# Health risks of nuclear power

2

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# Abstract

This study starts with a physical assessment of the quantities of the radioactivity being generated and mobilized by the entire system of related industrial processes making civilian nuclear power possible. It assesses the actual and potential exposure of the public to natural and human-made nuclear radioactivity, and it discusses empirical evidence of harmful health effects of these exposures. The biomedical effects of radionuclides in the human body are briefly discussed.

Furthermore this study analyses the mechanisms which may cause the uncontrolled spread of very large amounts of radioactivity into the environment. The study explains some consequences of a basic law of nature (Second Law) for the health risks of nuclear power now and in the future. Misconceptions, uncertainties and unknowns of the nuclear safety issue are addressed. Risk enhancing factors are discussed, along with the consequences of the present economic paradigm for the health risks of nuclear power at this moment and in the future.

## Acknowledgements

# Contents

# Summary

Assessment of nuclear health risks proves to be a complicated and multilayered issue. The first layer concerns the technical aspects and empirical observations. The second layer comprises the views and perspective of the nuclear industry and the information flow on nuclear matters to the public and to decision makers. The third layer concerns the relationship between health risks and common economic views.

Starting point of this study is formed the following observations:
• The generation of nuclear energy irrevocably goes together with the generation of immense amounts of human-made radioactivity.
• Radioactivity cannot be destroyed.
• Radioactivity cannot be made harmless to humans.

Nuclear power involves the mobilization of naturally occurring radioactivity and the generation of human-made radioactivity, a billionfold of the mobilized natural radioactivity. Each reactor of 1 GWe power generates each year as much radioactivity as 1000 exploded nuclear weapons (Hiroshima bombs).

Nuclear health risks are posed by the spread of radioactive substances into the environment. Non-radioactive substances posing health risks are not included in this study to limit its scope.

The only way to prevent disastrous exposure of the public to human-made radioactivity on unprecedented scale is to immobilize the radioactive waste physically and to isolate it from the biosphere in deep geologic repositories, lasting at least a million of years.

To deal with the global radioactive waste at the current rate of generation about every year a new large deep geological repository has to be opened, at an estimated cost of at least €10bn each. To dispose of the existing radioactive wastes from the past dozens of deep geologic repositories would be required.

**The nuclear energy system**

The technical assessment of the potential spread of radioactivity into the human environment is based on an elaborate life-cycle analysis (LCA) from cradle to grave of the complete system of industrial processes which makes nuclear power possible. This LCA uncovered a number of uncertainties and unknowns of great importance with respect to the viability and safety of nuclear power now and in the future.

In the first part of this study the present state of the nuclear energy system is briefly described in connection with the potential pathways of radioactive discharges. The analysis follows the course of events involving the mobilized radioactivity and especially the human-made radioactivity. Adequate solutions to immobilize and isolate the human-made radioactivity from the biosphere exist only in cyberspace. All anthropogenic radioactivity ever generated is present in mobile state within the human environment. The nuclear process chain is still open ended.

**Radioactivity and health effects**

Human-made radioactivity at the moment of its generation is contained in the spent nuclear fuel and comprises dozens of different radionuclides, representing all possible decay modes and all elements of the Periodic Table. A large number of the generated radionuclides have very long half-lives: thousands to millions of years. Even after a cooling period of a 100 years the specific radioactivity of spent fuel is still at such a high level that about 1 milligram of it ingested or inhaled would mean a lethal dose to a human.

The biological effects of radiation in living cells are a very complex matter, with many unknowns. The direct relationship between the exposure to a relatively low dosis of nuclear radiation (i.e. a dosis other than directly lethal) and the resulting adverse health effects on individual scale is very difficult to prove for a number of reasons, such as:

• long time delay (sometimes decades) between exposure and observable health effects
• stochastic character of radiation-induced health effects
• interference with other factors
• basic biomedical unknowns.

Only elaborate epidemiological studies can provide the empirical evidence of the relationship between radiation and health effects within large groups of individuals.

Exposure to radionuclides and nuclear radiation can cause carcinogenic, mutagenic and teratogenic effects, such as: cancers, leukemia, premature biths, low birth-weight, infant mortality, congenital defects and chronic diseases (e.g. