrations in the open ocean due to global fallout. Only the plutonium release for a disruptive event gives a higher concentration than the current background, and then only for a few years. The dose rates attributable to these concentrations are estimated in Section 9.

For releases at depth, the concentrations at Hao and Tahiti are predicted to be higher than at Tureia. However, when the data for these locations are averaged over the total depth of 450 m, they are all below the maximum values shown in Table LXIV

Part C
RESULTS IN PERSPECTIVE

9. RADIATION DOSES AND THEIR POTENTIAL FOR IMPACT ON HUMAN HEALTH

9.1. INTRODUCTION

The overall objective of the Study has been to evaluate the radiological situation at Mururoa and Fangataufa Atolls and, given this assessment, to recommend whether or not follow-up actions to reduce any possible radiological impact of the French weapon testing programme might be required. The doses experienced by potential inhabitants of the atolls, and by other populations in the region, are the basic measure of radiological impact.

As indicated in Section 2, Mururoa Atoll has been populated only occasionally in the past, and there is no evidence that Fangataufa has ever been inhabited. The lack of a water supply, and the vulnerability of the atolls to the sea, make it difficult for people to live there. However, for the purposes of the Study the existence of a hypothetical population resident on Mururoa has been assumed in order to determine potential radiation doses. The estimation of doses to more distant communities is also necessary in order to establish the significance of any releases of radioactive materials. This assessment takes account of the dispersion of radionuclides both from the underground and atmospheric tests, and from accelerated releases of material due to disruptive events of natural or human origin, such as a landslide, or to changes in climatic conditions.

The dose assessments undertaken for the purposes of the Study are summarized in this section, after a brief introduction to dose calculation methods More details are given in the Technical Report, Vol. 6

9 2. GENERAL METHODOLOGY FOR CALCULATING DOSES

People receive radiation doses[12] in several different ways. Radioactive sources emitting penetrating radiations, most commonly gamma radiation, can give rise to a radiation dose while the source is outside the body (external dose). However, radionuclides in the air, in foods or on the ground may also be taken into the body by inhalation, by ingestion or through cuts and wounds Once within the body, emitted radiation interacts with cells of organs where the radionuclides are stored and with those of neighbouring organs, resulting in a dose (internal dose).

Assessing doses is a three stage process The first stage is to gather information about the environment, specifically the concentrations of radionuclides in environmental materials For external doses, either the concentrations in soil or water or direct measurements are needed. For internal doses, it is necessary to know concentrations in foods or aerosols which may be taken into the body. Environmental conditions at the atolls, and at more distant locations, have been discussed in the previous sections of this report. The second stage of the process is to combine concentrations with lifestyle and dietary information to obtain the total intake of activity. For external doses, the amount of time spent in different radiation fields is needed, while for internal doses information on the amount of food eaten or air breathed is required. The final stage is to use standardized coefficients which either relate concentrations in soil to external dose rates or convert a unit of intake into internal dose These coefficients are estimated using complex mathematical models of radionuclide behaviour and radiation absorption in the body. Internationally agreed values of the committed effective dose per unit activity intake for a large number of radionuclides have been derived by the International Commission on Radiological Protection (ICRP) and are published in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (FAO et al 1996) These values have been used in the dose assessments made during the Study.

9.3. SOURCES AND PATHWAYS OF EXPOSURE

Radiation exposures to people living on and in the vicinity of Mururoa and Fangataufa would result from two sources: natural sources of radiation and residual radioactive material from nuclear weapon testing. The main exposure pathways are as follows:

(a) *External irradiation:* for example, from cosmic sources or from radionuclides deposited in soil or sediments;

[12] Unless otherwise stated, the term dose refers to effective dose as defined by the International Commission on Radiological Protection (ICRP) The term includes doses arising from external irradiation and doses integrated to age 70 from intakes of radionuclides

(b) *Inhalation:* of radionuclides in resuspended soil or sediments;
(c) *Ingestion:* of radionuclides in foods grown on the atolls or in foods obtained from the marine environment.

For natural sources of radiation, the main exposure pathways in this region are ingestion of radionuclides in marine foods and external irradiation from cosmic rays. The very low contribution to external exposure from primordial nuclides such as uranium and thorium is due to the almost complete absence of these elements from the corals and coral derived carbonates that comprise the surface layers of coral islands.

For residual radioactive material, the ingestion of foods grown on the atolls and derived from the marine environment is the pathway of greatest significance. For the sake of completeness, three additional pathways were also considered:

(d) Incorporation of plutonium-containing particles in a cut or wound,
(e) Ingestion of soil (pica) by young children,
(f) External irradiation from beaches and fishing gear.

In order to make an assessment of the doses to hypothetical inhabitants of Mururoa or Fangataufa, it is first necessary to make assumptions about their location, lifestyle and diet.

9.4. CHARACTERISTICS OF HYPOTHETICAL POPULATION

9.4.1. Location

For atolls in relatively close proximity, such as Mururoa and Fangataufa, a common residential pattern would be for one or more villages to be established on the larger islets of the larger atoll, and for the smaller atoll to be visited periodically for food gathering. Habitation is unlikely to be established in the future unless there are sufficient mature coconut groves, a village infrastructure, including rainwater collection and treatment, and transport links. If a hypothetical population group were to be established on Mururoa, therefore, it is likely that the village would be at the widest (i.e. eastern) and more protected end of the atoll, close to the airstrip (e.g Anémone) For the purposes of the Study, a hypothetical population at Anémone has therefore been assumed. Other Mururoa locations such as Faucon might conceivably support a very small and isolated group of not more than a few families. Fangataufa is more frequently subjected to inundation and would not appear suitable for extended habitation. However, the possible doses to a resident population in the Kilo–Empereur region of Fangataufa, where there are pockets with elevated levels of ^{137}Cs in the soil, have been assessed in the interests of providing a hypothetical maximum dose.

TABLE LXV. DIET (g/d) FOR ADULT TUREIA POPULATION ESTIMATED BY SMSRB (IPSN 1995)

Foodstuff	Tureia derived food	Imported food
Beverages		
Drinking water	2000	
Coconut milk	144	
Soft drinks		0 27
Fresh milk		0.52
Beer		108
Meat		
Dog	20	
Pork	2 1	
Chicken	5.4	33.0
Eggs		24.8
Beef		31.0
Fish		
Reef fish	395	
Seafood		
Giant clam	40	
Lobster	6 4	
Octopus	26.7	
Turbo	1.6	
Fruit		
Banana	7.7	
Coconut meat	104	
Papaya	15	
Breadfruit	7 2	
Other staples		
Bread		190
Pasta		4 1
Rice		85 5

9.4.2. Dietary habits

The atoll environment generally provides coconut and fish in abundance all year round, together with breadfruit, pandanus, bananas and other seasonal tree fruits Chickens, pigs and, in French Polynesia, dogs are also local sources of food. Total dependence on local foods no longer occurs, and imports of bread, rice and noodles have tended to replace traditional staples. Atoll

TABLE LXVI. ANNUAL DOSES (μSv) DUE TO NATURAL SOURCES

Source	Mururoa (Anémone)
External radiation	270
^{40}K (internal)	180[a]
^{210}Po + ^{210}Pb (internal)	900–2500[b]
Total	1400–3000

[a] Source IPSN (1995)

[b] Depending on the concentration of ^{210}Po in fish in the region

rainfall also affects soil quality and productivity. Actual diets vary regionally and with atoll group and local characteristics, such as income level and regularity and nature of transport from regional centres, but a comparison of diets from different Pacific areas shows general similarities.

The closest Polynesian population to Mururoa and Fangataufa, on which the habits of a hypothetical population could be based, lives on Tureia Atoll. The dietary information for Tureia, used by the Institut de protection et de sûreté nucléaire (IPSN) (1995) is shown in Table LXV. The Tureia diet contains a higher proportion of local food products than is observed in many other locations in the Pacific region. It is therefore considered to be a reasonable estimate of the diet of a hypothetical resident population at Mururoa, where there are constraints on imported food supplies. This diet was used to assess hypothetical doses at Mururoa. However, Tureia is an atoll with an entirely enclosed lagoon, noted for its production of clams, which are consumed in quantity by the local population. The ingestion rate for this particular food is likely to be higher than that of a Mururoa population.

9.5. RADIATION DOSES DUE TO NATURAL SOURCES

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has estimated the worldwide exposure to natural background radiation The average annual effective dose is 2.4 mSv (e.g. United Nations 1982)

Both the total dose and the contribution due to different natural sources vary from place to place in the world. In some areas the total dose can be an order of magnitude higher than the average. At Mururoa and Fangataufa the dose from natural sources is of the same order as the average, as shown in Table LXVI However, the relative contributions of the different sources to this total are different from those found in many other parts of the world The external radiation contribution is very largely made up of cosmic radiation, which has a fairly constant rate for sea level locations The contribution to external radiation exposure from naturally occurring radionuclides is very low because of the very low concentrations of these radionuclides in coral soils. The dose from inhalation of naturally occurring radon daughter products, while a major source of exposure to natural radiation sources in continental areas, is also very small on atolls because of the very low concentrations of uranium decay chain nuclides in the carbonate strata and remoteness from land masses (French Liaison Office Document No. 3).

Concentrations of ^{210}Po (and ^{210}Pb) in marine foodstuffs, used to estimate the background doses from these radionuclides given in Table LXVI, are derived from worldwide mean values obtained in an international study of doses from marine radioactive material (the MARDOS study) (Aarkrog et al 1997). However, the mean concentration of ^{210}Po in the flesh of reef fish from lagoons of coral atolls and in other seafood items in the equatorial Pacific may be considerably higher than the mean level encountered in different species of fish from continental shelf and colder areas A study by Jeffree et al. (1997) found enhanced uptake of ^{210}Po in zooplankton in French Polynesia. The concentrations of ^{210}Po in fish and other seafood species found by Noshkin et al. (1994) in the Marshall Islands are about two to three times greater than the mean values found in the MARDOS study. The present Study had no information on measured levels of ^{210}Po in fish in the region of Mururoa, but if similar concentrations apply at Mururoa as are found in the Marshall Islands, annual doses from naturally occurring sources could reach 3 mSv. The uncertainty in the annual doses associated with naturally occurring sources in this region is about 1 5 mSv.

9.6. RADIATION DOSES DUE TO RESIDUES FROM NUCLEAR TESTING

In order to assess both the present and possible future impacts of radioactive residues in the environment, it was necessary to calculate the doses to a number of different populations under a number of different conditions. Three types of exposure scenario resulting from the French tests and safety trials are considered in this section.

(a) Exposure arising from residual material already in the biosphere;

(b) Exposure arising from residual material, at present underground, that is released into the biosphere as a result of normal processes;
(c) Exposure arising from residual material, at present underground, that is released into the biosphere as a result of a possible disruptive event.

9.6.1. Doses arising from residual material already in biosphere

The impact of residual material already in the biosphere was assessed by estimating doses that would be received both by a hypothetical population at Mururoa Atoll and by the population of Tureia, the nearest inhabited island. These doses were estimated on the basis of measured present activity concentrations in the environment The variation of these doses with time was also considered.

9.6 1.1. Doses to a hypothetical population at Mururoa

For the purposes of dose calculation, a hypothetical population was assumed to be located in the Anémone area of Mururoa Atoll. Other areas of this atoll were assumed to be visited to collect food. These assumptions are based on known residential patterns on atolls in the Pacific, as indicated above.

External irradiation from radionuclides deposited in soil

The activity concentrations of ^{137}Cs in soil in the Anémone area, measured during the Study's terrestrial sampling campaign, were of the order of 1 Bq/kg or less. Monitoring in situ indicated areal deposition levels of less than 100 Bq/m^2 and very low concentrations of other gamma emitters (Technical Report, Vol 1) Measurements reported by Simon and Graham (1997) indicate that for coral soils an areal deposition of 100 Bq/m^2 of ^{137}Cs gives rise to an external effective dose rate of about 0.25 μSv/a. The external dose rates received by a hypothetical population resident at Anémone would therefore be much less than 1 μSv/a.

External gamma radiation from plutonium and americium in the Colette area of Mururoa, where the residual levels of $^{239+240}Pu$ are estimated to be about 3 MBq/m^2, could give annual effective doses of the order of 100 μSv for continuous occupancy in this area. However, continuous occupancy in this area is not considered plausible. The most likely form of exposure would derive from occasional visits by local inhabitants for fishing The dose likely to be received during these visits was assessed. If the Colette area were visited for a period of 4 h once every 20 d, the contribution to the annual dose from external radiation due to residual radioactive material would be around 1 μSv.

Inhalation of radionuclides in resuspended soil

Of the radionuclides present in the atoll environment, those of greatest potential significance for the inhalation exposure pathway are $^{239+240}Pu$ and ^{241}Am. These radionuclides are present in surface soil particles which may be resuspended by the action of wind or vehicles. Activity concentrations of $^{239+240}Pu$ in air at Anémone have been measured by French scientists as well as during the Study. The Study measurements were in agreement with the value of 75 nBq/m^3 at Anémone, measured in 1994 by the Service mixte de surveillance radiologique et biologique de l'homme et de l'environnement (SMSRB) (French Liaison Office Document No 3). The Study estimated that an adult resident in this area could receive an inhalation dose rate of between 0.01 and 0.03 μSv/a, depending upon the assumed chemical form of the radionuclide. The dose rate to a hypothetical resident child would be lower.

Airborne activity concentrations (Bq/m^3) may also be estimated from measurements of areal deposition (Bq/m^2) by using a 'resuspension factor' (in units of m^{-1}) This approach has been adopted to estimate hypothetical inhalation doses which may arise during periods spent on the Colette motu, where higher deposits of plutonium and americium remain. Detailed studies of coral soils in the northern Marshall Islands found that there is, on average, little resuspension from such soils The measured resuspension factors ranged from 10^{-11} to 10^{-10} m^{-1} (IAEA 1998). These data are supported by the similarly low resuspension factors found in the Palomares region of Spain, following an incident in which fissile material became dispersed (García-Olivares and Iranzo 1997). The Marshall Islands data were assumed to be applicable to the soils in the Colette area, where an average areal deposition of $^{239+240}Pu$ of around 3 MBq/m^2 was measured. In calculating the hypothetical dose from this pathway, account was also taken of the fact that less than 2% of this activity is associated with particles within the respirable range (Section 4). Continuous occupancy in this area would lead to a dose rate from resuspension of the order of 1–3 μSv/a, depending upon the assumed chemical form of the radionuclide. If members of a hypothetical population from Anémone made visits to the Colette area on the same basis as postulated above, the contribution to the total hypothetical annual dose from inhalation in the Colette area would be less than 0.1 μSv.

TABLE LXVII CONCENTRATION FACTORS AND ASSESSED CURRENT CONCENTRATIONS IN MARINE SPECIES IN MURUROA LAGOON

Radionuclide	Water	Fish		Molluscs		Crustaceans	
	(Bq/m^3)	CF	Bq/kg	CF	Bq/kg	CF	Bq/kg
^{90}Sr	2 0	2	0 004	1	0 002	2	0 004
^{137}Cs	2 1	100	0.21	30	0.063	30	0 063
^{238}Pu	0 05	40	0.002	3 000	0 15	300	0.015
$^{239+240}$Pu	0.25	40	0 01	3 000	0 75	300	0 075
^{241}Am	0.002 5	50	0 000 13	20 000	0 050	500	0 001 3

TABLE LXVIII. EFFECTIVE DOSE RATE CONTRIBUTIONS (μSv/a) FROM INGESTION FOR MURUROA RESIDENTS

	^{60}Co	^{90}Sr	^{137}Cs	^{238}Pu	$^{239+240}$Pu	^{241}Am	Total
Seafood	0 00	0.02	0 41	0 63	3 43	0 16	4 65
Other	0 00	0.05	0 86	0 00	0 00	0 00	0 91
Total diet	0 00	0.07	1.27	0 63	3.43	0 16	5 56

Ingestion of foodstuffs grown on the atolls and of fish and other marine environment species

Activity concentrations measured in the environment (Section 4 3) or predicted have been used in conjunction with the dietary information outlined in Section 9.4 and dose coefficients given in the Basic Safety Standards (FAO et al 1996) to give estimated doses to a hypothetical population at Mururoa

Where possible, ingestion doses to residents have been calculated on the basis of measured total activity concentrations of each radionuclide in local dietary items However, there are few examples of vegetation at Mururoa on which doses from ingestion of terrestrial foods from the atolls can be based Activity concentrations in coconuts were the only available direct measure of concentrations in food crops which might be grown on the atolls. As a result, plant to surface soil ratios based on data for Bikini Atoll (Robison et al. 1995) were employed to estimate expected plant and animal concentrations. The measured activity concentrations of radionuclides in lagoon water, and concentration factors proposed in Section 4, have been used to estimate concentrations in marine foods. These values are shown in Table LXVII

Assuming the Tureia diet (Table LXV), the annual effective dose to hypothetical residents of Anémone from ingestion of local foods is estimated to be 5 6 μSv. The contributions of different foods and radionuclides to this dose are summarized in Table LXVIII. The major components of this dose are the plutonium and americium in seafood (contributing about 4 μSv/a) and ^{137}Cs in other food items (0.9 μSv/a, mostly from coconuts).

Because the measured and estimated levels of ^{137}Cs in food items will contain some contribution from global fallout, not all of the dose component due to ^{137}Cs in Table LXVIII is attributable to the tests carried out at Mururoa and Fangataufa. For terrestrial food items the contribution from global fallout is not known. In the case of seafood, however, measurements of ^{137}Cs concentrations in lagoon (2.1 Bq/m^3) and ocean water (1.9 Bq/m^3) indicate that almost all of the ^{137}Cs in the lagoon water is derived from global fallout The dose rate from the ingestion of marine foods due to the total ^{137}Cs in lagoon water is around 0 4 μSv/a. The hypothetical annual dose from the residual radionuclides present due to French weapon testing at the atolls would therefore be somewhat less than the value of 5.6 μSv given above.

In the interests of determining the robustness of the above dose estimate, and more particularly the influence of the assumed diet on the estimated dose, doses were also estimated using two alternative diets. These alternative diets are based on independent dietary surveys of two atoll groups in the Marshall Islands, in situations where there were constraints on food imports — with a resulting high dependence on local foods — and in situations where imported foods were readily available (Robison et al. 1995, Dignan et al 1994). The diets are presented in Tables LXIX and LXX The hypothetical annual effective doses from ingestion corresponding to a

TABLE LXIX. LAWRENCE LIVERMORE NATIONAL LABORATORY MODEL OF DIET (g/d) FOR ADULTS ON BIKINI ISLAND
(Robison et al. 1995)

Local food	Imported foods included	Local foods only
Reef fish	24 2	86.8
Tuna	13 9	72 0
Mahi mahi	3 56	21 4
Marine crabs	1 68	19 5
Lobster	3.88	35 2
Clams	4 56	58 1
Trochus	0 10	0 24
Tridacna muscle	1 67	11 4
Jedrul	3 08	19 4
Coconut crabs	3.13	24 9
Octopus	4 51	49.0
Turtle	4 34	17.8
Chicken muscle	8 36	31 2
Chicken liver	4 50	17.7
Chicken gizzard	1.66	3 32
Pork muscle	5 67	13.9
Pork liver	2 60	6.70
Pork heart	0 31	0 62
Bird muscle	2 71	26 4
Bird eggs	1 54	22 8
Chicken eggs	7 25	41 2
Turtle eggs	9 36	235
Pandanus fruit	8.66	63 0
Pandanus nuts	0 50	2 00
Breadfruit	27 2	186
Coconut juice	99 1	333
Coconut milk	51.9	122
Drinking coconut meat	31 7	181
Copra meat	12 2	71.3
Sprouting coconut	7 79	122
Papaya	6 59	27 0
Pumpkin	1.24	5 44
Banana	0.020	0.58
Arrowroot	3 93	94.9
Citrus	0 10	0 20
Total (kcal/d)	547	2783

TABLE LXX. RONGELAP ADULT MALE DIET (g/d) ASSUMED FOR NATIONWIDE RADIOLOGICAL STUDY
(Dignan et al. 1994)

	18% local food + rice + imports	75% local food + rice only
Bird (kalo), roasted	14 0	59 7
Coconut cream (solid)	64 2	274 3
Coconut milk	16.1	68.8
Coconut, drinking	24 3	103.7
Coconut embryo	1 5	6.3
Coconut, hard (waini)	5.3	22 8
Coconut, soft (mede)	5 3	22 6
Coconut crab	1 3	5 4
Jekeru	83.5	357.1
Jemanin	3.7	15.8
Pandanus fruit, raw	12 7	54 5
Pandanus fruit, cooked	6 1	26 1
Papaya	6.9	29 4
Pork	2.7	11 4
Pumpkin	1 5	6 3
Reef fish	35 8	153 3
Ocean fish	20.1	86 2
Rice	500	500
Imported foods	~990	0
Total (kcal/d)	2484	2484

diet of mostly local foods are 9.7 and 3.1 μSv, respectively. The differences in annual doses between the three diets are very largely attributable to the differences in the amounts of molluscs, particularly clams, in the diets.

Incorporation of plutonium in a cut or wound

Active particles exist on the motus of Colette, Ariel and Vesta of Mururoa as a result of the atmospheric safety trials, and measurements to better characterize the level and distribution of this activity on the affected areas were conducted as part of the Study (Section 4 and Technical Report, Vol 1). The incorporation of active particles in cuts or wounds is a potential exposure pathway, the significance of which depends upon several factors, notably the activity and size distribution of the particles, the frequency of incidents leading to cuts and wounds, the treatment applied, and the behaviour of the radioactive material leached from the active particle when embedded in human tissue. A detailed description of the approach adopted by the Study to assess the radiological risk in this case, and the results, are given in the Technical Report, Vol. 6, but the main factors considered and indicative results are summarized below.

The most convenient measure of the potential impact of active particles on Mururoa is in terms of risk[13] rather than dose. This allows the probability of material becoming incorporated in a cut or wound (sustained, say, by a fall on the sharp coral) to be combined with the probability of an impact on health occurring as a

[13] Individual lifetime risk of a serious detriment to health in a given time period, usually a year (as defined by the ICRP)

consequence. For the purposes of the Study, the following components of the probability were combined in a Monte Carlo analysis to give an overall risk probability distribution:

- Probability of residence on the atoll (assumed equal to 1),
- Probability of spending a certain number of hours per year on the affected motus,
- Probability of an accident leading to a wound while in the area,
- Probability of a significantly active particle lodging in tissue via the wound and remaining there,
- Dose resulting from the incorporated material,
- Risk of serious health detriment arising from such a dose.

The values assumed for each of these components of the overall probability are discussed in the Technical Report, Vol. 6. The resulting risk of induction of a fatal cancer in the long term was assessed to be 7×10^{-7} per year (at the 99% confidence level). This is equal to the fatality risk associated with an annual effective dose of about 15 μSv, which is less than 1% of the local background dose and therefore represents a very small risk. The implications of these results are discussed later in this section and in Section 11.

Soil ingestion

There is evidence from some parts of the world of a tendency known as pica where individuals, primarily young children, ingest soil in significant quantities Such behaviour tends to be intermittent and not to be sustained over an extended period. If this condition were to persist for one year, between 0 1 and 1 kg of soil could be consumed during the year.

The mean $^{239+240}$Pu surface soil activity in the Anémone area, where the hypothetical group is assumed to live, is about 4 Bq/kg. The standard effective dose per unit intake for ingestion for a child of one to two years of age (FAO et al. 1996) would imply a maximum hypothetical effective dose rate from this route of about 2 μSv/a. It is likely that plutonium in soil is less available for uptake through the gut than that in usual dietary sources, suggesting that this dose may be an overestimate.

External irradiation from beaches and fishing gear

For assumed occupancies of 2 h/d for both beach use and fishing (730 h/a), the annual doses to hypothetical residents from external irradiation due to radionuclides present in lagoon water are several orders of magnitude below those due to ingestion. The primary contributor to external exposure would be ^{137}Cs.

9.6 1.2. Doses to a hypothetical population at Fangataufa

In the interests of estimating the maximum doses that could arise from residual radioactivity in the environment of the two atolls, the doses to a hypothetical population living in the Kilo–Empereur region of Fangataufa Atoll were assessed. This area received fallout from the Rigel barge test in the Frégate area of Fangataufa. Enhanced levels of ^{137}Cs were found to be very patchy, with a maximum, over small areas, of about 200 Bq/kg (Section 4.3.1.6). A necessarily small resident group of not more than a few families was assumed to derive all its terrestrial foodstuffs from a few hectares of land on the lagoon-side rim (in the Kilo area) where, it was assumed, all soil concentrations of ^{137}Cs were at the highest level measured (200 Bq/kg). Making this extreme assumption, a hypothetical annual effective dose from ingestion of about 160 μSv can be derived. A population continuously occupying this area would also receive a contribution from external exposure of about 60 μSv/a, giving a total dose rate to a member of this group of around 220 μSv/a. This is the highest dose rate assessed for any group in the Study, and is equivalent to about one tenth of that due to natural radiation sources. This dose rate would decrease with an effective half-life of less than 20 years (Section 9.6.1 5); that is, it would fall to 1–2 μSv/a within 100 years. However, such dose rates are most unlikely to be received in reality because of the virtual uninhabitability of Fangataufa Atoll.

9.6.1.3. Doses to the population of Tureia

The estimated present annual effective dose rates to residents of Tureia, the closest permanent population group to Mururoa and Fangataufa, are presented in Table LXXI. The total dose rate is about 5 μSv/a, most of which (4 μSv/a) is due to ^{137}Cs in coconuts. An indeterminate part of this dose arises from global fallout. The ingestion of terrestrial foods is more important on Tureia than for the hypothetical group at Mururoa because of the higher ^{137}Cs concentrations in soil found on Tureia than on Mururoa (Section 4.3.1 6) The relative contribution to the estimated dose at Tureia from global fallout will therefore be greater than for the hypothetical population on Mururoa. The contribution to dose from the ingestion of marine foods is very small, because of the absence at Tureia of the contribution from activity in sediments arising from the barge tests at Mururoa As for

TABLE LXXI. ANNUAL EFFECTIVE DOSE RATES (μSv/a) TO ADULT RESIDENTS OF MURUROA AND TUREIA FROM ARTIFICIAL RADIONUCLIDES IN THE ENVIRONMENT RESULTING FROM FRENCH NUCLEAR TESTS

Pathway	Mururoa (Anémone)	Tureia
External irradiation, excluding natural	~1.1	<1
Inhalation	<0.1	—[a]
Ingestion: terrestrial	0.9[b]	4[b]
Ingestion: marine	4.3[c]	0.01[c]
Total	~6	~5

[a] Not applicable.

[b] An indeterminate part of the dose arises from global fallout.

[c] The contribution to the marine ingestion dose rate of 0.4 μSv/a arising from global fallout is not included in these dose estimates.

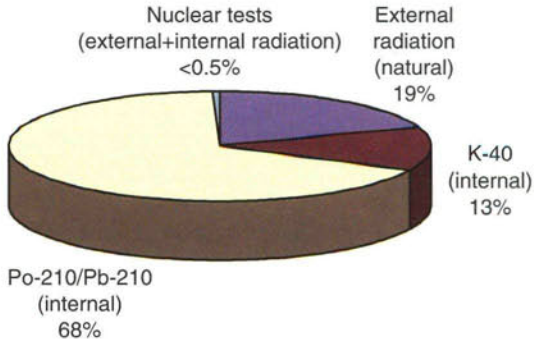


FIG. 132. Relative proportions of doses from residual radionuclides in the environment of the atolls arising from the French nuclear tests and from natural sources.

Mururoa, the global fallout contribution to the effective dose rate from the ingestion of local marine foods is around 0.4 μSv/a.

9.6.1.4. Summary of present doses from residual radioactive material in the environment as a result of the French weapon testing programme

Current dose rates to a hypothetical adult population resident in the Anémone area of Mururoa and for residents of Tureia are summarized in Table LXXI. The total annual dose from residual radionuclides in the environment arising from the French nuclear tests is not known precisely (some component of the terrestrial doses in Table LXXI arises from global fallout). However, it clearly a very small fraction of that due to natural sources, as shown in Fig. 132, and trivial in relation to the uncertainty of about 1500 μSv/a associated with the estimation of doses incurred from polonium naturally occurring in marine foodstuffs. The dose estimates presented above are in close agreement with French estimates for both Mururoa (Bourlat et al. 1996b) and Tureia (IPSN 1995, 1996).

9.6.1.5. Trends in doses from radionuclides currently in the environment

The current low levels of ^{90}Sr and ^{137}Cs in the terrestrial and marine environments at Mururoa and Fangataufa arising from atmospheric tests will decline at least as fast as the radioactive half-lives of the two nuclides (29 and 30 years, respectively). Natural removal processes will increase the rate of decline in concentrations, particularly in the marine environment, where decline with an effective half-life of less than 20 years can be expected (Section 4.3.2.4). The effective half-life of ^{137}Cs in the marine environment in the Polynesian ocean and currently in Mururoa lagoon waters appears to be about 15 years (French Liaison Office Document No. 3).

Actinides in lagoon sediments can be expected to make a small contribution to resident population doses over a long time. The effect of a small net sedimentation rate coupled with sediment removal from the lagoon will be to dilute the concentrations in surface layers. Assuming a small net sedimentation gain, and allowing for periodic turbulent mixing as a result of cyclones, the concentration of actinides in surface sediments could be expected to have declined to about one tenth or less of current levels after 1000 years. Concentrations in molluscs, as the main dietary contributor to doses from actinides, could also be expected to decline to at least a similar extent over this time. In practice, the observed rate of decline in plutonium concentration in filtered water from Mururoa lagoon has been particularly rapid, with a significant decline (an apparent half-life of about seven years; Section 4.3.2) over the last decade.

Estimated future annual effective doses arising from the declining levels of artificial radionuclides currently in the environment and from predicted future releases into the lagoons and ocean of radionuclides migrating from underground sources are discussed in the next section.

TABLE LXXII VARIATION IN ANNUAL EFFECTIVE DOSES (μSv) TO MURUROA RESIDENTS WITH TIME FOR PREDICTED FUTURE ENVIRONMENTAL CONCENTRATIONS OF RADIONUCLIDES

Years from 1995	0	20	50	100	200	500	1000	2000	5000	10 000
External irradiation	1 1	1.1	1.0	1 0	0 9	0 9	0.9	0.9	0 9	0 9
Ingestion terrestrial	0 9	0 5	0.2	0.1	<0 1	<0 1	<0 1	<0 1	<0 1	<0 1
Ingestion· marine	4 3	0 9	0 3	0.2	0.1	0.2	0 4	0 6	3.4	2 2
Total	6.3	2.5	1.5	1 2	1 0	1 1	1 3	1 5	4 3	3 1

9.6.2. Doses from modelled future releases into the environment

Potential future releases into the marine environment of residual radionuclides at present underground have been modelled as described in Sections 6 and 8. Doses from normal release scenarios are discussed in this section; the potential doses arising from possible disruptive release scenarios are discussed in Section 9.6.3 Estimates were made of the fractions of the material migrating to the carbonate zone that escape to the lagoons and directly to the ocean. The ocean releases were assumed to occur some hundreds of metres below the surface and beneath the thermocline The doses arising from such releases at Mururoa and other locations in the South Pacific have been calculated as described below.

9.6 2.1. Doses to a hypothetical population at Mururoa

Radionuclides in the lagoon provide the major component of doses to a hypothetical population at Mururoa, while at other Pacific locations activity in the ocean is of greater importance. Figure 109 shows the way in which the concentrations of ^{90}Sr, ^{137}Cs and plutonium in the lagoon waters of Mururoa are predicted to change with time Figure 114 shows the estimated fraction of the total release from the atoll to the ocean that occurs via the lagoon and the fraction that is released directly to the ocean. The releases would affect populations other than a hypothetical population at Mururoa

The predicted releases of ^{90}Sr and ^{137}Cs to the lagoon decrease with time and are indistinguishable within a few decades from ocean concentrations due to global fallout. The predicted release rate to Mururoa lagoon of plutonium declines initially with an effective half-life of about ten years, but after about 100 years contributions from underground sources begin to become apparent. A peak is reached in about 5000–6000 years, although at a level which is below the present rate.

On the basis of the predicted releases to Mururoa lagoon (Fig. 109), doses to Mururoa residents at future times from the ingestion of marine food items were calculated. The doses arising from ^{90}Sr and ^{137}Cs in the terrestrial environment were calculated on the basis of existing levels by assuming a 25 year effective half-life for decline in concentration The assumption was also made that the diets and lifestyles of residents would be unchanged in the long term. The variation with time of the total dose from artificial sources to a hypothetical population at Mururoa is shown in Table LXXII, together with the contributions of different exposure pathways The predicted future doses contain no contribution from global fallout since they are based on predicted future releases which lead to estimates of the elevations in concentrations in the sea above background levels.

Doses in the far future are dominated by the long term release rate of plutonium, but such doses continue to be a very small fraction of those arising from natural sources. The fraction of the total release that occurs through the lagoon is uncertain. There is even greater uncertainty associated with the hydrological pathway for movement of plutonium through the carbonates. The degree of retardation, often expressed in terms of a distribution coefficient, is not known. As a consequence, release rates have been calculated assuming no retardation in the carbonates. The estimated future releases therefore represent an upper limit of those which might be expected from underground sources. Nevertheless, on the basis of the assumptions made, the dose to a hypothetical population at Mururoa could rise, some 5000–6000 years from now, to a level three to four times greater than the lowest levels reached (at around 100–500 years). However, this dose will remain below the current estimated annual level of about 6 μSv.

9.6 2.2. Exposures in other areas of the South Pacific

The release of radionuclides from either current or future discharges from Mururoa and Fangataufa Atolls can contribute to radiation exposures of people

TABLE LXXIII. ANNUAL EFFECTIVE DOSES (μSv) FROM RADIONUCLIDES TO HIGH INTAKE SEAFOOD CONSUMERS FOR A SEAWATER CONCENTRATION OF 1 Bq/m^3 PER RADIONUCLIDE

Radionuclide	Dose
^{60}Co	2.9
^{90}Sr	0 014
^{129}I	0 52
^{137}Cs	0 20
^{237}Np	2.3
^{238}Pu	45 5
$^{239+240}$Pu	49.5
^{241}Am	208

TABLE LXXIV. CURRENT ANNUAL EFFECTIVE DOSES (μSv) TO HIGH INTAKE SEAFOOD CONSUMERS ON FRENCH POLYNESIAN ISLANDS ARISING FROM RELEASES FROM MURUROA AND FANGATAUFA

Location	Dose
Tureia	0 026
Tematangi	0 018
Mangareva	0.004 6
Hao	0 006 4
Tubuai	0.000 35
Tahiti	0 003 2

elsewhere in the South Pacific only by ocean transport, and primarily via seafood ingestion. Other, minor, pathways are external irradiation from radionuclides in beach sediments and, for people who fish, from the handling of fishing gear with adhering radioactive particulates. The nearest inhabited atolls are those of Tureia to the northeast and Tematangi to the west, both supporting small populations. Estimated future concentrations of ^{90}Sr, ^{137}Cs and $^{239+240}$Pu in ocean water at various South Pacific locations are presented in Section 8 for different postulated releases and release rates.

Doses to high intake seafood consumers resident in the South Pacific region have been estimated from the dietary intake proposed by the IAEA (1986). This diet comprises a somewhat extreme daily intake of 300 g of fish and 100 g each of molluscs, crustaceans and seaweed and should be considered to provide a basis for comparing upper limits of doses rather than for estimating actual doses that residents might receive. Generic concentration factors (CF, the ratio of the concentration in each type of seafood to that in sea water) for different elements have been published by the IAEA (1985). These data, together with the ingestion rates mentioned above and with internationally agreed dose conversion factors (FAO et al. 1996), have been used to derive a dose rate per unit seawater concentration conversion factor ((μSv·a^{-1})/(Bq·m^{-3})) for a number of significant radionuclides. These data are presented in Table LXXIII.

The Equidistant Grid Compartment Model (Section 8.5 3.1) provides estimates of surface water concentrations (of ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}$Pu) at various Pacific islands for the time dependent total releases shown in Fig. 114. The concentrations of ^{3}H, ^{137}Cs and $^{239+240}$Pu are shown in Figs 119–121 as a function of time (up to 100 000 years for plutonium) Estimated current doses (calculated for 1995) to high intake seafood consumers, as defined above, are given in Table LXXIV. Actinides provide the dominant contributions to the predicted ingestion doses. The contribution from ^{238}Pu has been included by assuming an initial concentration of 0.2 that of $^{239+240}$Pu and taking account of its radioactive decay. The highest dose rate due to releases from the atolls, received under present conditions, is at Tureia and amounts to approximately 0.03 μSv/a — about 1/100 000 of the dose rates received from natural sources. Over time, the dose to high intake seafood consumers in the South Pacific will follow the release rate from the atolls, so that in about 6000 years' time (Fig 121) annual doses are predicted to peak again, reaching about one third of the extremely low levels at present in the environment (Table LXXV).

An analysis of doses due to external irradiation from sediments on beaches and radioactive material attached to fishing gear indicates that they are unlikely to amount to as much as 1/1000 of those from ingestion, and that the greatest contributor to external exposure is ^{137}Cs (Technical Report, Vol. 6)

As a comparison of the magnitude of the doses arising from future releases from the two atolls, it may be noted that for Tureia, for example, the current annual doses are equivalent to the doses received from about 5 min of exposure to average natural radiation sources. Doses at other locations and times are all lower. In the Cook Islands, and farther west, annual doses to high intake seafood consumers are unlikely to exceed 0.001 μSv either now or at any future time

9.6.3. Exposures from possible disruptive or climate change events

A range of hypothetical disruptive and climate change events that could affect the atolls over the long term were described in Section 7. Of these, two were assessed as possibly having implications for modifying

TABLE LXXV. ANNUAL EFFECTIVE DOSES (μSv) FROM RESIDUAL RADIOACTIVITY AT MURUROA AND FANGATAUFA

Years from 1995	1	20	50	100	200	500	1 000	2 000	5 000	10 000
Mururoa residents	6	3	2	1	1	1	1	1	4	3
High intake seafood consumers:										
Tureia	0 03	0 01	0 004	0.004	0.001	0.001	0 001	0.002	0 008	0 005
Tubuai	0 000 4	0 000 2	0.000 06	0.000 05	0 000 01	0.000 01	0 000 02	0 000 03	0 000 01	0.000 07
Tahiti	0 003	0.002	0 000 5	0 000 5	0.000 1	0 000 1	0 000 2	0.000 2	0 001	0 001

TABLE LXXVI. MAXIMUM ANNUAL DOSES (μSv) TO HIGH INTAKE SEAFOOD CONSUMERS IN THE YEARS FOLLOWING A POSTULATED INSTANTANEOUS RELEASE RESULTING FROM A ROCK SLIDE

Location	Year: 1	2	3	5	10	20
Tureia	6.6	2.8	1.2	0.42	0 09	0.004
Hao	0 39	0.93	0 53	0 25	0.08	0.003
Tahiti	0.006	0 21	0.41	0 18	0 04	0 002

releases from the atolls, and therefore for human exposure The radiation dose implications are evaluated here.

9.6 3.1. Slide of carbonate rock

A slide occurring within the near future on the northern flank of Mururoa in an area which intersects the chimney of a 5 kt CRTV test and the zone of one safety trial containing 3.7 kg of plutonium is postulated in Section 7.3.1 Pessimistic assumptions provide the estimated radionuclide release shown in Table XLIX. The resulting activity concentrations in water at various Pacific locations have been assessed, as described in Section 8. If the release occurs above a depth of about 400 m, the peak concentrations at the nearest inhabited island of Tureia will occur within the first few months; for locations farther away, such as Hao and Tahiti, the peak concentrations are lower and two to three years later. If the releases were to occur at depths below the thermocline, higher concentrations at depth in sea water could occur at some islands, but there would be little impact on food sources, so that lower doses would result

The time variation of ingestion doses to high intake seafood consumers at Tureia, Hao and Tahiti is shown in Table LXXVI, as calculated for concentrations predicted by the Equidistant Grid Compartment Model (Section 8.5.3.1). For high intake seafood consumers resident on Tureia, the maximum dose, which would be received during the first year following the release, is about 7 μSv, declining to about 3 μSv in the second year. Even though the doses assessed are very low, the pessimistic nature of the assumptions underlying these dose estimates should be recognized. Most of the dose is contributed by the plutonium postulated to be involved in the slide and all of which is assumed to go into solution In reality this would be most unlikely to occur (Section 7.3 1)

9.6.3.2. Glaciation

An ice age after a postulated 50 000 years accompanied by a major fall in sea level of about 100 m (Section 7.3.2) would result in drainage of the lagoons and the potential for a resident population to be exposed by the inhalation of residual plutonium attached to lagoon sediments. Sediment production and exchange processes currently result in a loss of about 5.4 GBq/a from the lagoon, or about 0 03%/a of the total plutonium inventory in the sediments. Over recent years, however, the rate of loss has been declining, so that removal by solution and sediment transfer may be of less significance in the future Even if material were removed at a reduced rate in the future, a net increase in sediment thickness of about 2 mm/a would result in a very great reduction in surface concentrations over the period being

considered. The effect of sedimentation, coupled with periodic surface layer mixing resulting from storms and turnover by animals living in the sediment, would be continuous dilution of the concentration of radionuclides in the surface sediment layers. Assuming only radioactive decay, and a very low net sedimentation increase, the present mean surface concentration of less than 200 Bq/kg could be expected to decrease to well below 5Bq/kg over a period of 25 000 years, with at least a similar proportionate reduction in concentration over the following 25 000 years. The annual dose from resuspension and inhalation for a surface concentration of 5 Bq/kg and moderately dusty conditions (100 $\mu g/m^3$ with an enhancement factor of 3 (Shinn et al. 1997)) is about 0 6 μSv. If the lagoon beds were to become dry and exposed in 50 000 years' time, the consequent doses arising from inhalation of residual plutonium attached to the bed sediments would therefore be trivial.

The glaciation scenario discussed in Section 7.3.2 also postulated the formation of a freshwater lens, when the sea level has dropped by 100 m in the carbonate formations which could extend to the region of the safety trials carried out beneath the northern rim of Mururoa at depths greater than 280 m. The analysis, based on the unlikely assumption of total retention of plutonium released from the trial cavities in the carbonates, led to an average concentration in the water of about 3 Bq/m^3. If such water were used for drinking, then assuming a daily intake of 2 L, small annual doses of about 0.5 μSv could be received.

The possibility was also considered that plutonium plumes, in which the concentration would be at the solubility limit of plutonium (10^{-8}M, or 6×10^3 Bq/L; see Technical Report, Vol. 4), might continue to exist, 50 000 years from now, in the immediate vicinity of safety trial sites. A plume volume of about 200 m^3 of porous rock — implying, for a 30% porosity, a high concentration water volume of about 70 m^3 — in the vicinity of each of the four trial sites was estimated and the possibility considered of a borehole being drilled to a depth of 280 m into such a region. The continuous drinking of water at this concentration would lead to a dose rate of about 1 Sv/a, which would constitute a serious health risk. However, it is not conceivable that water of this concentration would be brought to the surface without dilution — a dilution of only 100 would reduce potential doses to about the IAEA suggested generic guideline for intervention of 10 mSv/a (Section 11). In addition, the probability that such exposures will occur must be extremely small. Taking account of the depth of the safety trials and the relatively very small size of each high concentration plume, and assuming that the extraction of fresh water would be more likely from shallower depths and towards the centre of the island rather than close to the sea, where the safety trials were carried out, the probability of direct extraction of high concentration plume water which would be drunk without testing or treatment is considered to be much less than 5×10^{-8} (Technical Report, Vol. 6).

Any analysis based on events in the far future must involve considerable conjecture. Thus, in this assessment, it has been assumed, for example, that the safety trial cavities will be in the freshwater lens, that underground bores would be the source of fresh water, rather than alternative technologies (such as desalination), that the water would not be analysed or treated before drinking, and that risk factors for ingestion of radionuclides would not have been reduced by advances in medical science. The risk associated with such a remote occurrence was considered to be so low that it was not explored further.

9.7. EVALUATION OF THE RADIOLOGICAL SITUATION

Current and future doses to a hypothetical population resident on Mururoa from both existing environmental concentrations and future releases of radionuclides in residual radioactive material are summarized in Table LXXV, Also included in the table are estimated doses to high intake seafood consumers on a number of French Polynesian islands arising from predicted releases from Mururoa and Fangataufa. The doses to these high intake seafood consumers do not include the larger contributions currently arising from deposition of radionuclides from atmospheric nuclear tests in the terrestrial and marine environments.

The estimated annual doses to possible inhabitants of Mururoa, from both present and projected levels of residual radionuclides in the environment, resulting from the French weapon testing in the region are all small in absolute terms. The annual dose from natural background radiation in the region is over two orders of magnitude higher than the estimated peak annual doses to hypothetical atoll inhabitants resulting from the residual radionuclides at the two atolls The accepted commonplace activity of air travel can lead to higher doses to passengers than the doses calculated here. For example, an air flight of 4 h duration at temperate latitudes will result in a dose of 15–20 μSv due to increased cosmic radiation. If the flight is across the North or South Pole, the dose could be up to around two times higher.

Another perspective on the significance of the radiation doses can be obtained from considering the current

system of radiological protection The annual dose limit for members of the public recommended by the ICRP, and adopted in the Basic Safety Standards (FAO et al 1996) is 1000 μSv. This limit applies to the sum of the exposures from beneficial activities by humans — termed 'practices' by the ICRP (Annex III). Furthermore, practices giving rise to annual radiation doses of less than 10 μSv are commonly exempted from regulatory requirements on the grounds that such doses are trivial

Another way of gaining a perspective on the levels of dose calculated here is to present the doses in terms of individual risk. As indicated in Annex III, the risk coefficient for fatal cancer in members of the public, as assessed by the ICRP, is 5×10^{-2}/Sv. An annual dose of the order of 5 μSv would therefore imply a risk of 2.5×10^{-7}/a. This may be compared with the risk associated with background radiation, which could be as much as 1.5×10^{-4}/a. Furthermore, if the average lifetime risk from residual radioactive material in the environment from French weapon testing were calculated (assuming a lifetime of 70 years), a total of 1.75×10^{-5} or around 0.002% would result. This is a very small fraction of the underlying lifetime risk of death from cancer of around 20%. This comparison implies not only that the risk from residual material at the atolls is extremely small, but also that epidemiological studies designed to measure increased incidence of cancer due to this source would not be worth while.

The radiation doses and risks to possible future inhabitants of Mururoa Atoll due to the general dispersion of the residual radionuclides from weapon testing into the environment are insignificant on the basis of existing criteria and other bases for comparison. However, there is the possibility, albeit very small, of higher doses being received from particles of plutonium-containing material, should they become incorporated in the body and retained there, e.g via a cut. These particles occur only in a very limited region of Mururoa Atoll. Considering the range of particle activity, together with the chance of a particle entering a wound and remaining there, the annual risk of fatal cancer to a future inhabitant of Mururoa from this route is around one in one million — a level of risk commonly regarded as trivial.

Annual doses to inhabitants of other Pacific islands due to releases from Mururoa and Fangataufa are also presented in Tables LXXIV and LXXV. Current annual doses at Tureia from existing radioactive material originating from French weapon testing, approximately 5 μSv, are similar to those calculated for Mururoa but the significant exposure pathways are different: for Mururoa, assumed mollusc consumption is important whereas for Tureia, consumption of terrestrial foods is important. This difference is due to a higher deposition of radionuclides at Tureia from the French atmospheric weapon tests. The doses are in all other cases very much lower than the hypothetical doses calculated for Mururoa and Fangataufa, with the exception of the doses calculated for the disruptive rock slide on the side of Mururoa. In this case, the dose to high intake seafood consumers on Tureia reaches about 7 μSv during the first year, a level similar to the peak annual dose on Mururoa from the normal release of radionuclides. This dose only occurs in the year of the rock slide; in subsequent years the doses are progressively lower as the activity disperses. Annual doses to high intake consumers of seafoods caught in more distant areas are all very low, typically several orders of magnitude below average natural background levels.

It is concluded that the calculated annual doses from dispersion of radionuclides from the French nuclear weapon testing programme at Mururoa and Fangataufa Atolls are all very small when compared with annual doses from other common sources; the corresponding health impact is similarly insignificant. Overall, the radiation risks to current and future generations from the French weapon testing programme at Mururoa and Fangataufa are so small that they can be considered to be negligible.

10. POTENTIAL IMPACT OF RADIATION DOSES ON BIOTA

The residual radioactive materials in the marine environments of Mururoa and Fangataufa from the French weapon testing programme have the potential to affect organisms other than humans. In contrast to the situation in human radiation protection, the object of concern for wild organisms is, in general, the population rather than the individual. Of interest, therefore, are the impacts of increased radiation exposure on the biological functions that influence the maintenance of healthy populations, but it is important to note that these derive from processes that operate at the level of the individual.

Reviews of the literature on the effects of increased radiation exposure on plants and animals are consistent in their conclusions that a sufficient basis exists to identify dose rates below which it is extremely unlikely that there would be any significant effects on the processes — morbidity, mortality, fertility, fecundity and mutation rate — that could influence the maintenance of healthy populations of wild organisms. An additional degree of conservatism is provided by the fact that these dose rates are assumed to apply to the most highly exposed individuals in the populations in the expectation that, under most circumstances, a wide range of lower dose rates would be experienced and the average dose rate across the populations would be lower.

10 1. ASSESSMENT OF DOSES TO ORGANISMS

The radionuclide concentration levels measured in the Study's sampling campaign, as well as the French data, indicated that it would be possible to estimate dose rates for zooplankton, benthic crustaceans, benthic molluscs and pelagic fish from both internal and external (water and sediment) sources. This variety of organisms was considered to be sufficiently wide in terms of size, behaviour pattern and physiology to provide a reasonable indication of the range of dose rates likely to be experienced by the organisms native to the atoll marine environment This dose assessment adopted the approach used in a number of recent studies (IAEA 1979, 1988, 1992, US National Council on Radiation Protection and Measurements (NCRP) 1991), adapting the dosimetry models to the particular organisms of interest in the atoll environment. The assessment is described in more detail in the Technical Report, Vol. 6. Doses from low linear energy transfer (LET) (beta and gamma) and high LET (alpha) radiation were assessed separately, as the appropriate radiation weighting factor to be applied to high LET exposures has yet to be determined for wild organisms. Estimates of the dose rates from naturally occurring ^{40}K were made for comparison.

The highest absorbed dose rates from internal sources are about 200 nGy/h from alpha radiation to the lagoon zooplankton and benthic crustaceans These are an order of magnitude higher than those in any of the other lagoon or oceanic organisms considered. Although higher than the absorbed dose rate (12 nGy/h) from the internal ^{40}K source, these values are lower than the estimated 4000 nGy/h to the testes of a small mid-water oceanic shrimp from the accumulated naturally occurring alpha emitting radionuclide ^{210}Po (United Nations 1996). The local absorbed dose rate to benthic organisms from contamination in the coral sand can reach about 900 nGy/h from ^{60}Co and ^{137}Cs in an area of about 1 km^2 at Dindon, Mururoa, and perhaps 200 nGy/h from ^{241}Am gamma rays in another small area, on the Colette sandbank, i e. up to about 200 times that from the ^{40}K in the sediment. However, coral sand is relatively deficient in ^{40}K and the radionuclides of the ^{238}U and ^{232}Th series; previous estimates of the gamma radiation exposure of benthic organisms from a wider range of sediment types have ranged up to 160 nGy/h (United Nations 1996).

For organisms living in and around the Colette sandbank of Mururoa, high dose rates could also be received from the active particles remaining from the safety trials on the adjacent motus; the plutonium content of the sediments can be as high as 10^6 Bq/kg dry weight. Estimates were made of the dose rates from external exposure (and, for larger organisms, from ingestion of active particles) and the amount of time for which the organisms are likely to be exposed. These estimates were based on the concentration of active particles in two sediment samples from the Colette sandbank, extrapolated to obtain estimates of the total number of particles in defined activity intervals. The dose rates from the active particles vary from about 1 Gy/h — for the smallest particles, and at the limit of the alpha particles' range in wet sediment (about 18 μm) — to about 300 Gy/h close to the surface of the largest particle. It was estimated that a small worm would be exposed at these dose rates for a total of between 20 min and 2 h (during its 30 d lifetime), whereas a larger organism — a burrowing shrimp — would be exposed at some point of its body surface more or less constantly.

10.2. POTENTIAL SIGNIFICANCE OF DOSES TO ORGANISMS

Overall, therefore, it appears that the dose rates to the great majority of the native marine organisms from the dispersed residual radionuclides in the atoll environments are less than, or of the same order as, the natural background. In fairly restricted areas, the exposure of benthic organisms from residual radionuclides in sediment may be as much as five times higher than the highest previous estimates of the natural gamma radiation background on the seabed. Additional exceptions to the general situation are the organisms living in the Colette sandbank, which are potentially exposed to alpha radiation from active particles. Here, absorbed dose rates of up to 300 Gy/h and total absorbed doses of several grays to small tissue volumes are a possibility.

Earlier studies by the IAEA (1976, 1988) and UNSCEAR (United Nations 1996) have concluded that there is no convincing evidence that chronic absorbed dose rates of less than 400 μGy/h to the most highly exposed members of populations of aquatic organisms would have any detrimental impact on the populations. Aside from the particular situation on the Colette sandbank, the highest dose rates estimated for the aquatic organisms in the vicinity of Mururoa and Fangataufa Atolls (even allowing for a possible fivefold enhancement of the high LET component of the exposure) are at least a factor of 200 lower than this value. It is unlikely, therefore, that the incremental radiation exposure from the widely dispersed radionuclides would induce any significant damage in the native aquatic fauna. On the Colette sandbank, however, it appears entirely possible that the organisms living in the sediment could receive absorbed doses from active particles that would be sufficient to produce deterministic effects in small volumes of tissue. The consequences of this for the individuals are unknown, but it is unlikely that there would be any deleterious impact on the wider populations of the whole lagoon.

11. THE NEED FOR REMEDIATION

11.1 INTRODUCTION

A brief introduction to the basic principles of radiation protection is provided in Annex III. The way in which these principles, and in particular the Basic Safety Standards (FAO et al. 1996), relate to the situation at Mururoa and Fangataufa now and in the future is discussed below.

The development and testing of nuclear weapons would clearly meet the formal definition of 'practice' given in the Basic Safety Standards "Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed." However, it is equally clear that this is not the type of practice that was envisaged in the development of international standards intended to regulate the peaceful, beneficial uses of radiation and nuclear energy. Regardless of the status of the original practice, however, nuclear weapon testing in French Polynesia has ceased, and the levels of residual radioactive material in the environment can no longer be controlled. The situation at Mururoa and Fangataufa Atolls is therefore only amenable to intervention, i.e. to remedial measures designed to reduce doses from an existing source of exposure.

There is the potential for chronic (persisting) exposure of inhabitants of neighbouring islands, and for chronic and acute (short term) exposure of individuals who might inhabit the atolls themselves. At the time when the site of the CEP was chosen, Mururoa and Fangataufa Atolls were uninhabited; as discussed in Section 2, there is no evidence of Fangataufa having ever been inhabited, whereas Mururoa has been settled only occasionally in the past This reflects the limited ability of the atolls to support a human population, there were no human-imposed restrictions preventing habitation before the CEP was established When the personnel currently working at the atolls leave, the atolls will (presumably) again be uninhabited, and might well remain so. However, one purpose of the Study was to determine whether remedial measures would be needed to ensure that there is no radiological reason why people could not live on Mururoa or Fangataufa

11 2. CRITERIA FOR REMEDIAL ACTION

There is currently no explicit international guidance on generic action levels for chronic exposure due to radioactive residues from previous activities and events, such as nuclear weapon testing However, the guidance established in the Basic Safety Standards for other situations can be used to provide indications of the levels that might be appropriate. Moreover, typical levels of doses caused by chronic exposure to the unavoidable natural background radiation could be used as a reference for comparisons.

The worldwide average annual dose due to radiation from natural sources is estimated to be 2.4 mSv (Annex III). The annual effective dose from natural sources at Mururoa could be up to 3 mSv There are, however, large variations in the doses from natural sources. Most people receive an annual effective dose from natural sources in the range 1–20 mSv, with some localized high levels above 100 mSv (no one receives less than about 1 mSv/a) Thus, although the global average annual dose due to natural background radiation is of the order of a few millisieverts, annual doses of about 10 mSv are not unusual and dose rates of 100 mSv/a or more are found in some places National authorities have considered these situations and decided not to implement remedial measures to reduce these dose levels except in the most extreme cases. Considering this, and action levels derived for other intervention situations, it appears that intervention in chronic exposure situations is unlikely to be warranted to effect a reduction in annual effective dose to levels of less than about 10 mSv. A dose in the region of 10 mSv therefore appears to be a reasonable generic guideline for intervention.

11.2.1. Criteria for assessing chronic potential exposures

Chronic potential exposure may arise where there is some probability that an adverse event will occur which would result in exposure to radiation. An example of a potential exposure situation exists in the Colette area of Mururoa, where there are three motus where particles containing plutonium and americium, resulting from the atmospheric safety trials, may still be found If such a particle were to be taken into the body and retained there, a significant radiation dose could result. The potential for exposure to occur in this area will persist unless the active particles are removed (by natural processes or human actions) or until the radionuclides decay to insignificant levels.

The ICRP, in its 1990 Recommendations (ICRP 1990), indicated that the "simplest way of dealing with the potential exposure of individuals is to consider the

overall probability of attributable death from cancer, rather than the effective dose...a restriction corresponding to a dose limit can then be expressed in the form of a risk limit, i.e. a limit on the fatality probability" Although this recommendation related to control of practices, if a similar approach were applied to intervention in chronic potential exposure situations, the quantity used in decision making would be the 'averted risk', i.e. the reduction in the overall probability of attributable death corresponding to the potential dose averted by intervention The action level expressed in terms of dose could be replaced by the corresponding probability of fatal cancer If an annual effective dose of about 10 mSv were used as a generic guideline for intervention, the risk coefficient of 5×10^{-2}/Sv, assessed by the ICRP for fatal cancer in members of the public, would imply a corresponding risk criterion for chronic potential exposure of 5×10^{-4}/a. Such an annual risk could be useful as a guideline to assess the significance of the radiation risk arising from the presence of active particles in the Colette area

11.3. APPLICATION TO MURUROA AND FANGATAUFA

As discussed in Section 9, the annual effective doses that could be received by a hypothetical population at Mururoa from present levels of residual radioactive material in the atoll environment do not generally exceed 0.01 mSv. The corresponding annual effective doses incurred by residents of Tureia, the closest inhabited island, are less than 0 0001 mSv, although this population receives an additional annual dose of about 0.005 mSv as a result of residues from atmospheric fallout Thus, the potential and actual doses resulting from present levels of residual activity in the atoll environments are an extremely small fraction of those that are, or would be, received from natural sources. Furthermore, any intervention action designed to reduce doses from this residual activity could only effect a dose reduction of a fraction of a millisievert. Such action would not be warranted in view of a generic guidance level for intervention of 10 mSv.

A hypothetical maximum dose from present levels of residual material was also postulated. A permanent resident in the Kilo–Empereur region of Fangataufa Atoll subsisting entirely on produce grown in that region might receive an annual effective dose of 0.25 mSv. Even this maximum hypothetical dose is one tenth of the dose from natural sources, and remedial action could achieve a reduction in dose of at most a small fraction of any likely generic guidance level for intervention

The risk associated with the potential exposure situation on the Colette motu of Mururoa (arising from possible incorporation of an active particle in a cut) was estimated, as described in Section 9. The probability of an individual who visits this area incurring fatal cancer — taking account of the overall probability of an accident which leads to a wound in which a particle becomes incorporated and retained, together with the consequent probability of harm as a result of the radiation dose received — is estimated to be less than one in one million per year. This is a small fraction of the generic risk criterion for chronic potential exposure introduced above and, furthermore, is at a level which is normally considered as negligible Remedial action to reduce this risk further would therefore not be warranted.

The doses resulting from possible future migration into the biosphere of residual material at present underground were also presented in Section 9 It was found that, under normal conditions, no population at any time in the future will incur annual doses significantly higher than the present extremely low dose of less than 0 0001 mSv being received at Tureia as a result of predicted releases of radioactive material into the ocean from the atolls The radiological consequences of postulated extreme events, such as a slide of carbonate rock that exposed radioactive material, and of potential climate changes were examined. The highest hypothetical dose to the residents of Tureia Atoll in the first year following such a rock slide would not be more than a few thousandths of a millisievert Thus, the predicted future doses arising from residual radioactive material are also a small fraction of those resulting from natural sources Remedial action to reduce these doses further would not be warranted on the basis of the arguments presented above.

11.4. REMEDIAL ACTION

Given the measured and predicted radionuclide activity levels, and the low dose levels estimated for the present and for the future, and with account taken of international guidance, it was concluded that no remedial action at Mururoa and Fangataufa Atolls is needed on radiological grounds, either now or in the future

Part D
CONCLUSIONS AND RECOMMENDATIONS

12. FINDINGS

12.1. RESIDUAL RADIOACTIVE MATERIAL ALREADY PRESENT IN THE ACCESSIBLE ENVIRONMENT OF THE ATOLLS

The Study found that the terrestrial and aquatic environments of Mururoa and Fangataufa Atolls that are accessible to people contain residual radioactive material attributable to the expériences nucléaires, but at generally very low concentrations which the Study concluded were of no radiological significance There are, however, some features of note whose radiological implications are examined in Section 12.3.

(a) Several kilograms of plutonium resulting from the atmospheric nuclear tests carried out at the atolls remain in sediments under the lagoon of each atoll. Some of the plutonium in the sediments of the Mururoa Atoll lagoon came from the atmospheric safety trials.
(b) The concentration of tritium in each lagoon was found to be higher than in the open ocean, as the result of leakages from a number of the cavity–chimneys created by underground nuclear tests.
(c) Particles containing plutonium and small amounts of americium resulting from atmospheric safety trials remain in the area of the trial sites — the motus of Colette, Ariel and Vesta on Mururoa Atoll. The Study analysed these types of particles, found in samples of sand and coral collected from the surface of the motu of Colette and in sand taken from a sandbank adjacent to it.
(d) Elevated levels of ^{137}Cs were found over small areas totalling several hectares on the Kilo–Empereur rim of Fangataufa Atoll.

12.2. RESIDUAL RADIOACTIVE MATERIAL UNDERGROUND AT THE ATOLLS

The Study found that the results of the assessments of the nuclear explosive yields of all underground nuclear tests and of the resulting inventories of residual radioactive material contained underground at the atolls are in good agreement with information made available for the Study from French sources.

From the measurements of the activity in underground water samples taken from the two cavity–chimneys selected for the in situ sampling, the Study found that the concentrations of highly refractory radionuclides, in particular of $^{239+240}Pu$, are extremely low, indicating a high level of retention of such radionuclides in the glass-like lava formed in the cavities by basalt rock melted in the underground explosions.

12.3. POTENTIAL RADIATION DOSES DUE TO RESIDUAL RADIOACTIVE MATERIAL ALREADY PRESENT IN THE ACCESSIBLE ENVIRONMENT OF THE ATOLLS

Although it is doubtful whether Mururoa Atoll — still less Fangataufa Atoll — could sustain a permanent population dependent solely on local resources for food, the Study assessed the radiation doses to hypothetical inhabitants that could result from the residual radioactive material at present in the terrestrial and aquatic environments of the two atolls. The Study found that a population permanently resident on the atolls, and living on a diet of local produce and seafood, would not generally receive a radiation dose attributable to the residual radioactive material exceeding 0 01 mSv per year, which is equivalent to a very small fraction (less than one part in 200) of the annual background radiation dose that such a resident population would unavoidably receive from natural radiation sources. The Study found it necessary, however, to examine specifically the four features of note identified in Section 12 1:

(a) *Plutonium in the lagoons:* The Study found that the inventory of plutonium in the sediments of the two lagoons, while large, is of little radiological significance, mainly because of the low rate of transfer of plutonium to people via feasible pathways. Also, the Study noted that the availability of the plutonium will decrease over time owing to (i) the removal of the lagoon sediments to the ocean and (ii) the gradual burial and dilution of lagoon sediments by the accumulation of fresh sediment.
(b) *Tritium in the lagoons:* Similarly, the Study found that concentrations of tritium in the lagoons are of no radiological significance even though they are at present higher than in the open ocean.
(c) *Plutonium-containing particles:* The Study noted that, if an individual were to visit the motus of Colette, Ariel or Vesta at Mururoa Atoll, there is a possibility that a particle containing plutonium with small amounts of americium could be incorporated into that individual's body — for example, through a

cut caused by a fall. The Study assessed the probability of the incorporation of such a particle and its long term retention within the body. It also assessed the associated radiation dose and the probability of harm as a result of the dose received. On this basis, the Study found that the probability that a hypothetical individual visiting and spending some time on any of the three motus would ultimately incur a fatal cancer attributable to the incorporation of a particle containing plutonium is less than one in one million per year.

(d) *Caesium-137 on the Kilo–Empereur rim.* The Study found that, if any population were to subsist entirely on produce grown on small areas of the Kilo–Empereur rim of Fangataufa Atoll, the estimated maximum radiation dose attributable to the ^{137}Cs in the rim would be about 0.25 mSv per year, equivalent to about one tenth of the total radiation dose which that population would unavoidably receive as a result of natural radiation sources. The Study considers, however, that this hypothetical situation is highly unlikely to arise, since — inter alia — the Kilo–Empereur rim is almost barren and virtually uninhabitable by people adopting a traditional semi-subsistence lifestyle

The Study found that the highest dose attributable to the residual radioactive material already present in the accessible environment of Mururoa and Fangataufa Atolls, which is estimated to be currently received by residents of Tureia Atoll, is less than 0.0001 mSv per year, which is a completely insignificant fraction (about one part in 10 000) of the annual background radiation dose that these residents will unavoidably receive from natural radiation sources. It should be noted, however, that Tureia Atoll did receive some immediate fallout from the atmospheric nuclear tests carried out at Mururoa and Fangataufa Atolls, in addition to the fallout globally experienced as a result of all atmospheric nuclear testing. The radiation doses currently being received by residents of Tureia Atoll as a result of residues from earlier fallout and due to the nuclear testing at Mururoa and Fangataufa Atolls were assessed and found to be about 0 005 mSv per year, which is an extremely small fraction (about two parts in 1000) of the annual background radiation doses that the residents will unavoidably receive from natural radiation sources.

The radiation doses due to the residual radioactive material already present in the accessible environment — principally arising from ^{137}Cs and plutonium isotopes — will persist, but they will decline owing to both radioactive decay and other processes that reduce the availability of these radionuclides in the environment. According to the Study estimates, the rate of leaching of the ^{137}Cs and the plutonium isotopes present in the lagoon sediments will continue to decrease with time, as will the estimated radiation doses associated with these radionuclides. The Study found that the highest estimated potential annual doses attributable to the residual radioactive material already present in the accessible environment of Mururoa and Fangataufa Atolls and their surrounding waters will decline from the present hypothetical maximum of no more than 0.01 mSv per year to about 0.001 mSv per year within 100 years

12.4 MIGRATION OF RESIDUAL RADIOACTIVE MATERIAL FROM UNDERGROUND

The Study estimated the rate of migration of the radionuclides in the radioactive material produced by the underground nuclear tests from the cavity–chimneys, through the geological media, into the lagoons and directly into the ocean over periods of more than 100 000 years. The Study found that, over the first few decades, most of the released radionuclides would come from the small number of underground nuclear test sites where the basalt basement above the nuclear test point provided inadequate confinement of the nuclear tests. In terms of amounts of activity, tritium would dominate the early releases, but with activity concentrations that are of no radiological significance. Other radionuclides, including ^{137}Cs and ^{90}Sr, would be effectively retained underground within the basalt basement, most of their activity decaying and only small amounts of activity being released. Plutonium would continue to be released over long periods of time but at very low rates. The modelling predicts that concentrations of ^{137}Cs and $^{239+240}Pu$ in the lagoon water are unlikely to exceed present levels at any time in the future. The concentrations of ^{90}Sr and ^{3}H could rise marginally above current levels, but only during the next few decades

12.5 DISPERSION OF RESIDUAL RADIOACTIVE MATERIAL THROUGHOUT THE OCEAN

The Study used regional and far field oceanographic models to estimate the concentrations in sea water at various locations and times of radionuclides released into the ocean from Mururoa and Fangataufa Atolls. The Study found that, except as a consequence of a hypothetical extreme disruptive event (Section 12.6), the predicted long term concentrations of radionuclides

decrease to background oceanic levels beyond about 100 km from the atolls; thus, at Tureia Atoll the predicted concentrations will be around background levels and of no radiological significance.

12.6 CONSEQUENCES OF POSTULATED DISRUPTIVE EVENTS

The only disruptive event that was found by the Study to warrant a thorough assessment was the hypothetical major breakaway and slide of the carbonate formations in the northern zone of Mururoa Atoll, in the area where the underground safety trials and some of the nuclear tests producing cavity–chimneys which penetrated into the carbonate formations were carried out. If such a hypothetical extreme event were to occur, ocean currents would carry the released radioactive material away from Mururoa Atoll and the highest potential annual dose would therefore be received by residents of nearby atolls. For the residents of Tureia Atoll, the dose in the first year following such a slide would not be more than a few thousandths of a millisievert — which is an extremely small fraction (a few parts in 1000) of the annual background radiation dose that the residents will unavoidably receive from natural radiation sources — even pessimistically assuming that all the plutonium involved in the slide went into solution

12.7. POTENTIAL DOSES IN THE FUTURE

The Study found that — except in the hypothetical situation discussed in Section 12.3 — no population group is likely to receive at any time in the future a dose attributable to the residual radioactive material at Mururoa and Fangataufa Atolls which exceeds approximately 1% of the background radiation dose that the group will unavoidably receive from natural radiation sources.

13. CONCLUSIONS

13.1. IMPLICATIONS FOR HUMAN HEALTH

The Study concluded that there will be no radiation health effects which could be either medically diagnosed in an individual or epidemiologically discerned in a group of people and which would be attributable to the estimated radiation doses that are now being received or that would be received in the future by people as a result of the residual radioactive material at Mururoa and Fangataufa Atolls.

Nevertheless, the Study noted that the reported cancer incidence in populations in the South Pacific region and throughout the world is changing for a number of reasons, including: the improved diagnosis and registration of cancer cases; modifications in environmental exposure to cancer causing agents and in personal habits (such as dietary and smoking habits); population migrations that alter baseline cancer incidence rates; and changes in the incidence of other diseases. The Study emphasized, however, that at the very low levels of dose estimated in the Study there will be no changes in cancer incidence rates in the region attributable to radiation exposure caused by the residual radioactive material at Mururoa and Fangataufa Atolls.

13.2. IMPLICATIONS FOR BIOTA

The Study assessed the dose rates to native biota resulting from the residual radioactive material at Mururoa and Fangataufa Atolls and, in the great majority of cases, found them to be similar to or lower than dose rates due to natural radiation sources. An exception is the potentially high dose rates that could be experienced by individual members of some species owing to plutonium contained in particulates — for example, from the sediment of the sandbank adjacent to the Colette motu in the northern part of Mururoa Atoll Overall, the Study concluded that the expected radiation dose rates and modes of exposure are such that no effects on biota population groups could arise, although occasionally individual members of species might be harmed, but not to the extent of endangering the whole species or creating imbalances between species.

13.3 REMEDIAL ACTIONS

Given the measured and predicted radionuclide activity levels, and the low dose levels estimated for the present and for the future, and with account taken of international guidance, the Study concluded that no remedial action at Mururoa and Fangataufa Atolls is needed on radiological protection grounds, either now or in the future.

13.4. MONITORING

Similarly, the Study concluded that no further environmental monitoring at Mururoa and Fangataufa Atolls is needed for purposes of radiological protection.

13.5. ROBUSTNESS OF THE CONCLUSIONS

Although many assumptions were made in the modelling of systems, the findings are robust: i.e the Study concluded that the expected extent of changes in the conclusions due to uncertainties in the parameters used in the modelling is slight. Furthermore, the predicted doses are so low that large errors (even of an order of magnitude) would not affect the conclusions.

14. RECOMMENDATION

The Study noted that a scientific programme of monitoring of the radionuclide concentrations in the carbonate formations and in the nuclear test cavity–chimneys is under way at Mururoa and Fangataufa Atolls. Should this programme continue, the Study recommends that emphasis be placed on monitoring the migration behaviour of long lived and relatively mobile radionuclides and radiocolloids because of its particular scientific interest. The scientific programme, supplemented by some monitoring of radionuclide levels in the biosphere, may also be useful in assuring the public about the continuing radiological safety of the atolls.

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Annex I

RETROSPECTIVE ASSESSMENT OF THE RADIATION DOSES ATTRIBUTABLE TO ATMOSPHERIC TESTING AT THE ATOLLS

The terms of reference of the Study relate only to the current and future radiological situations at the atolls; it was not intended that an assessment should be made of the doses to people in the region during the testing programme. Nevertheless, the International Advisory Committee (IAC) considered that it would be of interest to add to this report some discussion of the doses received at that time — particularly from exposure to short lived radionuclides associated with the atmospheric testing between 1966 and 1974 — and asked the Secretariat of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to review the existing data This annex is based on information provided by the Director of the Secretariat of UNSCEAR.

I-1. FALLOUT DEPOSITION FROM NUCLEAR WEAPON TESTS

Many measurements were made throughout the world during the period of atmospheric testing by the USA, the USSR, the UK, France and China (1945–1980), and much is known about the release, dispersion and deposition of radionuclides, as well as the resulting doses, arising from this practice. Exposures of the world population were estimated and presented in the 1982 and 1993 Reports of UNSCEAR (United Nations 1982, 1993). From this information, the deposition and doses from individual tests, or (as in this case) from the test series of a specific country, can be estimated.

Complete information on the fission and fusion yields of the atmospheric weapon tests is still not available, although more accurate data on the total yields of individual tests have recently been published (United States Department of Energy 1994, Ministry for Atomic Energy of the Russian Federation and Ministry of Defence of the Russian Federation 1996, Johnston 1995, Doury and Musa 1996). Present estimates of fission and total yields of atmospheric tests by all countries are given in Table I–I, the fission yields being based on several assumptions. For relatively low yield explosions (less than 0.5 Mt), the explosive yield may be assumed to be due to fission only, i.e. the fission and total explosive yields are the same. For thermonuclear tests, both fission and fusion yields contribute to the total explosive yields, and the fusion yields become dominant in the very high yield explosions For example, the largest test conducted (a 50 Mt device exploded on 30 October 1961 by the USSR) was reported to have a fission yield of 3% and a fusion yield of 97% (Ministry for Atomic Energy of the Russian Federation and Ministry of Defence of the Russian Federation 1996) If it is assumed that the fission yields of the tests in the 10–25 and 0.5–10 Mt ranges were 33 and 50% of the total yields, respectively, then the total fission yield of all tests matches the value inferred from global radionuclide deposition measurements.

The partitioning of debris in the atmosphere depends on the location and height of the burst. Surface explosions may result in up to 50% of the fission products being deposited nearby as local fallout, the remainder being distributed in the troposphere and stratosphere. Devices detonated at altitude (using rockets or balloons) deposit most of the radioactive debris in the stratosphere The height of the tropopause — the interface between the troposphere and the stratosphere — varies, but is roughly 17 km in the equatorial region (less than 30° latitude) and 9 km in the polar regions (greater than 60° latitude). The test sites of France in the Pacific Ocean and of the UK in Australia are in the equatorial region and those in the former USSR are in the polar region Nevada in the USA

TABLE I–I. ATMOSPHERIC NUCLEAR TESTS AND EXPLOSIVE YIELDS

	Number of tests	Estimated fission yield (Mt)	Reported total yield (Mt)
USA	217[a]	72.2	153 8
USSR	219[b]	87.9	247 3
UK	33[c]	4 4	8 05
France	50[d]	6 55	10 2
China	22	10 9	20 7
Total	541	182	440

[a] Includes five underwater tests, 22 safety trials and two combat explosions.

[b] Includes five underwater and water surface tests

[c] Includes 12 safety trials

[d] Includes five safety trials and four atmospheric tests in Algeria.

ANNEX I

TABLE I–II. ATMOSPHERIC PARTITIONING OF FISSION YIELDS RELATED TO LOCAL AND GLOBAL FALLOUT PRODUCTION

	Partitioned fission yield (Mt)			
	Local	Troposphere	Stratosphere	Global total[a]
USA	23 3	9 1	39 8	48 9
USSR	0 13	5 5	82 3	87 8
UK	0 07	1 9	2.4	4 3
France	0 23	0 57	5 76	6 3
China	0.2	0 7	9 96	10 7
Total	24	18	140	158
Estimate from global fallout deposition measurements				155

[a] Sum of troposphere and stratosphere inputs

and Lop Nor in China are at intermediate latitudes — 37° and 40° N, respectively

The partitioning in the atmosphere of debris from a specific explosion can be estimated on the basis of the stabilization heights of cloud formation following the explosion Empirical tables based on a number of observations were published by Peterson (1970). Bennett (1978) used these figures for the earlier estimates of fallout production from atmospheric testing that were quoted in the 1982 UNSCEAR Report (United Nations 1982). Adjustments have now been made to these estimates, using recently reported data on total yields and estimated fission yields, and the revised partitioning estimates are given in Table I–II. The total tropospheric and stratospheric yield estimated here agrees with the value obtained from fallout deposition measurements.

The deposition of fallout radionuclides has been determined from global monitoring programmes. The pattern for ^{90}Sr from all atmospheric tests was presented in the 1993 UNSCEAR Report (United Nations 1993, p. 122) and can be considered to be representative of other longer lived fission radionuclides Approximately 75% of the deposition occurs in the hemisphere in which the explosion took place, with enhanced levels in the midlatitude regions.

I–2. FRENCH ATMOSPHERIC TESTING PROGRAMME

The nuclear weapon tests carried out by France in the atmosphere at the Centre d'expérimentations du Pacifique (CEP) are listed in Section 3, including the published total yields for all tests and fission yields for about 75% of them (Doury and Musa 1996). The yields of earlier French tests in Algeria were very low, and therefore the total yield from French atmospheric testing may be assumed to be essentially that from atmospheric tests at the CEP. The atmospheric tests at Mururoa and Fangataufa mostly involved devices suspended from balloons, which minimized local fallout production, the debris from such tests went largely into the lower stratosphere. Only four of the tests were conducted on barges, and three were explosions of devices dropped from aircraft As noted in Section 3, five safety trials were also carried out above ground and would have caused local contamination with material from the weapon core.

I–2.1. Local deposition and dose estimates

The local and regional populations would not have been affected by most of the tests because the debris was dispersed almost exclusively in the troposphere and stratosphere. Doury and Musa (1996) have presented some contour maps of local deposition that occurred in uninhabited regions following several of the tests. The closest inhabited atoll is Tureia (120 persons in 1996), 130 km to the north of Mururoa, while only 5000 people live within 1000 km of the test site.

French scientists have identified five tests for which local exposures did occur, because of unusual wind and rainfall conditions at the time of the tests (French Liaison Office Document No. 13). The estimated doses, presented in Table I–III, are of the order of a few millisieverts within the first year The affected populations were in Tureia, the Gambier Islands (400 km southeast of Mururoa) and Tahiti (1200 km to the northwest) Only a few individuals on these islands would have received the maximum estimated doses shown in Table I–III. In Tahiti, for example, most people would have received doses from external sources only Although some higher doses from ^{131}I in milk might

TABLE I–III LOCAL EFFECTIVE DOSES (mSv) TO MAXIMALLY EXPOSED INDIVIDUALS WITHIN FIRST YEAR OF FRENCH ATMOSPHERIC TESTS[a]

Date of test	Location of exposure	External	Inhalation	Ingestion	Total
2 Jul 1966	Gambier Islands	3 4	0 18	1 9	5 5
2 Jul 1967	Tureia Atoll	0 7	0 023	0.17	0 9
12 Jun 1971	Tureia Atoll	0 9	0 003	0 43	1 3
8 Aug. 1971	Gambier Islands	0 9	0 002	0 24	1.2
17 Jul 1974	Tahiti (Mahina)	0.6	0 08	0 06	0 8

[a] Source French Liaison Office Document No 13

have occurred, as indicated by the estimate for infants in Table I–IV, the assumptions used in calculating these doses are probably unrealistic for most people in Tahiti. Local milk production provides only 18% of the local needs and is used mostly for cheese production (with maturing times of several weeks, during which ^{131}I will decay substantially), while infants consume only powdered milk (French Liaison Office Document No. 13). Some internal doses resulting from the ingestion of green vegetables or lagoon molluscs were estimated for the other islands These local doses, of the order of the normal annual natural background radiation levels, would have been of no health consequence to those exposed.

Data from the New Zealand fallout monitoring network for the South Pacific region confirm the local dose estimates (National Radiation Laboratory 1971–1976, New Zealand Ministry of Foreign Affairs 1984). The population of Tahiti was affected by the single rainout event (rainfall 'washing' radionuclides out of the atmosphere) following the test of 17 July 1974 The estimated annual dose in 1974 was 0.2 mSv (New Zealand Ministry of Foreign Affairs 1984), somewhat less than the estimate of 0.8 mSv in Table I–III. In all other years between 1966 and 1976, the estimated doses in Tahiti from nuclear test fallout were an order of magnitude less, and resulted largely from deposition following the earlier tests in the Northern Hemisphere.

I–2.2. Global deposition and dose estimates

Nuclear testing by France accounts for 3 6% of the fission yield and 2.3% of the total yield from all atmospheric testing The contribution of French testing to global fallout production can be estimated as follows from the total fission yield partitioned to the troposphere and the stratosphere from the French tests, which corresponds to 6 3 Mt (Table I–II).

A 1 Mt fission explosion is estimated to involve the fission of 1.45×10^{26} heavy nuclei Hence, the number of atoms of, say, ^{137}Cs generated per megaton is this value multiplied by the fission yield for ^{137}Cs (5.57%), which can be converted to activity by multiplying by the decay constant This gives a yield of 5.89 PBq (5.89×10^{15} Bq) ^{137}Cs per megaton, or a total of 37.3 PBq of globally dispersed ^{137}Cs from the French atmospheric tests.

This estimate of deposition and values for other radionuclides are listed in the 1993 UNSCEAR Report (United Nations 1993, p 121) Because the dominant input from French tests occurred in the Southern Hemisphere, the deposition of ^{137}Cs in the Southern Hemisphere is estimated to be 28 PBq (75%), with the remaining 9.3 PBq (25%) deposited in the Northern Hemisphere (Table I–V). Latitudinal patterns of ^{137}Cs deposition for both hemispheres using the proportions mentioned above have been derived from the measured deposition of ^{90}Sr and the values are presented in Table I–V.

I–2.2.1 Short lived radionuclides, ^{131}I

Doses from ^{131}I to infants (aged up to one year) can be much higher than average doses in the period soon after an atmospheric test The radioactive half-life of ^{131}I is short (about eight days), but following deposition ^{131}I can be transferred rapidly through the pasture–cow–milk–human pathway Iodine, whether radioactive or not, accumulates in the thyroid gland Moreover, infants are the main consumers of milk, and have small thyroid glands. Thus, since the dose to an organ is the energy deposited divided by the mass of the organ, the highest doses from intake of radioiodine typically occur in this age group

Because of the short half-life of ^{131}I, it does not have time to become well mixed in the atmosphere. Thus, radioiodine in the troposphere, from which deposition occurs within days or weeks, is much more important than that in the stratosphere, where residence half-times of aerosols are of the order of a year or longer. Because of this uneven mixing, and of variable rainfall leading to

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TABLE I–IV. ESTIMATED THYROID DOSES (mGy) TO INFANTS AT LOCATIONS IN THE SOUTHERN HEMISPHERE DURING THE PERIOD OF FRENCH ATMOSPHERIC TESTING[a]

Location	1966	1967	1968	1970	1971	1972	1973	1974
Argentina								
Buenos Aires	3 1	0 50	0 28	0 52	0.48	0 81	0.20	0 97
Australia								
Country average	0.43	0.10	0.16	0 15	0.13	0.013	0.008	0 090
Bolivia								
La Paz				1.2	0 30	0 44	0 60	0 35
Chile								
Santiago	0.50	0 090	0 10	0.30	0 60	0.22	0 03	0 24
Colombia								
Bogotá	0.05	0 05	0 10	0.10	0 08		0 18	0 01
Fiji								
Suva	2.1	0 33	0 51	0 43	0 33	0 05	0 05	0 28
French Polynesia								
Tahiti		0 55	0 60	1 3	2.1	0 12	1 3	6 8
New Caledonia								
Noumea		0.05		0 40	0 30			1.8
New Zealand								
Country average	0 17	0 05	0 08	0.08	0 05	0 05	0 05	0 05
Peru								
Lima	0 70	0.23	0.50	0 10	0.13			
Samoa								
Apia	1 7	0 97	0 38	0 71	0 84	0 05	0 13	0 51

Notes:

(1) Fresh milk consumption of 0.7 L/d was assumed.

(2) In 1969, there were no atmospheric tests, and consequently there was no exposure from local fallout

[a] Source United Nations (1977).

deposition, concentrations in air and transfers to milk vary greatly from site to site, even within the same geographical region.

Measurements of ^{131}I concentrations in milk were made at many locations in the Southern Hemisphere during the period of French atmospheric testing. Doses were estimated by assuming that an infant consumes 0.7 L of fresh milk daily. Such estimates, collected in the 1977 UNSCEAR Report (United Nations 1977), ranged up to 3 1 mGy at Buenos Aires in 1966 and 6.8 mGy at Tahiti in 1974 (absorbed doses in the thyroid gland) Some of the results for sites with more complete monitoring records are listed in Table I–IV. These values are considered to be the highest individual doses to thyroids and would apply only in cases where the actual milk intake is comparable to that assumed. Doses to adults are generally considered to be lower by an order of magnitude because of reduced milk consumption and lower dose per unit intake.

The results listed in Table I–IV indicate that the highest doses in the South Pacific region generally occurred in 1966, following the surface tests that were conducted in that year. Lower doses are indicated for tests in subsequent years In a few cases, maximum doses resulted from tests in later years (Table I–III). The contributions to the effective doses are obtained by multiplying the thyroid doses by the tissue weighting factor of 0.05 (International Commission on Radiological Protection 1990), giving effective doses of, for example, 160 μSv for Buenos Aires and 9 μSv for New Zealand in 1966.

I–2.2 2. Long lived radionuclides: ^{90}Sr and ^{137}Cs

The proportion of globally dispersed radionuclides, including the longer lived important contributors to dose, ^{90}Sr and ^{137}Cs, attributable to the French tests is assumed to be the same as the fraction of the fission yield (partitioned to the troposphere and stratosphere), i.e 3.6%. The estimated deposition in the Northern Hemisphere from French tests was only 1.3% of that from all tests, most of the testing by the USA, the USSR and China having been carried out in the Northern Hemisphere, whereas for the Southern Hemisphere the French tests represent 13% of the total. The dose rates from deposited

TABLE I–V. ESTIMATED WORLDWIDE DEPOSITION OF ^{137}Cs PRODUCED IN ATMOSPHERIC NUCLEAR TESTS

Latitude band (deg)	Area of band (10^{12} m^2)	Integrated deposition (PBq)		Integrated deposition density (Bq/m^2)	
		French tests	All tests	French tests	All tests
		Northern Hemisphere			
80–90	3 9	0 02	1.5	5 4	390
70–80	11 6	0 16	11 9	14	1030
60–70	18.9	0 67	49.7	35	2630
50–60	25 6	1.50	112	59	4360
40–50	31 5	2.06	153	65	4880
30–40	36.4	1 72	129	47	3530
20–30	40.2	1.44	108	36	2670
10–20	42 8	1 03	76.8	24	1800
0–10	44 1	0 72	53.9	16	1220
Total (hemisphere)		9 3 (25%)	695 (76%)	43[a]	3230[a]
		Southern Hemisphere			
0–10	44.1	4 08	31 7	93	720
10–20	42.8	3 47	26 9	81	630
20–30	40 2	5 45	42.4	130	1060
30–40	36.4	5.37	41.7	150	1150
40–50	31 5	5.45	42.4	170	1340
50–60	25 6	2.35	18 3	92	710
60–70	18.9	1 30	10 1	69	530
70–80	11.6	0.49	3 8	42	330
80–90	3 9	0 06	0.5	15	120
Total (hemisphere)		28 (75%)	217 (24%)	105[a]	815[a]
Total (world)		37 3 (100%)	912 (100%)	50[a]	2960[a]

[a] Population weighted values

radionuclides thus result primarily from global atmospheric testing, with only a small component attributable to tests conducted by France.

The latitudinal distribution of the deposition of ^{137}Cs is given in Table I–V. Because of the nature of the stratosphere–troposphere exchange and of air movements in the troposphere, deposition of radionuclides is greatest in the midlatitude region of the hemisphere (40–50° latitude). For the latitude band of interest to the Study (20–30° S), the cumulative deposition density of ^{137}Cs resulting from atmospheric tests conducted by France was 130 Bq/m^2 (Table I–V). This deposition occurred primarily in 1969–1972, with annual deposition amounts of the order of 30 Bq/m^2 in each of those years. The dose rate from external exposure to ^{137}Cs has been estimated to be 2.4 μSv/a per kBq/m^2 (United Nations 1993). This implies that the initial dose rate from this pathway during the years of maximum deposition was about 0.07 μSv/a. Many short lived radionuclides contribute greatly to the annual dose rate for the first year after deposition and it is calculated that external exposure from ^{137}Cs contributes about 2% of the total initial annual dose rate (from all radionuclides and all pathways). Therefore, the total dose rate was approximately 50 times greater, or 3.5 μSv/a, during 1969–1972.

In addition to dose rates caused by deposition of radionuclides originating in French atmospheric tests, dose rates about seven times greater were attributable to global fallout from tests carried out by other countries. For example, at 20–30° S, ^{137}Cs deposition was 130 Bq/m^2 from French tests and 930 Bq/m^2 from tests of other countries (Table I–V). The dose rates during the initial years of deposition were thus approximately 25 μSv/a (3.5 μSv/a × 7), and these occurred somewhat earlier (1962–1966) than the maximum dose rates attributed to French testing (1969–1972) These estimates of annual dose rates are confirmed by results reported from New Zealand of 10–30 μSv/a during 1965–1980 from

the total global fallout (National Radiation Laboratory 1971–1976, New Zealand Ministry of Foreign Affairs 1984).

Following the initial year of deposition of radionuclides, exposures continue from longer lived radionuclides and are related to the cumulative deposition amounts. Caesium-137 is a major contributor to the annual dose rates at long times after deposition, but the total annual dose rate is still less than that which occurred during the years of maximum deposition The annual dose rates did not exceed 25 μSv/a during the whole period in which atmospheric testing took place

During 1998 the residual deposition density of ^{137}Cs in the 20–30° S latitude band is about 530 Bq/m^2 (approximately one half-life since deposition), of which 70 Bq/m^2 was contributed by French testing. External exposure rates from ^{137}Cs are thus of the order of 1.3 μSv/a and this pathway accounts for 50% of the total exposure Thus, the present dose rate from global fallout in this region is of the order of 2–3 μSv/a, of which about 0 4 μSv/a can be attributed to French testing.

The maximum annual dose rates from all radionuclides in global fallout (25 μSv/a) were two orders of magnitude less than the normal background rate from natural radiation, and at present the annual dose rates are three orders of magnitude less (2–3 μSv/a) Less than 15% of these dose rates can be attributed to deposition of radionuclides that originated in atmospheric tests conducted by France

I–3 CONCLUSION

Atmospheric testing by France took place from 1960 to 1974 and involved 45 tests. All but four low yield tests took place in the South Pacific Ocean at Mururoa and Fangataufa The total yield of all French tests amounted to just over 2% of that from all atmospheric testing. Most residents of the South Pacific region received annual effective doses of no more than 25 μSv during the years in which the atmospheric testing took place. Four French tests (carried out between 1966 and 1971) were identified that caused effective doses of 1–5 mSv to residents of Tureia and the Gambier Islands, and one test (in 1974) caused doses of up to 0.8 mSv to residents of Tahiti. These doses, which were received within one year of the test, are less than or, in the case of one test, twice the dose received each year from natural background radiation (about 2–3 mSv/a).

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Annex II

CIGUATERA: INCIDENCE AND CAUSE

II–1. BACKGROUND

Ciguatera is caused by consumption of flesh and viscera of fish contaminated with ciguatoxin. It is rarely fatal Victims report a heterogeneity of symptoms and complications. Gut involvement usually consists of a syndrome similar to gastroenteritis. Neurological symptoms generally include numbness and tingling of limbs but occasionally there are motor symptoms. Symptoms and severity vary considerably even among individuals poisoned by the same fish. In severe cases coma and ataxia may be seen and some chronic symptoms such as joint pain may persist for months and be exacerbated by the consumption of certain foods (Lewis and Ruff 1993). This range of symptoms sometimes makes diagnosis difficult but a combination of compatible gastrointestinal and neurological symptoms following ingestion of potentially toxic species is the measure used today (Gillespie et al. 1986) However, this combination of symptoms has been recognized for over one hundred years.

II–2. INCIDENCE

Ciguatera type fish poisoning predates nuclear activities in the Pacific and elsewhere. A medical officer in the Marshall Islands reported cases of fish poisoning, with the mix of symptoms described as ciguatera today, during 1893–1894 (Steinbach 1895). Japanese scientists further investigated the problem of fish poisoning in the Marshall Islands between 1923 and 1943 (Hiyama 1943). Symptoms consistent with ciguatera were reported in Australia as early as 1924 (Paradise 1924).

Ciguatera, as a name, was first used by the Spanish explorers in describing fish poisoning in the Caribbean (Gudger 1930). Today, ciguatera fish poisoning is known to be endemic in tropical islands and atolls of the Caribbean and the Indian and Pacific Oceans (Bagnis 1981, Banner and Helfrich 1964) and in subtropical coastal regions, including Australia, the Florida coast of the USA and the Mexican Pacific coast (Gillespie et al. 1986, Lechuga-Deveze and Sierra-Beltran 1995) Outbreaks of the disease are unpredictable and sporadic, with increases in incidence sometimes occurring dramatically over a short period followed by a rapid and often exponential decline (Lewis 1992a) Globally, the disease affects in excess of 25 000 persons annually (Lewis and Holmes 1993).

Reports submitted to the South Pacific Epidemiological and Health Information Service show that the highest incidence of ciguatera in the Pacific over the period 1985–1990 was in Kiribati, Tokelau and Tuvalu (approximately 100 cases per 10 000 population), with the average incidence in French Polynesia being less than half this figure (Lewis 1992b) French Polynesia experienced an increase in ciguatera incidence between 1960 and 1973, epidemiological studies being introduced there from 1960 (Bagnis et al 1985). While the growth in incidence in French Polynesia has since slowed, the incidence appears to have grown in other Pacific countries (Lewis 1992b)

While outbreaks have occurred after the disturbance of coral reefs by natural causes, anthropogenic factors appear to contribute to an increase in the risk of ciguatera (Cooper 1964, Bagnis et al 1988, Tebano and Lewis 1990). Human activities that may increase the risk of ciguatera include (Lewis 1992a):

- Pollution of groundwater and sea water on atoll islands (e.g. due to human waste);
- Pollution of sea water on high islands (e.g due to human and industrial wastes, farming and land clearance);
- Reef degradation (e g due to dredging, ship groundings, trampling, anchors, removal, blasting and construction);
- Translocation of causative organisms (e.g from rafting, ship hulls and ballast water).

Given the range of human activities which may influence the incidence of ciguatera, it is likely that construction work on atolls and channel dredging, which accompanied military activity on French Polynesian and other Pacific atolls, could have locally influenced the potential for ciguatera. However, not every instance of reef disturbance is followed by an upsurge in fish toxicity. There is no evidence in the scientific literature of radiation influencing the occurrence of the disease.

It is unclear whether an increase in incidence or severity is related to an increase in the numbers of the organism now identified as the causal agent or to increased toxin production by individual organisms. No relationship has been found between radioactivity of fish

and ciguatera toxicity (Helfrich 1960), nor any significant influence by El Niño events (Lewis 1992a).

II–3. CAUSAL AGENT

Ciguatera is believed to be caused by the dinoflagellate *Gambierdiscus toxicus* Adachi et Fukuyo, which adheres to dead coral surfaces and bottom associated algae Benthic fish and other organisms graze on this material, ingesting the causal organism. The toxin is subsequently transferred to other, carnivorous fish species. In Australia, over 25 species of fish have been proven to give rise to outbreaks (Gillespie et al. 1986) and in French Polynesia some 100 species have been implicated (Bagnis et al 1985) Many of the fish which are typically involved are considered 'fatty'. Moray eels are often highly toxic.

Research, aided by improved separation technologies in the 1980s, suggests that there are three forms of heat-stable lipid-soluble ciguatoxins, which affect sodium channels in the cell membrane (Murata et al. 1990, Lewis et al 1991) The widespread distribution of such channels in nerve and muscle accounts for the range of effects seen in humans. Despite the fact that isolated *G toxicus* organisms have been found to contain ciguatoxin and some laboratory cultures produce the toxin, consistently inducing its production by cultured organisms has proved difficult

II–4. CONCLUSION

Ciguatera fish poisoning is the most common type of marine biotoxin ingestion. The disease poses important health, economic and social problems for the inhabitants of endemic areas, these being in regions of warm water throughout the world. The causative organism and the nature of the toxin have been identified. A variety of disturbances of coral reefs may be associated with outbreaks of the disease but no correlation with radiation has been found.

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Annex III

IONIZING RADIATION: LEVELS AND BIOLOGICAL EFFECTS

This annex provides an overview of ionizing radiation and its effects, and of the principles for controlling the use of radiation and radioactive materials. As an introduction to these issues, and also to those discussed in Annex IV, some of the relevant physics is described.

III–1. ATOMS AND NUCLIDES

All matter is made up of atoms, and each atom is made up of a nucleus and electrons. The fundamental particles that make up the nucleus are neutrons (n) and protons (p), known collectively as nucleons[1]. The proton has one unit of positive electric charge and the neutron has no charge, so the number of protons in a nucleus determines the number of positive charges of the nucleus These positive charges are neutralized in the atom by an equal number of negatively charged electrons orbiting the nucleus. The number of electrons determines the chemical behaviour of the atom and is called the 'atomic number', Z (which is, of course, also equal to the number of protons in the nucleus). The total number of nucleons, A, existing within a nucleus determines the mass of the atom and is called its 'mass number'. Protons and neutrons have approximately equal masses, while electrons have relatively very little mass. The number of neutrons, N, in the nucleus is $A - Z$. The general term for a type of atom, as defined by its atomic number and mass number, is a nuclide.

All of the atoms of a particular chemical element have the same atomic number. However, atoms of an element can have different mass numbers (because they have different numbers of neutrons); these different types of atom are called isotopes of that element. Any nuclide can therefore be represented uniquely by the name of the element (or its symbol) and the mass number of the isotope. For example, a nuclide referred to frequently in this report — the isotope of plutonium (atomic number 94) with 145 neutrons, and hence a mass number 239 — is designated as plutonium-239 (^{239}Pu).

[1] Nucleons are themselves made up of yet smaller particles, known as quarks, but for this discussion it is sufficient to treat protons and neutrons as fundamental particles

III–2. RADIOACTIVITY AND RADIOACTIVE DECAY

The exact nature of the forces holding an atomic nucleus together is not completely understood. Clearly, there must be a force that holds the positively charged protons together in spite of the repulsion between like electric charges, but there must also be a force that prevents the nucleons from coalescing

Empirically, it is clear that nuclei are stable only if they have approximately the right ratio of neutrons to protons From studies of stable nuclei, it is evident that the values of this ratio all lie within a narrow range, and that the 'ideal' ratio for stability increases slowly as the mass of the nucleus increases, from 1 (equal numbers of neutrons and protons) for light elements to about 1.6 (60% more neutrons than protons) for the heaviest elements. If the ratio differs from this ideal value by too much in either direction, i.e. if there are too many or too few neutrons for the number of protons present, then the nucleus will be unstable. If there are far too many or far too few neutrons, then the nuclide will not exist at all because it would be so unstable. In less extreme cases, unstable nuclei can exist for a significant period of time before undergoing spontaneous rearrangements until a stable configuration is achieved. These rearrangements take a number of different forms, but all involve the emission from the nucleus of some particle or form of radiation, and are termed generally 'radioactive decay'. These types of unstable nuclei are termed radioactive nuclides, usually shortened to 'radionuclides'.

Radioactive decay is a property of the nucleus that is unaffected by the chemical or physical state of the atom, or the temperature or pressure conditions. The 'activity' of a radioactive substance is a measure of the rate at which it decays (and hence the rate at which it emits radiation), and is defined in terms of the number of nuclear disintegrations per unit time. The unit of activity in the International System of Units (SI) is the becquerel (Bq), which is equivalent to one disintegration per second. An older unit named the curie (Ci), equivalent to 37 GBq (3.7×10^{10} Bq), is also sometimes used This rather peculiar number arose because the activity of 1 g ^{226}Ra was used as a standard of activity until recently.

Individual atoms of a radionuclide decay randomly, but the total activity of a large number of atoms of a

given radionuclide falls off exponentially with time, the 'half-life' is used to characterize this decay. The physical half-life of a radionuclide is the time taken for the activity to be halved as a result of radioactive decay, and is a constant for any given radionuclide Where the term half-life is used on its own, it may normally be assumed to mean the physical half-life, but two other concepts are also used· the biological half-life and the effective half-life. The biological half-life is the time taken for an organism to eliminate half the amount of a given substance from its body (or a particular part of the body) by biological processes. The effective half-life combines the physical and the biological half-lives to give a measure of the overall rate at which the amount of radioactive material in an organism is reduced.

III–3. RADIATION

There are a number of ways in which an unstable nucleus may achieve a more stable state, and a number of different types of radiation can be emitted in the process.

III–3.1. Beta and gamma radiation

In those nuclei with excess neutrons, a neutron can convert into a proton by emitting a (negatively charged) electron, called a 'beta particle' (β^-) This decay by beta radiation leaves the nucleus with one more positive charge, so its atomic number increases by one and it becomes the nucleus of an atom of a different chemical element Three examples are presented below:

$$^{40}K \rightarrow {}^{40}Ca + \beta^- + Q$$

$$^{90}Sr \rightarrow \beta^- + Q + {}^{90}Y \rightarrow {}^{90}Zr + \beta^- + Q$$

$$^{137}Cs \rightarrow {}^{137}Ba + \beta^- + \gamma + Q$$

In each case, Q indicates the energy that is released in the form of radiation plus the kinetic energy of the decay products, the significance of this is discussed in Annex IV. In the second equation, in order for the ^{90}Sr nucleus to reach the stable configuration of the ^{90}Zr nucleus, the transformation of two neutrons in a two step adjustment (via the unstable ^{90}Y nucleus) is required. This is called a 'decay chain'. For some nuclei very far from stability, the decay chain can comprise many steps. Long decay chains are characteristic of the radioactive decay of the heavy elements. The ^{238}U isotope of natural uranium, for instance, is transformed successively into 13 unstable nuclei before it reaches a stable configuration as the lead isotope ^{206}Pb.

The third equation illustrates another type of radiation: gamma radiation is electromagnetic radiation which is usually emitted during reorganization of the nucleus after radioactive decay Although gamma rays behave in many ways like waves, the manner in which they transfer energy to matter is more like that of a particle, and therefore gamma radiation is often discussed in terms of 'packets' of radiation, known as photons. Gamma radiation is emitted by a wide range of nuclei undergoing various types of radioactive decay, but is perhaps most commonly associated with beta decay, where it can often be more important than the beta radiation. In the example above, the beta decay of ^{137}Cs initially produces nuclei of ^{137}Ba in a short lived metastable state, which then release energy in the form of gamma radiation as they transform into their more normal (and stable) state.

The ^{40}K nucleus may also give rise to the emission of gamma rays In about 11% of disintegrations, its excess positive charge is reduced by capture of one of the orbital electrons, a process called 'electron capture'. This results in the number of positive charges being decreased by one, giving rise to a nucleus of the element argon. When it is formed, the ^{40}Ar nucleus is in an excited state and it reaches stability by emitting an energetic (1.46 MeV) gamma ray (where one mega-electronvolt (MeV) is equal to 1.602×10^{-13} joules (Section IV–1 of Annex IV)) This is the origin of the major part of the gamma activity in the human body and is readily measured nowadays by sensitive 'whole body counters'.

Alternatively, if there is an excess of protons, a proton can change into a neutron by emitting a positively charged beta particle (a positron, β^+), thereby reducing the number of protons in the nucleus by one, giving a nucleus of the element with atomic number $Z - 1$.

There are a few rare nuclides (produced during the fission process) which have a considerable number of excess neutrons and which emit a neutron directly rather than undergoing beta decay

III–3.2. Alpha radiation

The heaviest elements — those with atomic numbers greater than about 80 — can undergo another mode of rearrangement to modify the neutron to proton ratio: the emission of two protons and two neutrons as a particle. This particle is identical to the nucleus of a helium atom, ^4He, but is normally called an 'alpha particle', the name given by early investigators into radioactivity. For example:

$$^{239}Pu \rightarrow \alpha + \gamma + {}^{235}U$$

Gamma rays are emitted in very few of the disintegrations of ^{239}Pu and these emissions are of low energy. This makes ^{239}Pu difficult to measure by means of gamma emissions, particularly in the field. In the laboratory, one of the more energetic of the gamma rays can be used, even though emitted in only a very small proportion of the disintegrations. In the field, the presence of ^{239}Pu is usually inferred from measurements of ^{241}Am, another alpha emitting nuclide which almost invariably accompanies ^{239}Pu and which has a gamma ray of reasonable intensity, although this is of rather low energy (59 5 keV). Americium-241, which has a half-life of 433 years, comes from the beta decay of ^{241}Pu (half-life 14.4 years), which is always present as an impurity in the plutonium produced in nuclear reactors.

III–3.3. Other radiation types

Other types of radiation exist, but are less relevant to this report For example:

— Neutrons can be emitted as a type of radiation, but generally only while nuclear fission or fusion is taking place (Annex IV)
— X rays, like gamma radiation, are a type of electromagnetic radiation which can also be emitted in the course of radioactive decay They have a lower energy than gamma radiation and generally result from rearrangements of the electrons in an atom, not from rearrangements of the nucleons in a nucleus. Being of lower energy than gamma radiation, they are of less importance in the context of this report
— Waves from all other parts of the electromagnetic spectrum — from radio waves and microwaves through infrared to visible and ultraviolet light, and even the electromagnetic waves induced by electric power lines — are all types of radiation. However, they are not ionizing radiation (see below) and are therefore not of relevance to this report.

III–4. IONIZING RADIATION

The alpha, beta and gamma rays described above are all examples of 'ionizing radiation'. When such radiations interact with matter, they can transfer enough energy to the constituent atoms to cause the orbital electrons to be ejected, leaving behind positively charged ions (this process is termed ionization). From the point of view of potential impacts on the health of humans or other organisms, ionizing radiations are far more important in their effect than non-ionizing radiations (such as radio waves).

The rate at which ionization is produced along the path of a charged particle as it passes through a material depends upon the mass, charge and speed of the particle, whereas for a gamma ray the rate depends on the energy of the radiation. Highly charged heavy particles lose energy rapidly and therefore do not penetrate deeply into matter, alpha particles, for example, do not penetrate the layer of dead cells on the surface of the skin. Beta particles may penetrate up to a few centimetres of body tissue. Electromagnetic radiations, on the other hand, such as X rays and gamma radiation, have considerable penetrating power and, depending on their energy, may pass through tens of centimetres of body tissue.

III–5. PRIMARY DOSIMETRIC QUANTITIES

Radiation cannot be detected with the human senses, but in most cases it can easily be measured. A number of quantities are discussed below that are used to measure radiation and estimate the likelihood of health effects.

III–5.1. Absorbed dose

As radiation passes through air, it can be measured by counting the number of ionized particles that it leaves behind. As radiation penetrates any material, its energy is absorbed and then rereleased by the constituent atoms. The absorbed energy per unit mass of material is termed the 'absorbed dose', D The SI unit of absorbed dose is the gray (Gy), one gray being equal to one joule of energy absorbed per kilogram of matter (an older unit, the rad, is also still used occasionally, 1 Gy being equivalent to 100 rad) The biological effects of radiation on biological materials, such as tissue, depend on the magnitude of the absorbed dose

III–5.2. Radiation weighting factors and equivalent dose

The biological effects of radiation depend not only on the absorbed dose but also on the type and energy of the radiation causing the dose. For radiation protection purposes, these factors are taken into account by weighting the absorbed dose in a tissue or organ of the body by a factor related to the 'relative biological effectiveness' of the radiation. For beta and gamma radiation, this 'radiation weighting factor', w_R, is unity For alpha particles, which deposit their energy in a much smaller volume of tissue and hence cause higher local concentrations of ions, a value of 20 is used, because they are considered to cause about 20 times more damage per unit of absorbed dose than electrons or photons. The

absorbed dose weighted by the radiation weighting factor is termed the 'equivalent dose' in a tissue or organ and is given by the expression:

$$H_T = \sum_R w_R D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose in the tissue or organ T (the 'organ dose') due to radiation type R. The unit of equivalent dose is the joule per kilogram and is termed the sievert (Sv). Since the sievert is a relatively large unit of dose, the subunits millisievert and microsievert are more frequently used in the Study

III–5.3. Tissue weighting factors and effective dose

For a given equivalent dose, the likelihood of a radiation induced health effect in the human body is found also to depend on which tissue or organ is irradiated — some tissues and organs are more sensitive than others. A further quantity is therefore defined, derived from the equivalent dose, to indicate the combined effect of different doses to different tissues. The factor by which the equivalent dose in a tissue or organ T is multiplied is termed the 'tissue weighting factor', w_T, which represents the fraction of the total harm (or detriment) that would be incurred by that tissue or organ if the whole body were irradiated uniformly. The weighted equivalent dose (a doubly weighted absorbed dose) is termed the 'effective dose', E·

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

The effective dose is thus a measure of the total risk due to any combination of radiations affecting any organs of the body, and is therefore the most commonly used measure of dose in the context of assessing human health effects.

III–6. SUBSIDIARY DOSIMETRIC QUANTITIES

III–6.1. Committed dose

If a person receives a radiation dose from a source outside his or her body (a process referred to as 'external exposure', e.g. from radioactive material on the ground or natural cosmic radiation from space), then clearly the dose is that received during the time of exposure to the source However, if radioactive material is taken into the body, for example by eating food that contains radionuclides, or inhaling radioactive material in the air, this material (and its decay products if they are radioactive) will then continue to give a dose (a process referred to as 'internal exposure') until it leaves the body or decays to a stable nuclide. The dose received will therefore depend on the effective half-life of the radionuclide in the body (Section III–2), which can be very long Furthermore, because the material can move within the body, its position in relation to the different tissues and organs can change, which will also affect the doses that the tissues and organs receive.

The idea of a 'committed dose' (which could be the committed equivalent dose to a tissue or organ, or a committed effective dose if risk to the body as a whole is being assessed) is intended to allow for this. The committed dose can be calculated for a defined activity of a specific radionuclide by using mathematical models of its behaviour in the human body to estimate the relevant dose over a defined period. The most commonly used periods are 50 years (for intake by an adult) or to age 70 years (for intake by a child), which are intended to represent the times over which the dose is accumulated over the rest of the person's life as a result of the intake.

For radionuclides with an effective half-life longer than a year, only part of the committed dose is received within one year of intake If the intake is continued at a uniform rate over a number of years, the annual dose rate to the individual will build up until an equilibrium is reached which is equal to the committed dose per year. This is the situation that would obtain, for example, if people consumed food produced in an environment containing persistent levels of radioactive materials.

III–6.2. Collective dose

The dosimetric quantity referred to above relates to the exposure of an individual Other quantities relate to exposed groups or populations. These quantities, referred to generically as 'collective dose', were introduced initially by the International Commission on Radiological Protection (ICRP) to take account of the number of people exposed to a source by multiplying the average dose to the exposed group by the number of individuals in the group. The relevant quantities derived are the 'collective equivalent dose' for a tissue or organ and, more commonly, the 'collective effective dose'. If several different groups of people are involved, the total collective dose is the sum of the collective doses for each group. The unit for these collective quantities is the man-sievert. These quantities can be thought of as representing the total consequences of the exposure of a

population or group, but their use in this way should be limited to situations in which the consequences are truly proportional to both the dosimetric quantity and the number of people exposed, and in which the relationship between the magnitude of the consequences and the size of the dose is known

The collective dose idea can be extended further The collective effective dose to a population resulting from the presence of radioactive materials in the environment may be accumulated over long periods encompassing successive generations. The total collective effective dose to be expected in a given situation is the integral over all time of the collective effective dose rate resulting from a single release or, in the case of a continuing practice (Section III–11.1.1), the releases within a defined period. If the integration is not performed over infinite time, the collective dose is described as being truncated, and the time of truncation should be specified. If the range of individual doses is large or the time over which they are delivered is long, it may be useful to divide the collective quantities into elements covering more limited ranges of dose and time In some cases of continuing practices, it may also be convenient to distinguish between the collective effective dose already delivered and the collective effective dose committed over all time.

In its Publication 77, the ICRP (1998) clarified its intentions regarding the use of collective dose, stating that the unlimited aggregation of collective dose over time and space into a single value is unhelpful because it deprives the decision maker of much necessary information. The levels of individual dose and the time distribution of collective dose may be significant factors in making decisions. In addition, the ICRP indicated that the problems of estimating collective dose over long periods are those of uncertainty Both the individual doses and the size of the exposed population become increasingly uncertain as the time increases Furthermore, the current judgements about the relationship between dose and detriment may not be valid for future populations. Because some situations can be forecast with confidence further into the future than can others, decisions must be made on a case by case basis. In general, however, forecasts of collective dose over times longer than several thousand years and forecasts of health detriment over times longer than several hundred years should be examined critically.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has used the quantity collective dose to assess the global impact of atmospheric testing by summing the individual doses estimated to be received by a world population of a few thousand million which increases with time.

III–6.3. Effective dose commitment

The quantity 'effective dose commitment' was introduced by UNSCEAR at a time when nuclear weapon test explosions in the atmosphere introduced time elements that made the source of radiation different from previously considered sources in the sense that, although the period of practice was limited, the period of exposure was protracted. After each test, some long lived radionuclides were released which would persist in the biosphere for many years, causing radiation exposure to future populations. To quantify the situation more precisely, UNSCEAR introduced the concept of dose commitment, defined as the integral over infinite time of the per caput dose rates delivered to the world population as a result of a specific nuclear explosion or series of explosions. The concept was originally introduced to estimate future doses from practices which would continue over long periods.

The quantity has been used to estimate the total dose liable to be received from radionuclides released into the atmosphere from the testing of nuclear weapons. It represents the summation of individual doses over all time, about 70% of the total dose being contributed by ^{14}C over a period of the order of 10 000 years. However, the dose commitment is a hypothetical dose received by all present and future generations and therefore does not represent the dose that is received by any individual either in a year or in his or her lifetime. In circumstances where a practice continues over a prolonged period, however, the dose commitment over a year will give the annual doses to individuals under equilibrium conditions.

III–7. MODES OF RADIATION EXPOSURE

The pathways by which humans may be exposed following a release of radioactive material to the environment are qualitatively well known and their relative importance is understood. If reliable quantitative data are available for the various processes involved, then assessments of the exposure via each of the pathways are possible.

Exposure pathways which follow an atmospheric release are possibly the easiest to visualize. In this case, a radioactive cloud is dispersed and transported by the prevailing winds, and people can initially be exposed to radiation by two principal pathways: external irradiation from material in the cloud and internal irradiation from radioactive material inhaled in the air as they breathe. The radioactivity in the cloud is gradually depleted

during its dispersion by radioactive decay and by removal of radioactive materials from the cloud by rainout and by deposition on the ground and water surfaces, this removal occurs in all weather conditions, but will be more rapid if there is precipitation or fog. Following deposition, people may be exposed and may continue to be exposed by other pathways, the three main ones being external irradiation from the deposited material itself, the inhalation of any material resuspended into the atmosphere by the wind (or, for example, by traffic) and the transfer of material through the terrestrial and aquatic environments to food and water.

Radioactive material released into an aquatic environment is dispersed by the movement of water and sediment. In general, some of the material will dissolve in the water, and will therefore move with the water, while some will become attached (by chemical reaction) to the sediment suspended in the water column or on the bed of the water body, so that it moves with the sediment. The water- and sediment-borne materials can be taken up by aquatic plants and animals, and thus enter the food chain. Eating fish and other aquatic foods is therefore one pathway by which humans may be exposed, other pathways include external exposure from radionuclides in sediments (e g. those washed up on the shore), drinking (or inadvertently swallowing) the water itself, handling fishing gear and inhaling 'sea spray', i.e. water resuspended by the action of waves. The main exposure pathways are considered in turn in the following sections

III–7.1. External exposure

As discussed above, radionuclides may emit alpha particles, beta particles or photons of gamma radiation, or some combination of these Because alpha particles are rapidly absorbed within a few centimetres of air, they do not usually penetrate the outer layers of dead skin. Therefore, alpha radiation is not an external exposure hazard Beta particles travel no more than several metres in air before being absorbed. Because of this, the beta radiation dose will depend only on the concentration of beta emitters close to an individual. Beta radiation also has only a limited range in tissue, a few centimetres at the most, and thus represents a radiation hazard only to those organs situated close to the body surface, particularly the skin. Gamma rays travel typically hundreds of metres in air and this highly penetrating radiation can lead to exposure of all tissues of the body Thus, the gamma radiation dose can include contributions from gamma emitters at large distances from an individual However, the dose distribution within the body due to gamma radiation is much more uniform than that produced by beta emitters, particularly for higher energy photons. In general, then, the exposure due to penetrating photons is the most significant source of external exposure, although beta irradiation can be a significant component of the skin dose.

III–7.2. Internal exposure

The two important pathways by which radionuclides can enter the body are by inhalation and ingestion. Another possible route of intake is through the skin. It is rare for chemicals to be able to transfer through intact skin, and the only radioactive material for which this exposure route is normally important is tritiated water, i.e. water in which one of the hydrogen atoms has been replaced by tritium (^{3}H), the radioactive isotope of hydrogen. The entry of radioactive material through the intact skin is generally of minor importance and is not discussed further here. Radioactive material, especially if in particulate form, could, however, enter the body through the skin via cuts and abrasions. There, it could lead to local irradiation of the tissue surrounding the particle or, if the radioactive material is soluble in body fluids, the solubilized material may be transferred to other body organs.

As mentioned above, radionuclides in air can be inhaled directly from a cloud of material as it passes overhead, or following the resuspension of radionuclides deposited onto the ground, or in water resuspended as sea spray. The amount of a radionuclide inhaled can be assessed by estimating the concentration of the radionuclide in air at the point of interest and multiplying this by a breathing rate and the length of time for which a person breathes the air containing the radionuclide. Breathing rates depend on age, size and exercise level.

As indicated earlier, radionuclides may also be transferred through terrestrial and aquatic food chains Intakes by ingestion may be assessed if the radionuclide concentration in the food is known, either from measurements of the food itself or from modelling. Detailed models of the transfer of radionuclides through both types of environment have been developed which make it possible to assess the activity concentration of a given radionuclide in a food on the basis of measurements of the level elsewhere in the environment, or even a knowledge of the releases into the environment. These models take account of the nature of the environment and the chemical properties of the radionuclide

Once the level of intake by either inhalation or ingestion is known, doses can be estimated by making assumptions about the behaviour of radionuclides within the body. This is normally achieved by applying a suitable dosimetric model, as outlined below.

III–7.2.1. Internal dosimetry

As mentioned in the discussion on committed dose (Section III–6.1), internal irradiation is protracted in time after an intake of radioactive materials. Doses to the different tissues and organs in the body following intake of a radionuclide depend on many factors, including the physical and chemical form of the nuclide, the nature of the radiation emitted and the metabolism of the individual concerned Metabolic data and models are required to determine the distribution and retention of the radionuclides in the body Once the distribution of the radionuclide in the body has been estimated, an assessment is then required of the irradiation of individual organs and tissues, both from the activity within the organ or tissue itself and from that in surrounding parts of the body.

For intake by inhalation, the models used to predict the behaviour of radionuclides in the body represent the extent to which radioactive material is deposited in different regions of the respiratory system, the length of time it is retained there and how much is transferred to the body fluids for circulation to other organs. Similarly, for ingestion, transfer through the gastrointestinal tract is considered, together with the extent to which radionuclides cross the walls of the tract to enter the circulatory system. The ICRP model used for the calculation of doses from radionuclides which have entered the gastrointestinal tract consists of four sections. stomach, small intestine, upper large intestine and lower large intestine Values of gut absorption, i.e. the fraction of an element reaching the body fluids following ingestion with food or drinking water, tend to be greater in the newborn, in most cases reaching adult values by about the time of weaning Whether the radionuclides enter the body fluids from the respiratory or the gastrointestinal system, their subsequent transfer to body organs is generally treated in the same way. Radionuclides will be deposited in various organs and will also be removed from the body by excretion. The pattern of deposition and removal from various organs and tissues will vary markedly, depending on the element concerned and its physical and chemical forms.

The results of this modelling are generally expressed as dose coefficients, which represent the committed effective dose from intake (by a specified route) of 1 Bq of a specific radionuclide. Obviously, these vary from nuclide to nuclide and by several orders of magnitude in some cases. The values for a given nuclide also depend on the type of intake (inhalation or ingestion) and the characteristics, particularly the age, of the individual; the variation with age alone can be as much as an order of magnitude. The dose coefficients used in the Study are those listed in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Food and Agriculture Organization of the United Nations (FAO) et al. 1996).

III–8 RADIATION EXPOSURES IN EVERYDAY LIFE

This section is intended to give an overview of the radiation doses that people receive in their everyday lives There has always been, and continues to be, a background of natural radiation on Earth Recent human activities have modified the relative magnitudes of some of these natural sources, and introduced some new ones

III–8.1. Natural radiation environment

Natural sources deliver the highest radiation doses that most people receive. The worldwide average annual dose due to natural sources is some 2.4 mSv. Within this worldwide average there are national average doses ranging up to more than 5 mSv, local averages of tens of millisieverts and individual cases ranging up to hundreds of millisieverts. There are, however, no known examples of people receiving less than 1 mSv/a from natural sources.

The two major natural radiation sources are outer space, from which the Earth is irradiated continuously by cosmic radiation, and the Earth's biosphere, which includes radionuclides that have been present, mainly in the Earth's crust, for several thousand million years. Human irradiation occurs both externally, through exposures to cosmic radiation and to radiation from naturally occurring radioactive materials outside the human body, and internally, through exposure to radionuclides that are naturally present in the human body and naturally occurring radionuclides in air, water and food Terrestrial radiation sources are the largest natural cause of irradiation, contributing as much as 85% to the average annual dose

III–8.1.1. Cosmic radiation

Levels of cosmic radiation are relatively stable at the Earth's surface (sea level), although they are affected by the Earth's magnetic field, so that polar regions receive more than equatorial regions More importantly, the level increases greatly with altitude (the atmosphere attenuates the radiation, but there is less atmosphere at altitude for the radiation to traverse), doubling approximately every 1500 m. Most people worldwide live at or close to sea level, so there is little variation around the average dose rate of about 0.3 mSv/a due to cosmic radiation

However, in cities at high altitudes (such as La Paz in Bolivia, Bogotá in Colombia and Denver in Colorado, USA) the annual doses of cosmic radiation may be much higher than the average level, reaching 1 mSv or more. This increase with altitude also means that people travelling by air receive extra doses; for example, a passenger taking a flight from Europe to North America would receive approximately 0 05 mSv As a consequence, air crews are among the groups of people who receive the most radiation as a result of their work.

III–8 1.2. Terrestrial sources

Levels of exposure to terrestrial radiation sources vary throughout the environment, depending on the activity concentration in such natural materials as rocks, soils, water and air, in food and even in the human body. The most important terrestrial sources from the point of view of human radiation exposure are very long lived radionuclides of primordial origin ^{40}K, ^{87}Rb and the two chains of radionuclides arising from the decay of ^{238}U and ^{232}Th. Other radionuclides, such as those in the ^{235}U decay series, make little contribution to total radiation exposure because of their low abundance in the contemporary environment.

Outdoors, the radioactivity in certain rocks and soils is the main source of terrestrial radiation. Generally, igneous rocks such as granite are more radioactive than sedimentary rocks, although highly radioactive shales and phosphate rocks are notable exceptions to this rule

Because most people spend the majority of their time indoors, radiation levels in dwellings are generally more important to their overall exposures. Most indoor terrestrial radiation can be traced to one ubiquitous source, the noble gas radon, although most of the dose actually comes from the decay products generated as radon decays (the 'radon daughters'). The fact that radon is an inert gas, and therefore extremely mobile, makes this source so important. On average, radon, created by the decay of naturally occurring radionuclides in rocks, soil and building materials, causes slightly more than half (1.3 mSv) of the average (per caput) annual effective dose due to natural background radiation. However, this worldwide average is influenced by the much higher exposure indoors in parts of the world where houses have low ventilation rates and therefore concentrate radon to levels much higher than those outdoors

Internal irradiation by terrestrial sources other than radon is mainly due to the inevitable occurrence of ^{40}K in all potassium in the tissues of the body, and the intake of ^{210}Pb and ^{210}Po (members of the ^{238}U decay chain) in foods. Compared with radon exposure, their contribution to the average annual dose level is small. As the level of potassium, and therefore ^{40}K, is homeostatically controlled in the body, most adults receive about the same annual dose of 200 μSv from this source. However, dietary patterns can influence internal exposures to ^{210}Pb and ^{210}Po. For example, these nuclides are concentrated in seafood, and in Japan, where this is a preferred food, doses from ^{210}Pb and ^{210}Po in seafood are found to be five times higher than in Germany and India, and ten times higher than in the USA. Levels of ^{210}Po are also high in the zooplankton and seafood of the South Pacific Ocean.

III–8.2. Human activities affecting the radiation environment

Four human activities in particular have added to the natural radiation environment: the use of radiation for medical purposes, the atmospheric testing of nuclear weapons, industrial processes that use materials containing natural radionuclides, and the generation of electricity by nuclear power.

III–8 2.1. Medical uses of radiation

Medical procedures are one of the major sources of human radiation doses. Estimates of the average annual dose in advanced countries due to medical irradiation are between 0 4 and 1 mSv

III–8.2.2 Nuclear weapon testing

Between 1945 and 1980, there were more than 500 nuclear explosions in the atmosphere for the purpose of testing nuclear weapons. Atmospheric testing had two peak periods, 1957–1958 and 1961–1962; in each of these periods there were 128 tests, but the explosive yield for the latter period was about four times higher than that for the earlier one. These tests released substantial amounts of radioactive material into the environment.

The global fallout from atmospheric testing contains a large number of different radionuclides, but only four are of concern to present and future populations. ^{14}C (with a half-life of 5730 years), ^{137}Cs (half-life 30 years), ^{90}Sr (half-life 29 years) and tritium (half-life 12 years). Carbon-14 accounts for about 70% of the committed exposures because of the relatively short half-lives of the other radionuclides. A very small contribution from ^{239}Pu, ^{240}Pu and ^{241}Am (0 1%) to the dose rate will occur over thousands of years The worldwide per caput annual dose due to atmospheric testing is, at this time, 0.01 mSv; however, because of the long lived nuclides produced, the collective dose commitment due to

atmospheric testing is the largest of all those from artificial sources.

In 1963, the USSR, the UK and the USA concluded the Partial Test Ban Treaty, undertaking to cease atmospheric testing. Subsequent atmospheric tests by France and China were considerably less frequent and smaller in yield. The radioactive materials present underground as a consequence of underground tests are not widely dispersed in the environment in the same way as those from atmospheric testing, and therefore do not result in a widespread contribution to dose in the same way.

III–8.2.3. Industrial processes and natural radionuclides

Some industrial processes, such as geothermal energy production and phosphate mining, bring materials to the Earth's surface which have higher than average concentrations of naturally occurring radionuclides. Other processes, such as coal burning and phosphate fertilizer production, involve materials with average or above average amounts of natural radionuclides, but lead to radionuclides becoming concentrated in one or more products or by-products. Their contributions to the general radiation environment have not been significant.

III–8.2.4. Radiation and nuclear energy

The generation of electricity using nuclear power results in some radioactive materials being released into the environment. Under normal circumstances the amounts released are negligible in the context of the overall radiation environment, on average, the annual dose from all practices in the nuclear fuel cycle is only about 1 μSv at present, a tiny fraction of that from natural radiation.

In addition, nuclear generation of electricity, like all industrial activities, has the potential for accidents. After the first commercial nuclear power plant began operation in 1956, the nuclear power industry worldwide accumulated more than 5000 reactor-years of operation without experiencing any large accidental release of radioactive materials into the environment, until the accident at Chernobyl took severe accidents out of the hypothetical realm. Given the uneven distribution of exposures, it is questionable whether the average global exposures due to the Chernobyl accident should be compared with those from steady sources, including natural radiation However, such comparisons may be useful for understanding the impact of the accident in particular, and of nuclear energy in general, on the radiation environment It may be noted that the global collective dose over the next 30 years resulting from the Chernobyl accident will correspond to three weeks of exposure to natural background radiation. However, individual doses due to the accident were very unevenly distributed.

III–9. SIGNIFICANT RADIONUCLIDES FOR THE STUDY

III–9.1. Caesium-137

Caesium-137, with a physical half-life of 30 years, is encountered following a nuclear explosion because it is a major fission product of both uranium and plutonium (Annex IV). If present in the environment, it can be a significant source of both external and internal exposure Furthermore, a particular feature of atolls is that their soils tend to be deficient in potassium. Therefore, caesium, being chemically similar to potassium, may be taken up by plants to a greater extent than would be the case in normal soils. Caesium is soluble in body fluids; upon ingestion it is absorbed rapidly, distributed almost uniformly throughout the body and finally eliminated by the kidneys with a biological half-life in adults of 70–110 d Its biological half-life in children is much shorter, ranging from 12 d in infants to 57 d in older children; it is also somewhat shorter in women than in men.

Another radioactive isotope of caesium, ^{134}Cs, is also a fission product, but owing to its shorter half-life (2.1 years) and very small fission yield, it is of less radiological importance than ^{137}Cs. It is produced in significant quantities in nuclear reactors but hardly at all in nuclear weapons. However, it can also be produced by the neutron irradiation of stable caesium (^{133}Cs), so that it could be formed in the vicinity of underground nuclear explosions through the activation of caesium in the surrounding rock.

III–9.2. Strontium-90

The fission product ^{90}Sr is the most important radioisotope of strontium, having a fairly long physical half-life (29 years) and strong beta emissions. Strontium-89 is an indirect fission product of uranium and has a physical half-life of 51 d. Experience suggests that after a single intake by ingestion, about 25% of strontium will be absorbed into extracellular fluid (after inhalation, about one third is absorbed into extracellular fluid) and about half this amount is deposited in bone. Beta particles are emitted by ^{90}Sr and its daughter product and irradiate both calcified bone and adjacent bone marrow. The effective half-life for ^{90}Sr in the body is about 15 years.

III–9.3. Plutonium-239

Plutonium-239 is a radioisotope whose radiobiology has caused much concern. It has a physical half-life of about 24 000 years and emits energetic alpha particles that have a range of 24 μm in bone and 40 μm in soft tissue. Because ^{239}Pu emits mainly alpha particles, it represents a biological hazard only when it is inside the body. Inhalation is the route of most concern for internal contamination by plutonium. Deposition patterns and the retention of plutonium in the lungs depend on its physical and chemical properties, including its solubility and particulate size Relatively insoluble particles have a high degree of retention in the lungs and lymph nodes. The retention half-life in the lungs is between 150 and 1000 d. If plutonium is in a soluble form or becomes soluble, the distribution in the body is likely to be approximately 45% in the skeleton, 45% in the liver and 10% in other tissues The biological half-life in humans is about 200 years, with half-lives in the liver and the skeleton of about 40 and 100 years, respectively.

In the Study, it is to be noted that ^{239}Pu usually occurs together with ^{240}Pu, formed when ^{239}Pu absorbs neutrons rather than undergoing fission. Simple methods for detecting plutonium do not easily distinguish between these two isotopes, and therefore measurements are often quoted in terms of the activity of $^{239+240}Pu$, i.e. the total activity of both isotopes. The relative contributions of the two isotopes to this total activity depend on the nature of the plutonium; for very pure, 'weapons grade', plutonium (Annex IV), approximately 80% of the activity may be assumed to be in the form of ^{239}Pu.[2]

III–10. HEALTH EFFECTS OF RADIATION EXPOSURE

Knowledge of the effects of radiation exposure on human health is derived from extensive in vitro and in vivo animal experiments, and from epidemiological studies of the survivors of the atomic bombings of Hiroshima and Nagasaki in 1945 and of groups exposed to relatively high doses in radiotherapy, as well as in accidents and in some occupational situations. This evidence allows a number of qualitative and quantitative conclusions to be drawn about the interaction of ionizing radiation with cells and the implications for human health

As ionizing radiation passes through human tissue, it can transfer energy and ionize atoms in important molecules within human cells. The ionization of an atom produces a free electron as well as an ion or free radical These species are highly chemically reactive, so they will normally recombine. Occasionally, however, recombination does not occur and the ions or free radicals interact with other molecules within the cell. This may cause deactivation of cellular mechanisms or lead to interaction with genetic material. Changes of this type occur throughout normal life as a result of many causes, of which radiation is only one example. In most cases, the organism can repair cellular damage. The success rate for such repair is higher if there is a relatively long time for repair before more damage occurs, in the case of damage caused by radiation, this would mean when the dose rate is low

If cellular damage occurs and is not adequately repaired, however, it may kill the cell or prevent it from reproducing, or it may result in a viable but modified cell The two outcomes have profoundly different implications for the organism as a whole, leading to 'deterministic' and 'stochastic' effects. Deterministic effects only occur at higher doses and dose rates than those considered in this report Therefore, these effects are not discussed further.

III–10.1. Stochastic effects

Stochastic effects may occur if an irradiated cell is modified rather than killed. Despite highly effective biological defence mechanisms, the cloning of cells resulting from the reproduction of a modified but viable somatic cell may eventually result in a cancer after a latency period which could be anything from a few years to several decades.

The probability of radiation carcinogenesis is assumed to increase proportionately with dose, with no threshold of dose below which the probability is zero. This is termed the linear, no threshold dose–response relationship. The severity of the effect does not depend on the level of dose.

If the damage occurs in a cell whose function is to transmit genetic information to later generations, any consequences could be expressed in the progeny of the exposed person as a hereditary effect

III–10.1.1 Radiation carcinogenesis

Most of the evidence for radiation carcinogenesis in humans relates to individuals who have incurred relatively high doses, most commonly delivered at high dose rates. Efforts to quantify with certainty the incidence of

[2] Weapons grade plutonium is typically at least 94% ^{239}Pu by mass but, because ^{239}Pu has a longer half-life than ^{240}Pu, the proportion of the activity from ^{239}Pu is lower

radiation carcinogenesis in human populations receiving relatively low doses are constrained by many factors, including the high natural incidence of cancer, the vast number of known carcinogenic agents, the insufficiency of information on the mechanisms of cancer induction, the inescapable exposure to natural background radiation and the extremely small estimated likelihood of cancer induction at low doses.

Studies of the survivors of the atomic bombings in Japan in 1945 are the most valuable source of information Since 1947, the Radiation Effects Research Foundation, jointly funded by the Governments of Japan and the USA, has closely monitored the medical health patterns of over 100 000 people who received relatively high doses of whole body radiation. Other large population study groups include some 200 000 persons who received high doses of radiation to specific parts of the body for medical treatment of ailments, such as spinal arthritis and cervical cancer Although lifetime data for these groups are incomplete, data from the follow-up period are extensive, in the case of the survivors of the atomic bombings, the follow-up is well into its fifth decade Findings of the above mentioned studies for these survivors show a statistically significant increase in the frequency of death due to leukaemia as well as to many solid cancers; in addition to the some 20 000 (20%) of that population who would have been expected to incur cancer even if they had not been exposed, it is estimated that around 1000 incurred cancer from doses received as a result of the bombings. However, it is not possible, even in these circumstances, to identify the specific cases caused by radiation exposure, only to estimate statistically the number of extra cancers that radiation may have caused in the population

UNSCEAR compiles, assesses and disseminates information on the health effects of radiation, and on levels of radiation exposure due to different sources. Its most recent evaluation of the probability (averaged over a population of all ages) that a low dose of radiation will cause a fatal cancer is about 0.05 per sievert. In simple terms this means that if, in a typical population, each person incurred a dose of 1 mSv, then 0.005% (5 in every 100 000) of those people might die from a radiation induced malignancy. This should be contrasted with the normal spontaneous cancer incidence of about 30% in most developed countries, and a probability of about 20% that death will be due to cancer.

There are, of course, a number of uncertainties associated with the estimation of this coefficient, the most significant of which are as follows:

— As noted above, the evidence for the relationship between fatal cancer and dose is mostly from populations exposed at relatively high doses and dose rates. Because of the time dependence of cellular repair mechanisms, the observed figures should be reduced for application at low doses and low dose rates, but the precise factor by which they should be reduced is not certain, although, on the basis of available evidence, the ICRP recommends that a value of 2 be used.
— Because some members of the study populations are still alive, the epidemiological data must be extrapolated to give estimates of the lifetime probability of attributable cancer.
— The use of observations on one population to derive estimates of the potential effects on different populations with different characteristics necessarily introduces some uncertainty

The combined effect of these factors introduces an uncertainty into the risk assessment which may represent an overestimation of the risk of cancer by about a factor of 3 It is unlikely that the current risk coefficients underestimate this risk.

III–10 1 2. Hereditary effects

Radiation has been demonstrated to cause hereditary defects in animals and plants exposed experimentally to high radiation doses. However, there is no epidemiological evidence linking exposure at any dose level to severe hereditary defects in human populations. Genetic and cytogenetic studies of the nearly 15 000 children born to the survivors of the atomic bombings in Japan have so far yielded no evidence of a statistically significant increase in severe hereditary defects. In the absence of useful data on human populations, the only way to evaluate the hereditary risk to humans is to make a number of reasonable assumptions and to use experimentally observed data for other mammals, notably for mice UNSCEAR estimates the risk coefficient for severe hereditary effects of radiation to be around one tenth of that for fatal cancer, i e. 0.005 per sievert.

III–11. RADIATION PROTECTION

The acceptance by society of risks associated with the beneficial uses of radiation is conditional on the benefits to be gained. Nonetheless, the risks must be restricted and protected against by the application of radiation safety standards. The Basic Safety Standards (FAO et al. 1996) provide an international consensus for this purpose These standards provide the context within

which the results of the Study are assessed. As a result, the framework and the basic principles underlying the Basic Safety Standards are briefly introduced here for ease of reference.

The Basic Safety Standards draw upon information derived from extensive research and development work on the health effects of radiation, techniques for the safe design and operation of radiation sources, and experience in many countries in the use of radiation and nuclear techniques. Information from UNSCEAR and the ICRP was taken into account in developing the Basic Safety Standards. Purely scientific considerations, however, provide only part of the basis for decisions on protection and safety, and the Basic Safety Standards implicitly encourage decision makers to make value judgements about the relative importance of risks of different kinds and about the balancing of risks and benefits.

III–11.1. Basic principles

The principles of radiation protection and safety on which the Basic Safety Standards are based are those developed by the ICRP and by the International Nuclear Safety Advisory Group (INSAG, an advisory group to the Director General of the IAEA). Although the detailed formulation of these principles can be found in various publications of these bodies, a brief and somewhat simplified summary can be given as follows:

(1) A practice that entails or that could entail exposure to radiation should only be adopted if it yields sufficient benefit to the exposed individuals or to society, thus outweighing the radiation detriment that it causes or could cause (i.e. the practice must be justified).[3]
(2) Individual doses due to the combination of exposures from all relevant practices should not exceed specified dose limits.
(3) Radiation sources and installations should be provided with the best available protection and safety measures under the prevailing circumstances, so that the magnitudes and likelihood of exposures and the numbers of individuals exposed are kept as low as reasonably achievable, economic and social factors being taken into account, while the doses they deliver and the risk they entail are constrained (i.e. protection and safety should be optimized).
(4) Radiation exposure due to sources of radiation that are not part of a practice should be reduced by intervention when this is justified, and the intervention measures should be optimized; the legal person authorized to engage in a practice involving a source of radiation should bear the primary responsibility for protection and safety.
(5) A safety culture should be established that governs the attitudes and behaviour in relation to protection and safety of all individuals and organizations dealing with sources of radiation.
(6) In-depth defensive measures should be incorporated into the design and operating procedures for radiation sources to compensate for potential failures in protection or safety measures.
(7) Protection and safety should be ensured by sound management and good engineering, quality assurance, training and qualification of personnel, and comprehensive safety assessments, as well as attention to lessons learned from experience and research

III–11 1.1. Practices and interventions

Human activities which add radiation exposure to the levels that people normally receive from background radiation, or which increase the likelihood of their incurring exposure, are called practices in the Basic Safety Standards. Human activities which seek to reduce existing radiation exposures, or the existing likelihood of incurring an exposure that is not part of a controlled practice, are termed 'interventions' These standards apply to both the commencement and the continuation of practices which involve or could involve radiation exposure, and also to existing de facto situations in which exposure or its likelihood can be reduced or prevented by means of some remedial action or intervention. As regards practices, provisions for radiation protection and safety can be planned and implemented before their commencement, so that the radiation exposures and their associated likelihood can be restricted from the outset. In the case of interventions, the circumstances giving rise to exposure or the likelihood of exposure already exist, and their reduction can only be achieved by means of remedial or protective actions.

Specific examples of practices are. activities involving the production of radiation sources, the use of radiation and radioactive substances in medicine, research, industry, agriculture and teaching; the generation of nuclear power, including the entire cycle of related activities from the mining and processing of radioactive ores to the operation of nuclear reactors and fuel cycle facilities and the management of radioactive wastes; and activities such as the underground mining of coal and of

[3] Usually, compliance with the principle of justification is adequately demonstrated with respect to a type of activity by the existence or the laying down of regulations specifically concerning the type of activity

phosphatic and other minerals that may enhance exposure to naturally occurring radioactive substances. Situations that may require intervention include chronic exposure to naturally occurring sources of radiation, such as radon in dwellings, and to radioactive residues from past activities and events, as well as emergency exposure situations such as might result from accidents or from deficiencies in existing installations.

III–11.1.2 Normal and potential exposures

It is almost inevitable that some radiation exposure will result from the performance of practices and that the magnitude will be predictable, albeit with some degree of uncertainty. such expected exposures are referred to in the Basic Safety Standards as 'normal exposures'. Also, exposure scenarios can be envisaged for which there is a potential for exposure but no certainty that an exposure will in fact occur, such unplanned but feasible exposures are termed 'potential exposures'. Potential exposures can become actual exposures if the unplanned situation does occur, for example as a consequence of equipment failure, design or operating errors, or unforeseen changes in environmental conditions (e.g. at a disposal site for radioactive waste). If the occurrence of such events can be foreseen, the probability of their occurrence and the resulting radiation exposure can then be estimated.

The means specified in the Basic Safety Standards for controlling normal exposures involve the restriction of the doses that are delivered. The primary method for controlling potential exposures is through good design of installations, equipment and operating procedures; this is intended to restrict the probability of occurrence of events that could lead to unplanned exposures and to restrict the magnitude of the exposures that could result if such events were to occur.

The relevant radiation exposures covered by the Basic Safety Standards encompass the exposures, both normal and potential, of workers carrying out their occupations, of patients in diagnosis or treatment, and of members of the public who may be affected by a practice or by an intervention. For intervention situations, the exposure can be chronic or, in some emergencies, temporary. Thus, exposures are divided into: 'occupational exposures', which are incurred at work and principally as a result of work; 'medical exposures', which are principally exposures of patients in diagnosis or treatment, and 'public exposures', which comprise all other exposures.

The Basic Safety Standards are intended to apply to all people who may be exposed to radiation, including those in future generations who could be affected by present practices or interventions.

III–12 CRITERIA FOR REMEDIAL ACTION

Two types of intervention situation are recognized in the Basic Safety Standards. The first is 'emergency exposure situations', such as the immediate aftermath of a radiological accident, where protective actions may be needed to reduce or avert the short term doses (acute exposures) caused by the situation. The other category is termed 'chronic exposure situations', where long term environmental radiation levels exist, leading to continuing exposure of a resident population, and where remedial actions might be needed to reduce the long term exposures. (It should be noted that the terms 'acute exposure' and 'chronic exposure' are used only as an indication of the duration of exposure, and do not carry any connotation as to the magnitude of exposure.)

III–12.1. Generic intervention levels

The policy on intervention set out in the Basic Safety Standards is that decisions on whether or not to intervene — and if so, to what extent — depend on the circumstances of each individual case. The numerical criteria used in determining whether and when an intervention should be undertaken are referred to as 'intervention levels' and 'action levels' These are determined by reference to the dose expected to be averted by a specific remedial action, i.e. the amount by which the remedial action would be expected to reduce the dose received, and are usually expressed in quantities derived from the avertable dose. In the case of chronic exposure situations, the important derived quantities are action levels, expressed in terms of dose rates or activity concentrations which, if exceeded, indicate that remedial actions, or remediation, to reduce exposure levels should be carried out Action levels for intervention are therefore expected to be established on a case by case basis, and tailored to the specific circumstances of the intervention situation.

However, a need has been recognized for simple and internationally agreed guidance on generic levels applicable to any intervention situations, particularly to cases of chronic exposure situations. The Basic Safety Standards establish some generic levels for interventions, based on the application of the principles of justification and optimization of intervention to generalized types of situation, as follows:

— Levels of dose above which intervention is expected to be undertaken under any circumstances;
— Levels of avertable dose indicating when sheltering, evacuation and iodine prophylaxis should be used in the emergency phase of an accident;

— Levels of dose for relocating and permanently resettling populations following an accident,
— Levels of activity concentrations in foodstuffs following an accident, above which food would not be acceptable for international trade;
— Levels of radon concentration in the air, for dwellings and for workplaces, above which remedial actions are needed.

There is currently no explicit international guidance on generic action levels for chronic exposure due to radioactive residues from previous activities and events, such as nuclear weapon testing. However, the guidance established in the Basic Safety Standards for other situations can be used to provide indications of the levels that might be appropriate Moreover, typical levels of doses caused by chronic exposure to the unavoidable natural background radiation could also be used as a reference for comparisons. With this in mind, the generic criteria listed above are discussed in more detail below

III–12.2. Guidelines for justifying intervention

The Basic Safety Standards establish that if doses approach levels at which the likelihood of deleterious health effects is very high, intervention would be expected to be undertaken under almost any circumstances. These quasi-mandatory levels depend on the organ exposed, and for chronic exposure situations vary from an annual equivalent dose of 100 mSv for the lens of the eye to 400 mSv for the bone marrow. From these established levels of equivalent doses, and on the basis of recommended tissue weighting factors to take account of the radiosensitivity of the relevant organs, it could be construed that intervention would be unlikely unless the annual effective dose exceeded several tens of millisieverts. At lower doses, proposed interventions must be justified case by case; the following sections discuss some generic guidance for such cases

III–12.3. Guidelines for emergency exposure situations that may be applicable to chronic exposure situations

Temporary relocation and permanent resettlement are among the more extreme protective measures available to control exposures to the public in the event of a radiological emergency. Temporary relocation is the organized removal of people from an affected area for an extended but limited period (typically several months) The purpose of this is normally to avert exposures from radioactive material deposited on the ground, and from inhalation of any resuspended radioactive particulates, by allowing short lived radionuclides to decay. During this period, people would typically be housed in temporary accommodation. The generic guidelines to initiate and terminate relocation refer to relatively high levels of dose over a relatively short time — 30 and 10 mSv per month, respectively — but it is implicitly assumed that the dose rate will fall significantly within a matter of months Hence, the doses that these criteria imply in the first year would be no more than a few times higher than the figure for the first month, and the annual doses in subsequent years would be much lower

Permanent resettlement is the removal of people from an affected area with no expectation of their return. This should, according to the Basic Safety Standards, be considered if the lifetime dose (represented, cautiously, by the dose over the next 70 years) cannot be reduced by other means and is projected to exceed 1 Sv. When doses are below this level, permanent resettlement is unlikely to be necessary. For a chronic exposure situation, where the dose rate is fairly constant year after year, this lifetime dose would correspond to an average annual dose of about 14 mSv.

III–12.4. Guidelines for a chronic exposure situation

The Basic Safety Standards state that remedial actions in a chronic exposure situation are not normally likely to be necessary unless relevant (generic) action levels are exceeded. However, the Basic Safety Standards provide numerical values of action levels only for the cases of exposure to airborne radon in dwellings and in workplaces. As the former case relates to chronic exposure of members of the public, it could be used as a point of reference for other generic chronic exposure situations involving the public.

According to the Basic Safety Standards, the optimized action levels for radon in dwellings should, in most situations, fall within a range of concentrations (averaged over a year) of 200–600 Bq/m^3 of ^{222}Rn in air. The relevant conversion coefficients in the Basic Safety Standards imply that the annual dose from radon (and its decay products) in a dwelling is about 17 μSv per Bq/m^3 of ^{222}Rn in the air (again, averaged over a year). Thus, the optimized action level for radon in dwellings can be translated approximately to an annual individual dose in the range 3–10 mSv.

III–12.5. Reference for comparison: Doses due to natural background radiation

As stated earlier, the worldwide average annual dose due to radiation from natural sources is estimated to be

2.4 mSv, of which about half is due to exposure to airborne radon and its decay products There are, however, large variations in the doses from natural sources, it is common to find large regions with exposures elevated by up to an order of magnitude and smaller regions with even higher levels. For example.

— The dose rate from cosmic radiation depends on height above sea level and on latitude. The annual doses in areas of high exposure (locations at higher elevations) are about five times the average.
— The dose rate from terrestrial sources depends on local geology, with a high level typically being about ten times the average. The effective dose to communities living near reserves of some types of mineral sand may be up to about 100 times the average
— The dose rate from radon decay products depends on the local geology and on housing construction and use, with the dose in some regions being about ten times the average Local geology and the type and ventilation of some houses may combine to give effective dose rates from radon decay products of several hundred times the average.

Most people receive an annual effective dose from natural sources in the range 1–20 mSv, with some localized high levels above 100 mSv (no one receives less than 1 mSv/a). Thus, although the global annual average dose due to natural background radiation is of the order of a few millisieverts, annual doses of about 10 mSv are not unusual and doses of 100 mSv or more are found in some places National authorities have considered these situations and decided not to take remedial actions except in the most extreme cases It therefore appears that the less extreme, but nevertheless significantly elevated, doses from natural sources can be used as another reference for deciding on interventions under chronic exposure situations

III–12.6. Generic guidance for rehabilitation of areas of chronic exposure

From the foregoing discussion it appears that an annual effective dose of up to about 10 mSv can be used as a robust and pragmatic guideline in setting generic action levels for remedial actions in areas of chronic exposure, such as those with residual radioactive material from the testing of nuclear weapons If projected dose rates are greater than 10 mSv/a, this would usually indicate a need for some form of remedial action, or for some form of restriction on access to (or use of) the area in question. That is to say, it is unlikely that a situation in which expected dose rates exceed 10 mSv/a could be accepted as being sufficiently safe as to be of no further concern. For doses below such an action level, the specific situation would still need careful consideration, but it would be much more likely that the situation could be taken as generally safe for the population without further remedial action.

It must be emphasized that this generically acceptable action level does not imply that below such a level it would never be worth while to reduce the radiation exposure. If it is justified on radiological grounds, intervention for purposes of radiological protection should always be undertaken, and the form, scale and duration of the intervention would be determined by a process of optimization of protection However, provided that the principles of radiation protection set out in the Basic Safety Standards have been applied, a situation in which chronic exposures give rise to dose rates of less than 10 mSv/a should normally be acceptable.

One remaining issue is whether the action level refers only to the dose attributable to the residual radionuclides from the nuclear testing or to the total dose (including the natural background dose). Because the theoretical basis for action levels lies in analysis of the doses averted by intervention, in theory only the avertable dose would be considered in comparisons with the action level

III–12.7. Criteria to assess chronic potential exposures

Chronic potential exposure may arise where there is some probability that an adverse event will occur which would result in exposure to radiation Potential exposure has commonly been thought of in terms of radiation sources or radioactive materials in shielded or contained configurations, but which in accident situations could give rise to radiation exposures or releases of radionuclides. Situations may also arise, however, where there is a potential for exposure, for example as a result of an accident, from residual activity in the environment. For example, there may be a potential for an accident to occur in an area where some residual material is present in the form of highly active plutonium-containing particles There is then the potential for such particles, if retained at the site of a wound, to produce a significant radiation dose The potential for exposure to occur as a result of an accident in this area will persist unless the active particles are removed (by natural processes or human actions) or until the radionuclides decay to insignificant levels, and this can therefore be considered as a chronic potential exposure situation.

The ICRP, in its 1990 Recommendations (ICRP 1990), indicated that the objectives to be pursued in potential exposure situations (in the context of practices)

are prevention (reducing the probability of exposure) and mitigation (reducing the size of the doses if they should occur). It noted also that the "simplest way of dealing with the potential exposure of individuals is to consider the overall probability of attributable death from cancer, rather than the effective dose...a restriction corresponding to a dose limit can then be expressed in the form of a risk limit, i.e. a limit on the fatality probability". If this approach were applied to intervention situations of chronic potential exposure, then it would imply that the quantity to be used in decision making is the 'averted risk' — the reduction in the probability of attributable death corresponding to the dose averted by intervention — and that the action level expressed in terms of dose may be replaced by the corresponding probability of fatal cancer. The previous discussion establishes that annual effective doses of up to about 10 mSv can be used as a generic guideline for intervention in rehabilitation of areas subject to chronic exposure. On the basis of the risk coefficient of 5×10^{-2} per sievert assessed by the ICRP for fatal cancer in members of the public, the corresponding risk criterion for chronic potential exposure is 5×10^{-4} per year.

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Annex IV

SOME FISSION AND FUSION PHYSICS AND THE TESTING OF NUCLEAR WEAPONS

The radiological assessments described in the Study were carried out without special knowledge of the design and construction of nuclear weapons. The basic physics is, however, well known, and a general idea of what needs to be done to bring about a major energy release by fission, and even by fusion, is public knowledge. This knowledge is reviewed here to assist in understanding those sections of this report where some familiarity is assumed with these basic concepts.

IV–1. ENERGY EQUIVALENCE OF MASS

Annex III describes how unstable nuclei undergo radioactive decay. As noted there (Section III–3), the decay equations indicate that, in reaching a new state, an amount of energy, Q, is emitted from the nucleus. The energy released is distributed between the emitted radiations and the kinetic energy of the residual nucleus. Though the energy released per nucleus in radioactive decay is minute, the enormous number of atoms present in a small amount of material (for example, there are 6.022×10^{23} atoms in the number of grams of an element equal to its mass number, i.e. 40 g ^{40}K or 239 g ^{239}Pu) means that the amount of energy released on a macroscopic scale can be quite large.

The source of this energy is a tiny loss of mass that occurs during the decay process. The masses of the fundamental particles and of nuclei have been measured to extremely high precision. When the masses of all the particles resulting from the decay of a radioactive nucleus are added together, the total is always slightly less than the mass of the original nucleus. It was one of the fundamental predictions of Einstein's special theory of relativity that mass and energy should be interchangeable, and that the inherent energy (in joules) associated with a mass of m kilograms is given by

$$E = mc^2$$

where c is the velocity of light in metres per second. The velocity of light is very large (nearly 3×10^8 m/s), so 1 g of matter is equivalent to about 9×10^{13} J, which, as will be discussed later, is the energy released in the explosion of about 20 000 tons of trinitrotoluene (TNT).

Energy at the nuclear level is normally measured in terms of a special unit, the electronvolt (eV), or, more commonly, its multiples kiloelectronvolt (keV) and megaelectronvolt (MeV). The relationship is 1 MeV = 1.602×10^{-13} J, so that in these units the energy equivalent of 1 g of matter is about 5.6×10^{26} MeV. The energies associated with radioactive decay are typically of the order of a few megaelectronvolts per nucleus; for example, the energy of the emitted beta and gamma rays is generally less than 2–3 MeV, while some alpha particles may reach 8–9 MeV.

IV–2. NUCLEAR REACTIONS

Given that nuclear stability depends upon an ideal balance of neutrons and protons, it might be expected that nuclei can be made unstable by introducing additional protons or neutrons into the nucleus. This is indeed the case. Inserting a proton into a nucleus would, however, require a significant amount of energy to overcome the force of repulsion created by the positive charge of the nucleus. Neutrons, having no electric charge, face no such barrier.

Free neutrons (i e. neutrons that are not inside a nucleus) occur in nature or can be generated with a wide range of kinetic energies. The lowest energy neutrons of interest here are those whose energies have equilibrated with that of the motion of atoms at room temperature, called 'thermal neutrons' Their mean energy is 0.025 eV (and their average speed is about 2000 m/s) Another category of neutrons is 'fast neutrons'. This term is generally used to refer to neutrons with energies in the range 10 keV to 10 MeV Fission (Section IV–3) gives rise to neutrons, collectively referred to as 'fission neutrons', which have energies up to 10 MeV. The neutrons produced by the fusion of light nuclei in atomic weapons (Section IV–4.1) can have energies far in excess of 10 MeV and are sometimes referred to as 'high energy neutrons'.

In principle, neutrons of almost any energy can enter virtually any nucleus, but the probability of the neutron being captured depends very much on the particular nucleus and the energy of the neutron. The probability of a neutron being able to penetrate into a given nucleus is

expressed in terms of the apparent cross-sectional area of the nucleus as 'seen' by the neutron; this is called the 'cross-section' (in this case, the cross-section for neutron capture) and has the dimensions of area. The larger the cross-section the higher the probability of a neutron being captured.

IV–2.1. Radiative capture: (n,γ) reactions

After the capture of a neutron, the atomic number of the nucleus remains the same, so it is still the same element, but the mass number increases by one. The nucleus also possesses an excess of energy, and is said to be in an excited state. It will often get rid of this energy immediately by emitting a gamma ray, in which case the process is called 'radiative capture' Usually, the residual nucleus, being unstable, will subsequently undergo radioactive decay. For example

$$^{59}Co + n \xrightarrow{\text{capture}} \gamma + {}^{60}Co \xrightarrow{\text{decay}} {}^{60}Ni + \beta^- + \gamma$$

The isotopes resulting from neutron capture are commonly called 'activation products'. For example, the traces of ^{60}Co measured on the atolls have almost certainly resulted from the activation of cobalt in structural steel in the vicinity of atmospheric weapon explosions.

Neutron capture by ^{238}U, an isotope that makes up 99.3% of natural uranium by weight, is a particularly important process in the following:

$$^{238}U + n \xrightarrow{\text{capture}} \gamma + {}^{239}U$$
$$^{239}U \xrightarrow{\text{decay}} \beta^- + \gamma + {}^{239}Np$$
$$^{239}Np \xrightarrow{\text{decay}} {}^{239}Pu + \beta^- + \gamma$$

This series of reactions not only leads to the production of ^{239}Pu, an isotope of an element virtually non-existent in nature that is at the heart of nuclear weapon manufacture, but it also involves absorption of neutrons. As a result, when a mass of natural uranium is irradiated by neutrons, neutron capture by ^{238}U is in competition for neutrons that might go on to produce other nuclear reactions. The major competing reaction of interest in the present context is nuclear fission, which is discussed below

IV–2.2. (n,α) reactions

Neutron bombardment of nuclei also produces other nuclear reactions. For example:

$$^{6}Li + n \rightarrow {}^{3}H + \alpha$$

Lithium-6 is a naturally occurring stable isotope making up 7.6% of all lithium. Tritium (^{3}H, the radioactive isotope of hydrogen), which is produced in this reaction, is known to be a component of nuclear weapons, both in 'boosted' fission devices (Section IV–5.2) and in fully fledged thermonuclear or fusion weapons ('H bombs'). At least some of the tritium is manufactured in situ via this reaction by incorporating lithium deuteride, a stable solid material, in the device.

IV–2.3. (n,p) and (n,2n) reactions

Other reactions are possible which involve the emission of a charged particle (e g. a proton) or two or more neutrons, especially as the energy of the incident neutron increases. The energy required to bring about an (n,p) or (n,2n) reaction must exceed a certain threshold, which varies from element to element. For the (n,2n) reaction, energies in excess of about 9 MeV are required.

One such reaction of interest here is the (n,2n) reaction in ^{238}U This leads to the production of ^{237}U, which decays with a half-life of 6.75 d to the long lived ^{237}Np, according to the following scheme·

$$^{238}U + n \rightarrow 2n + {}^{237}U \rightarrow {}^{237}Np + \beta^- + \gamma$$

Because the activation of ^{238}U via this reaction can only take place with neutrons above a certain (high) energy threshold, ^{238}U can be used as a detector of such neutrons. The ^{237}Np activity within the uranium can be used as a measure of the number of incident neutrons having an energy above the threshold

IV–3. FISSION

For the heaviest elements — those with a mass number greater than about 230 — the absorption of a neutron by the nucleus can lead to 'fission', in which a much more dramatic rearrangement of the nucleons takes place The compound nucleus (i.e. the original nucleus plus the neutron) can split into two lighter elements, called 'fission products', simultaneously emitting gamma rays, some two or three neutrons and a large amount of energy (e.g a total of 220 MeV per fission of a ^{239}Pu nucleus). The total mass of the resulting nuclei and the emitted particles is found to be less than that of the compound nucleus, and again the energy comes from the transformation of this mass difference Most of the energy released appears as kinetic energy of the two fission products, which is rapidly converted into heat.

All the heaviest elements have nuclei that can be fissioned when bombarded by neutrons, but the probability that fission will occur depends very much upon the energy of the neutrons and the relative number of protons and neutrons in the target nucleus. For nuclei having an even number of protons but an odd number of neutrons, such as ^{235}U and ^{239}Pu, fission can be caused by neutrons of virtually any energy, down to thermal neutrons. On the other hand, nuclei having even numbers of both protons and neutrons, such as ^{232}Th, ^{238}U and ^{240}Pu, can only be fissioned by fast neutrons; the incident neutron must have a kinetic energy above some lower limit (about 1 MeV), but the higher the energy above this threshold the greater the probability that fission will occur

IV–3.1. Fission products

When a nucleus undergoes fission, it very seldom divides into two equal parts. On the contrary, there are several hundred ways in which it may split and a great number of different fission products can be formed, for the most part isotopes of elements with atomic numbers between 30 (zinc) and 65 (terbium). The most likely split is into two fragments having mass numbers near 95 and 140, although the precise split depends on the target nucleus and the energy of the neutron that induces the fission.

Most fission products are themselves unstable and will decay to less unstable, and finally to stable, nuclides. Some of the energy resulting from fission will therefore be released over time. The half-lives of the residual products vary from fractions of a second to many years, and there are a few, produced with very small yields, that have half-lives of hundreds of thousands of years. For example, ^{129}I has a half-life of 16 million years and that of ^{99}Tc is 210 000 years

IV–3.2. Fission yield

The percentage of fissions that leads to the formation of a given fission product (or the probability that it will be formed) is called the 'yield' of the fission product A number of different yields are defined the probability that a certain nuclide will be formed directly is called the 'independent yield', and the probability that a nuclide of a certain mass will be formed is called the 'mass yield'. As the energy of the incident neutron increases, the yields for all the fission products change, and the likelihood of fission into two products of similar mass increases. Two fission products of particular interest are ^{90}Sr and ^{137}Cs. For thermal neutrons and 14 MeV neutrons, respectively, the ^{235}U fission yields for ^{90}Sr are 5.77 and 4 5%, whereas for ^{137}Cs they are 6.15 and 5.9%.

Fission product yields vary not only with incident neutron energy but are also different for different target nuclides. Of particular interest in examining the residues from nuclear weapon explosions are the yields for ^{235}U, ^{238}U and ^{239}Pu, involving neutrons having the spectrum of energies associated with the fission process. By examining the ratio of the activities of individual residual fission products, e.g. $^{137}Cs/^{90}Sr$, after a nuclear explosion, something may be learned about the relative amount of fission due to each of the three materials in the nuclear device. This ratio for the fission yields of ^{235}U, ^{238}U and ^{239}Pu induced by fission spectrum neutrons (see below) is 1 09, 1.78 and 3.07, respectively

IV–3.3. Number of neutrons per fission and their energy

The number of neutrons released in the fission process also varies with the energy of the incident neutron and the nucleus that is fissioned. In the fast fission of ^{235}U, ^{238}U and ^{239}Pu, an average of 2.5 to 3 neutrons are emitted per fission The distribution of energy of the emitted neutrons (i.e the fission neutron spectrum) ranges between very small energies and several megaelectronvolts, but the median energy lies between 1 and 2 MeV. Thus, the fission neutrons are, for the most part, fast neutrons. The probability that fission neutrons will be captured to cause further fissions therefore remains high

IV–3.4. Chain reaction

Not all of the neutrons emitted in a mass of fissionable material will be available to enter other nuclei and cause further fissions — some will be absorbed in non-fission reactions (e.g. radiative capture) and some will escape from the surface of the material However, these effects can be controlled so that at least one neutron survives per fission within the material to go on to produce another fission, and so a 'chain reaction' can be established. To obtain a steady, controlled chain reaction, for example in a nuclear power plant, each fission should be producing just enough neutrons so that one is left over to cause the next fission (although more may be needed when first starting up) For the uncontrolled chain reaction in a nuclear weapon, on the other hand, the aim is to maximize the number of neutrons causing fission. For example, if two neutrons survive from each fission to produce two further fissions, then in, say, 80 generations, 2^{80} (1.2×10^{24}) fissions will have taken place.

IV–3.5. Critical mass

To maintain a chain reaction in a mass of material, the capture of neutrons in non-fission reactions, and also the escape of neutrons from the mass, must be reduced below some threshold level. Neutron capture can be controlled by adjusting the ratio of nuclei with significant cross-sections for neutron capture compared with those that can undergo fission. In a nuclear weapon, where an uncontrolled chain reaction is required, this is done simply by using a highly refined ('weapons grade') material in which as many as possible of the atoms will undergo fission rather than just capturing neutrons. In a nuclear power plant, the aim is to produce a controlled chain reaction, which can be achieved using a much less pure source of fissionable nuclei. The reaction in commercial nuclear power plants is based on fission by thermal rather than fast neutrons; the neutrons are slowed down by collisions with the nuclei of a material of light mass (called a 'moderator') that neither fissions nor absorbs neutrons As mentioned earlier, this means that ^{235}U will undergo fission, whereas ^{238}U, which is fissionable only by fast neutrons, actually behaves as an absorber of thermal neutrons Hence, natural uranium (0.7% ^{235}U, 99.3% ^{238}U by weight) or, more commonly, enriched uranium (typically 3% ^{235}U) can be used as a fuel with a 'built-in' supply of neutron absorbers which helps to prevent an uncontrolled chain reaction.

The loss of neutrons by escape from the mass of fissionable material can be minimized by arranging the shape of the mass so that its surface area is as small as possible Clearly a sphere would be the ideal shape because it has the smallest surface area of any shape for a given volume. The loss of neutrons can also be reduced by reflecting some of those escaping back into the system.

The minimum mass of fissionable material that can sustain a chain reaction within a given system is called the 'critical mass' The critical mass of a bare sphere of plutonium, for example, will be larger than that for a sphere surrounded by a neutron reflector. It will be seen that the basic fission device used in French nuclear weapons probably brings together a sphere, by implosion, of weapons grade plutonium (well over 90% ^{239}Pu by weight) weighing nearly 4 kg.

IV–4. NUCLEAR EXPLOSIONS

The time taken for each fission generation in a nuclear weapon is of the order of 10 ns, and most of the 2.5 to 3 neutrons emitted are emitted virtually instantaneously, so that all the energy associated with the fission of, say, the 2^{80} nuclei mentioned earlier is emitted within a time of the order of 1 μs. Most of this energy is released not only instantaneously but also in a confined space. Each fission of a ^{239}Pu nucleus releases a total energy of 220 MeV, but essentially only the kinetic energy of the fission products and some fraction of the prompt gamma radiation (about 182 MeV for ^{239}Pu) can be converted immediately into explosive power. One kilogram of ^{239}Pu contains 2.5×10^{24} atoms. The complete fissioning of all these atoms would release 4.57×10^{26} MeV of explosive energy, which is the energy equivalent of about 0.8 g of matter. In more familiar macroscopic units, this is 7.3×10^{13} J or 1.75×10^{13} cal

The explosive power of a nuclear explosion is called its 'yield' and is expressed in terms of the equivalent number of tons of TNT, usually in the form of kilotons (kt) or megatons (Mt) (The explosive yield should not be confused with the fission product yield mentioned above; both may simply be called yield, but the context should make clear which yield is being referred to.) The energy associated with the explosion of 1 t of TNT is taken to be 4.18×10^9 J (or 10^9 cal), so the complete fissioning of 1 kg ^{239}Pu is equivalent to the explosion of about 17.5 kt of TNT.

IV–4.1. Fusion

There is another process whereby nuclear components can be rearranged so that the mass of the resultant nucleus becomes less than the sum of its constituent parts, with a corresponding release of energy. This process, which consists of combining the nuclei of two light elements, is called 'fusion' Two examples are the fusion of two deuterium nuclei and that of a deuterium nucleus with a tritium nucleus. These reactions and the associated energies that would be released are presented below.

$$^2H + {}^2H \rightarrow {}^3H + {}^1H + 4.04 \text{ MeV}$$

$$^2H + {}^3H \rightarrow \alpha + n + 17.6 \text{ MeV}$$

These reactions occur naturally in the Sun, and are fundamental in the manufacture of thermonuclear weapons, the deuterium being inserted directly and the tritium being manufactured in situ by the deuterium–deuterium reaction given above and by the (n,α) reaction in ^6Li as discussed previously. A major problem is to bring the hydrogen isotopes sufficiently close together to fuse because, each nucleus having a positive electric charge, there is a repulsive electric force acting between them. A method is required to give the nuclei sufficient energy to penetrate this barrier. This can be achieved by

raising the temperature of a mixture of the nuclei. The temperature at which the average kinetic energy of the nuclei is sufficient to bring about fusion is of the order of some tens of millions of degrees, which is the temperature of the interior of the Sun. Such temperatures can be achieved on Earth in the heart of a fission explosion. At such temperatures, all atoms are completely stripped of their orbital electrons and reactions will occur between bare nuclei.

It might be thought, therefore, that a substantial output of fusion energy could be obtained in an arrangement whereby a fission explosion was utilized to heat the light element fuel to the required temperature of some tens of millions of degrees. This turns out not to be the case because, at such enormous temperatures, the heat energy radiates away before it can contribute to the thermonuclear reactions. This situation has been compared to that of a piece of petrol soaked cotton wool placed on top of a wooden plank: igniting the cotton wool would certainly not set the wood on fire.

IV–5. DEVELOPMENT AND TESTING OF NUCLEAR WEAPONS

The basic physical concepts needed to design a device that could release nuclear energy, by either fission or fusion, are therefore well understood. The 'secret of the atomic bomb' is not the basic physics of how such bombs work, but rather how to make them work in practice Modern nuclear weapons are complex industrial products that required extensive development and testing before they could be serially produced. Also, if nuclear weapons are to become part of an operational military stockpile they must be reliable and safe against accidental initiation This aspect of weapon design has been investigated through what are called 'safety trials' (though the fission energy release in these trials is usually zero, or at the most quite minor, they are often counted as nuclear tests in the statistics of nuclear weapon tests, which can be the cause of some confusion).

It must be assumed that each nuclear weapon State has followed a path of steady improvement and development of its nuclear weapons, and that this has not been possible without extensive testing of devices at full or in some cases (e.g. in underground testing) reduced explosive yield. At the commencement of the Study (April 1996), the USA had conducted 1125 nuclear weapon tests, the former USSR 969, the UK 57, France 210, China 44 and India 1. The French authorities have revealed that they performed, on average, 20 nuclear yield experiments for each new weapon type that entered the military stockpile.

IV–5.1. Primary fission device

Though there have been, and possibly still are, devices that achieve a critical mass by bringing together two subcritical masses at high speed using a cannon-like assembly, the basic fission device undoubtedly employs an implosion technique in which a subcritical mass of plutonium is compressed by carefully shaped conventional explosives. Initial designs used a solid sphere of plutonium, but this was soon replaced by a hollow shell (sometimes called a 'pit'), and mixed cores comprising both plutonium and uranium. This basic device is limited in explosive yield because the core blows itself apart so quickly that no more than a relatively small fraction (10–20%) of the fuel can be fissioned It seems that only 1 kg or so of the plutonium can be consumed in such devices and the explosive yield is limited to a few tens of kilotons.

IV–5.2. Boosting

A more complete utilization of the fuel can be achieved if the number of neutrons available is increased in some way. The answer to this lies in 'boosting', whereby a few grams of a deuterium–tritium gas mixture are introduced into the core of an implosion device. When the charge is set off, the temperature and pressure build up in the centre of the core to levels sufficient to create a small thermonuclear flame. The deuterium and tritium nuclei fuse and produce a small amount of additional energy and, more importantly, a number of neutrons. These neutrons are absorbed by the plutonium and cause new fission chains, so boosting the total fission yield significantly. Yields may be doubled, and in some cases increased by up to a factor of 10. By such means, the yield of a fission bomb may reach several hundreds of kilotons.

IV–5.3. Thermonuclear weapons

Higher yields than those achievable with boosting are possible through the addition of fusion, leading to the thermonuclear weapon. The solution to the reduction in radiation heat loss mentioned above was the Teller–Ulam configuration (once called 'the secret of the H bomb'), the general concept of which has been made public. In this configuration, the fission trigger is separated from the thermonuclear fuel package, and the pressure associated with the huge quantity of X radiation energy arising in the primary fission charge is used to compress the fusion fuel in such a way that the thermonuclear reaction rate is increased and the rate of radiant heat loss is reduced.

The development of different types and sizes of thermonuclear charges was apparently the main incentive for the extensive atmospheric nuclear testing carried out by the USA and the USSR in the 1960s. One difference between fission weapons and fusion devices is that the explosive yield of the latter is, in principle, virtually unlimited, being dependent on the amount of thermonuclear fuel included in the device However, it is not necessary to include a large amount of fuel in the thermonuclear package if the sole concern is to test a design in order to ensure that ignition and burning will be achieved; the thermonuclear stage can be curtailed before it fully develops. This makes it practical to test thermonuclear weapons at much reduced yields underground.

IV–5.4. Fission–fusion–fission weapons

In a thermonuclear explosion a dense flux of fast neutrons is released in the fusion process, having energies well above the 1 MeV threshold for fast fission in ^{238}U By enclosing the fusion fuel in uranium (or cheap 'depleted uranium', the residue from the uranium enrichment process in which most of the ^{235}U in natural uranium is removed), the yield of a large fusion device can easily be doubled. This was the way in which the very high yields were achieved in some of the tests carried out in the 1950s and early 1960s. The additional fission leads to the production of large amounts of additional fission products. These fission–fusion–fission devices were called 'dirty bombs' and contributed much to global fallout.

IV–5.5. Safety trials

As mentioned above, not all the tests conducted in a nuclear testing programme lead to the release of fission energy. A number of experiments with more or less fully developed weapons are carried out to determine the behaviour of a device under simulated accident conditions. In such tests, the conventional explosive charge is triggered and the core destroyed, with the wide dispersion of finely divided fuel if the explosion is not contained. The French authorities call these tests 'expériences de sécurité'; in this report they are called 'safety trials' to distinguish them from the nuclear tests ('essais nucléaires'), where there is a substantial release of fission energy. As all weapons are designed to give little or no yield in the case of fire, bombardment or accidental dropping, a successful safety trial should involve at most negligible release of fission energy. Quite often, though, the trial is designed to produce a small nuclear yield, in order to extract more detailed and better information on the margins of safety. There were 15 safety trials carried out in the French testing programme, 5 in the atmosphere and 10 underground, and there was a small release of fission energy in two of the atmospheric trials and three of the underground trials. In the statistics relating to underground testing compiled by the French Government, the three underground trials in which there was some fission yield are counted as nuclear tests.

IV–5.6. Other nuclear experiments

There are other kinds of experiment that may be carried out as part of a nuclear weapon testing programme: hydrodynamic tests, in which the functioning of the chemical explosive system in compressing the nuclear fuel is studied; and hydronuclear tests, in which the initiation of the nuclear reaction is investigated (possibly with the development of a very small amount of fission energy). These experiments can lead to the production of waste nuclear fuel that needs to be disposed of at the test site Neither of these kinds of experiment is included in nuclear test statistics.

IV–5.7. Past nuclear weapon testing

The history of nuclear weapon testing is being revealed in some detail by nuclear weapon States. At the commencement of the Study, there had been a total of 2408 (De Geer 1996) nuclear devices exploded on Earth since 1945, including the bombs dropped on Hiroshima and Nagasaki. This number includes all test explosions for both military (92.9%) and peaceful (7 1%) purposes. It includes all events in which the conventional explosive of a full fission device has been set off This means that safety trials are included and that 'salvo tests', in which two or more individual devices are exploded simultaneously, are counted as the number of devices exploded in each salvo. This detail has only been made available recently with the release by nuclear weapon States of previously classified information. Seismic monitoring stations can only register salvo tests as one event and cannot detect safety trials The number of 'tests' based on seismic monitoring is some 400 less than the number given above

The total nuclear yield of all these tests has been estimated by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to be 530 Mt, comprising 233 Mt of fission energy release and 297 Mt from fusion A total of 440 Mt was exploded in the atmosphere (182 Mt of fission and 258 Mt of fusion) and 90 Mt underground (51 Mt fission and 39 Mt fusion). Of the 90 Mt exploded underground, around 3 Mt was

spent on experiments with civilian applications, such as digging channels, creating underground storage for oil and gas, seismic prospecting and extracting natural resources. A total of 171 such explosions were carried out, mainly in the former USSR.

REFERENCE

De Geer, L-E, The Closing Quotation of the Nuclear Explosion Tests, Rep No. 5, Natl Defence Research Establishment, Stockholm (1996) (in Swedish)

GLOSSARY

absorbed dose. The fundamental dosimetric quantity D, defined as:

$$D = \frac{d\varepsilon}{dm}$$

where $d\varepsilon$ is the mean energy imparted by ionizing radiation to matter in a volume element and dm is the mass of matter in the volume element. The energy can be averaged over any defined volume, the average dose being equal to the total energy imparted in the volume divided by the mass in the volume. The SI unit of absorbed dose is the joule per kilogram (J/kg), termed the gray (Gy).

action level. The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations.

activity. The quantity A for an amount of radionuclide in a given energy state at a given time, defined as:

$$A = \frac{dN}{dt}$$

where dN is the expectation value of the number of spontaneous nuclear transformations from the given energy state in the time interval dt The SI unit of activity is the reciprocal second (s^{-1}), termed the becquerel (Bq).

alkali basalt. Basalt rich in alkali metals (lithium, sodium, potassium, rubidium, caesium).

alpha (α) particle. A particle consisting of two neutrons and two protons (identical to the nucleus of a helium atom), emitted spontaneously by certain radioactive nuclei (such nuclei are often known as alpha emitters) Radiation composed of alpha particles penetrates only a few centimetres in air.

alteration. Physical, chemical and mineralogical change brought about in rocks — in particular, the volcanic and carbonate formations of the atolls — by the interaction of emerged formations with rainwater and underground formations with circulating saline groundwater. Alteration results in changes on the microscopic scale and changes affecting the whole massif. Thus, at the atolls, alteration in the carbonates has led to the formation of the karst topography and accounts for the development of the dolomites within the carbonates. Alteration in the volcanics takes place as a result of dissolution of the rock and precipitation of secondary minerals within the pore spaces.

avertable dose. The dose to be saved by a protective action; that is, the difference between the dose to be expected with the protective action and that to be expected without it.

barrier reef. A coral reef situated offshore from an island or continent, sometimes forming a ring. Such a reef may later develop into an atoll by gradual subsidence of the central area.

basalt. A dark, fine grained volcanic rock, composed of plagioclase feldspar, pyroxene and magnetite, with or without olivine.

benthic. On or near the bottom of the ocean. The benthos is the group of (benthic) organisms living on or near the bottom of the ocean.

beta (β) particle. An electron (β^-) or positron (β^+) emitted spontaneously by certain radioactive nuclei (such nuclei are often known as beta emitters). Radiation consisting of beta particles penetrates a few tens of centimetres in air (somewhat farther than alpha radiation).

biological half-life. The time taken for the quantity of a material in a specified tissue, organ or region of the body of an organism to halve as a result of biological processes.

breccia. A type of coarse grained rock, formed mostly of angular fragments cemented by finer material.

calcite. A crystalline form of calcium carbonate, containing variable amounts of magnesium. It is the principal constituent of limestone.

carbonate cap. For the atolls of Mururoa and Fangataufa, the carbonate covering of the

volcanic rock, comprising mainly limestones and dolomites. This layer varies between 150 and 450 m in thickness.

cavity. A roughly spherical space produced by an underground nuclear explosion or safety trial.

chimney. A cylindrical, rubble filled space underground created by the collapse of the vault above a cavity. Chimney height is related to the size of the cavity (being approximately five to eight times the cavity radius) and therefore to the yield and depth of the explosion.

chronic exposure. Exposure persisting in time

collective dose. An expression for the total radiation dose incurred by a population, defined as the product of the number of individuals exposed to a source and their average radiation dose. The collective dose is expressed in man-sieverts (man Sv).

committed dose. Committed effective dose and/or committed equivalent dose.

committed effective dose. The quantity $E(\tau)$, defined as:

$$E(\tau) = \sum_{T} w_T H_T(\tau)$$

where $H_T(\tau)$ is the committed equivalent dose to tissue T over the integration time τ and w_T is the tissue weighting factor for tissue T. When τ is not specified it will be taken to be 50 years for adults and to age 70 years for intakes by children.

committed equivalent dose. The quantity $H(\tau)$, defined as:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\,dt$$

where t_0 is the time of intake, $\dot{H}_T(t)$ is the equivalent dose rate at time t in an organ or tissue T and τ is the time elapsed after an intake of radioactive substances When τ is not specified it will be taken to be 50 years for adults and to age 70 years for intakes by children.

conglomerate. A rock comprising subangular to well rounded grains, pebbles, cobbles or boulders cemented in a finer matrix

coral rim. A ring shaped section of reef above sea level, forming the emergent part of an atoll.

critical group. A group of members of the public which is reasonably homogeneous with respect to its exposure for a given radiation source and given exposure pathway and is typical of individuals receiving the highest effective dose or equivalent dose (as applicable) by the given exposure pathway from the given source.

criticality. A condition achieved within a mass of fissionable material when a chain reaction becomes self-sustaining, with the release of energy from nuclear fission and the production of fission products.

Darcy's law. A law that describes the rate of movement of water through porous media. It states that the rate of water movement is proportional to the hydraulic gradient. The *Darcy velocity,* or specific discharge, is the volumetric rate of flow per unit area through which flow occurs (i.e. it is a hypothetical discharge rate where it is assumed that water moves through the entire cross-sectional area in question). It has the same dimensions as velocity, but it is not the speed at which the fluid moves In reality, the water moves only through interconnected pore spaces, which represent only a certain proportion of the total rock volume.

detriment. The total harm that would eventually be experienced by an exposed group and its descendants as a result of the group's exposure to radiation from a source.

detrital. Formed from fragmented material derived from the erosion of previously existing rocks (detrital deposits are commonly interbedded within carbonate formations).

diagenesis. Physical and chemical processes which affect a sedimentary deposit after its burial under further sediment, leading progressively to its lithification.

dolomite. A mixed carbonate of calcium and magnesium, also, a sedimentary rock type formed of this mineral.

dose. A measure of the radiation received or 'absorbed' by a target The quantities termed absorbed dose, organ dose, equivalent dose, effective dose,

committed equivalent dose or committed effective dose are used, depending on the context The modifying terms are often omitted when they are not necessary for defining the quantity of interest.

dose coefficient. The committed effective dose from intake, by a specified means (usually ingestion or inhalation), of unit activity of a specified radionuclide in a specified chemical form [1] Formerly termed dose per unit intake

dose equivalent. A quantity used by the International Commission on Radiation Units and Measurements (ICRU) in defining the operational quantities ambient dose equivalent, directional dose equivalent and personal dose equivalent. The quantity dose equivalent has been superseded for radiation protection purposes by equivalent dose.[2]

dose limit. The value of the effective dose or the equivalent dose to individuals from controlled practices that shall not be exceeded

dyke. An intrusion of (volcanic) rock cutting through the previously existing strata. Most dykes are vertical or near vertical. Their emplacement is controlled by fractures and faults in the overlying strata.

effective dose. The quantity E, defined as a summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor:

$$E = \sum_{T} w_T H_T$$

where H_T is the equivalent dose in tissue T and w_T is the tissue weighting factor for tissue T. From the definition of equivalent dose, it follows that:

$$E = \sum_{T} w_T \sum_{R} w_R D_{T,R}$$

where w_R is the radiation weighting factor for radiation R and $D_{T,R}$ is the average absorbed dose in the organ or tissue T. The SI unit of effective dose is the joule per kilogram (J/kg), termed the sievert (Sv).

effective half-life. The time taken for the activity of a radionuclide in a specified place to halve as a result of all relevant processes (radioactive decay, erosion, biological clearance, etc.)

endo-upwelling. Geothermal circulation occurring when groundwater rises near the centre of an atoll, and cool ocean water is drawn inwards across the flanks of the atoll to support upward flow

equivalent dose. The quantity $H_{T,R}$, defined as:

$$H_{T,R} = D_{T,R} w_R$$

where $D_{T,R}$ is the absorbed dose delivered by radiation type R averaged over a tissue or organ T and w_R is the radiation weighting factor for radiation type R.
When the radiation field is composed of different radiation types with different values of w_R, the equivalent dose is.

$$H_T = \sum_{R} w_R D_{T,R}$$

The SI unit of equivalent dose is the joule per kilogram (J/kg), termed the sievert (Sv)

exposure. The act or condition of being subject to irradiation. Exposure can be either external exposure (irradiation by sources outside the body) or internal exposure (irradiation by sources inside the body) Exposure can be classified as either normal exposure or potential exposure, occupational, medical or public exposure; and, in intervention situations, either emergency exposure or chronic exposure The term exposure is also used in radiodosimetry to express the amount of ionization produced in air by ionizing radiation.

exposure pathways. The routes by which radioactive material can reach or irradiate humans.

gamma (γ) radiation. High energy electromagnetic radiation of short wavelengths (approximately 10^{-13} to 10^{-10} m) emitted by radioactive nuclei, commonly associated with the emission of alpha or beta particles (such nuclei are often known as gamma emitters if this is the predominant type of

[1] Values are specified in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Safety Series No 115, IAEA, Vienna (1996))

[2] An explanation of these terms is given in Quantities and Units in Radiation Protection Dosimetry (ICRU Rep 51, Bethesda, MD (1993))

radiation emitted). Most gamma radiation can penetrate the human body.

ground zero. The point on the surface of the water or the ground situated vertically below (atmospheric explosions) or above (underground explosions) the point of detonation (the zero point).

half-life. The time taken for the activity of a radionuclide to halve as a result of radioactive decay. Also used with qualifiers to indicate the time taken for the quantity of a specified material (e.g a radionuclide) in a specified place to halve as a result of any specified process or processes that follow similar exponential patterns to radioactive decay. (See also biological half-life and effective half-life.)

high LET radiation. Radiation with high linear energy transfer, i.e. that loses its energy quickly when it interacts with matter (and therefore has low penetration of matter). Normally assumed to include protons, neutrons and alpha particles (or other particles of similar or greater mass).

hoa. A channel between two motus (islets) of a coral rim, allowing exchange between ocean and lagoon.

hyaloclastic tuff. Volcanic ash deposit composed of glassy fragments less than 2 mm in size, often produced by violent fragmentation of lava in contact with surface waters (also called vitric tuff).

hydraulic conductivity. The capacity for a porous medium to conduct a liquid, defined by the expression:

$$K = \frac{k\rho g}{\mu}$$

where K is the hydraulic conductivity (m/s), k is the intrinsic permeability of the porous medium (m^2), ρ is the fluid density (kg/m^3), g is the gravitational acceleration (m/s^2) and μ is the viscosity of the fluid (Pa·s).

intervention. Any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident.

intervention level. The level of avertable dose at which a specific protective action or remedial action is taken in an emergency exposure situation or a chronic exposure situation.

isotope. One of two or more varieties of a chemical element whose atoms have the same number of protons but different numbers of neutrons in their nucleus.

karst. A type of topography found in limestone terrains, formed as a result of variable degrees of erosion of the rock by rainwater. Characterized by enlarged fractures, enhanced porosity, caves and underground drainage or sometimes sink holes at the surface. Such features occur at varying depths and are related to past low sea levels.

kiloton (kt). A unit used to quantify the energy released by nuclear and thermonuclear explosions. It corresponds to the energy released by one thousand tons of the chemical explosive TNT, namely 4.18×10^{12} joules (10^{12} calories). The megaton (1 Mt, equal to 10^3 kt) is also sometimes used.

lithification. The process by which unconsolidated sediment changes into rock. This involves cementation of the grains, but not necessarily burial, alteration or compaction. (See also diagenesis.)

low LET radiation. Radiation with low linear energy transfer, i.e. that loses its energy only gradually when it interacts with matter (and therefore has high penetration of matter). Normally assumed to include photons (X rays and gamma radiation) and beta particles.

mantle. The shell of the Earth situated beneath the continental or oceanic crust.

mollusc. An invertebrate animal (of the phylum Mollusca) with a soft body and generally a shell. Molluscs include limpets, cuttlefish, oysters, mussels, octopus and squid.

monitoring. The measurement of dose or contamination for reasons related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results.

motu. A small coral islet constituting part of the reef of an atoll. (See also hoa.)

naturally occurring radionuclides. Radionuclides that occur naturally in significant quantities on the

Earth. In practice, the term often refers to ^{235}U, ^{238}U, ^{232}Th and their radioactive decay products, but strictly it also includes ^{40}K, ^{14}C and ^{3}H.

optimization. For a practice, the process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, "as low as reasonably achievable, economic and social factors being taken into account" (ALARA), as required by the System of Radiological Protection (optimization of protection) of the International Commission on Radiological Protection. For intervention, the process of determining the form and duration of intervention that produce the maximum net benefit.

organ dose. The mean dose D_T in a specified tissue or organ T of the human body, given by:

$$D_T = \frac{1}{m_T} \int_{m_T} D \, dm$$

where m_T is the mass of the tissue or organ and D is the absorbed dose in the mass element dm.

pelagic. Pertaining to the open marine environment; pelagic sediments settle from suspension in the open oceans and contain the skeletal remains of organisms living within the surface waters.

permeability. The ability to transmit water (see also Darcy's law); the primary or matrix permeability is governed mainly by the degree of connection between the pores. (See also porosity.)

pore water. Water contained within the pores of a geological formation.

porosity. The fraction of the total volume of a rock sample or formation that is pore space (i.e. not solid material).

practice. Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed.

projected dose. The dose to be expected if no protective or remedial action is taken.

radiation weighting factor. A multiplier (see table) of absorbed dose used for radiation protection purposes to account for the relative effectiveness of different types of radiation in inducing health effects.

Type and energy range of radiation	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies[a]	1
Neutrons, energy <10 keV	5
10 keV to 100 keV	10
>100 keV to 2 MeV	20
>2 MeV to 20 MeV	10
>20 MeV	5
Protons, other than recoil protons, energy >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[a] Excluding Auger electrons emitted from nuclei to DNA, for which special microdosimetric considerations apply.

remedial action. Action taken when a specified action level is exceeded, to reduce radiation doses that might otherwise be received, in an intervention situation involving chronic exposure.

risk. In the context of this report, the probability of harm (taken to be radiation induced cancer) arising from the presence of radioactive material at the atolls. The risk is a product of three components: the probability that an event will occur that could expose an individual to radiation; the probability that a certain dose will be received as a consequence of that event; and the probability that such a dose will lead to cancer. As the probabilities of an initiating event and of exposure occurring depend on the time period considered, risk may be expressed as probability per unit time, usually probability per year.

scoria. Subaerial volcanic products made up of fragments (2–15 cm in size) of coarsely frothy basaltic lavas and cinders.

sediments. In the particular case of the atolls, unconsolidated 'coral sand' (almost entirely calcium carbonate) covering much of the bottom of the lagoons, derived from plant and animal remains, including corals, calcareous algae, marine protozoa with calcareous shells and molluscs. The sediments are colonized by animals living on the surface (e.g. molluscs and crustaceans) or buried

in the sediments (certain worms), which can lead to mixing within the upper layers.

seismic wave. Compression wave that propagates through the Earth as a vibration, generated by an earthquake or underground nuclear explosion.

sill. A tabular intrusion of volcanic rock having concordant surfaces of contact (i.e. running parallel to the previously existing strata).

slide. The most widespread form of submarine slope instability on the side of an atoll that may involve rock or soft sediment.

stratosphere. The region corresponding to the maximum density of ozone in the atmosphere, located between altitudes of 10 and 60 km.

subaerial volcanic rocks. Rocks formed when the top of the volcano emerged from the ocean. They overlie submarine volcanic rocks. Subaerial volcanics are more diverse and spatially variable than submarine volcanics. Rock types vary from massive basalts to volcanic cinder deposits.

submarine volcanic rocks. Rocks formed while the top of the volcano was still below sea level. On Mururoa and Fangataufa, these consist of pillow lavas and associated breccias, autoclastites and hyaloclastites.

transition zone. A sedimentary layer separating the underlying volcanic formations of an atoll from the carbonate cap. The thickness varies from 0 m under the lagoon to 100 m at the periphery of the atoll.

troposphere. The layer of atmosphere below the stratosphere, in which the temperature decreases with altitude.

zero point. The exact point of detonation. (See also ground zero)

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MEETINGS

29–31 January 1996
Informal technical consultation meeting, Vienna

28–29 March 1996
Initial meeting of Task and
Working Group Chairmen of International Advisory
Committee (IAC) and
French Liaison Office, Montlhéry, France

11–12 April 1996
Meeting of Chairmen of Task and Working Groups, Vienna

13–14 April 1996
First formal meeting of IAC, Vienna

13–15 May 1996
First meeting of Task Group A (TG-A), Monaco

19–21 June 1996
First meeting of Working Group 5 (WG-5), Monaco

22, 24 June 1996
First meeting of Working Group 4 (WG-4), Paris

1–2 July 1996
First meeting of Working Group 3 (WG-3), Paris

2–3 July 1996
First meeting of Task Group B (TG-B), Paris

10–13 September 1996
First review and co-ordination meeting of IAC Chairman
with TG Chairmen and WG-5 Chairman, Vienna

29 September–2 October 1996
Second meeting of WG-3, Stockholm

2–4 December 1996 (Suva, Fiji) and
4–6 December 1996 (Papeete, Tahiti)
Second formal meeting of IAC

24–27 February 1997
Second meeting of WG-4, Paris

18–21 April 1997
Second meeting of WG-5, Monaco

12–14 May 1997
Second meeting of TG-B, Vienna

14–16 May 1997
Second meeting of TG-A, Vienna

15–16 August 1997
Third meeting of WG-4, Vienna

20–22 August 1997
Third meeting of TG-B, Vienna

25–27 August 1997
Third meeting of WG-5, Monaco

17–19 September 1997
Second review and co-ordination meeting of IAC Chairman
with TG and WG Chairmen, Vienna

24–28 November 1997
Meeting of TG Chairmen, Vienna

3–5 February 1998
Third formal meeting of IAC, Vienna

98-02100

INTERNATIONAL ATOMIC ENERGY AGENCY

THE RADIOLOGICAL SITUATION AT THE ATOLLS OF MURUROA AND FANGATAUFA
Reports by an International Advisory Committee

The Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa was conducted at the request of the Government of France to determine whether, as a consequence of French nuclear tests above and beneath these atolls, radiological hazards could arise, now or in the future; and to recommend the form, scale and duration of any monitoring, remedial action or follow-up action that might be required. An International Advisory Committee was convened by the Director General of the IAEA to provide scientific direction and guidance to the IAEA on the conduct of the Study. The first meeting of the IAC was held in April 1996 and its final meeting in February 1998. In addition to IAEA Secretariat staff, 55 scientists from 18 countries and four international organizations participated in the Study, including the environmental sampling and surveillance campaigns, which involved 18 laboratories in 12 countries.

The results of the Study are presented in three publications The Main Report (which includes the Executive Summary); a Summary Report; and the Technical Report in six volumes. The Main Report is the primary publication of the Study and provides a detailed scientific account, together with findings, conclusions and recommendation. It is supported by the Technical Report, which is intended for the scientific specialist. The Summary Report provides an extended summary of the Study and its findings, conclusions and recommendation for the benefit of a wider audience.

An International Conference was held from 29 June to 3 July 1998 to present the Study to the scientific community. The proceedings of the discussions will be issued by the IAEA.

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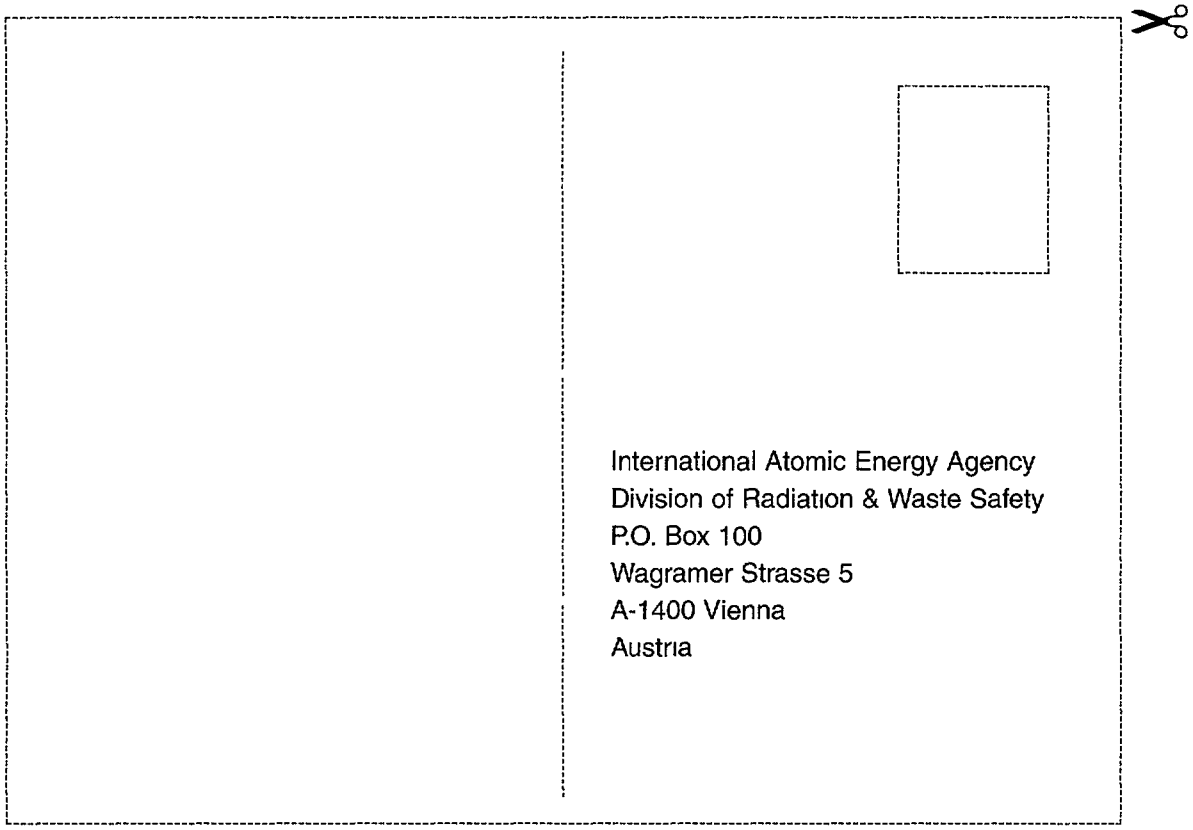

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 92–0–101198–9
ISSN 1020–6566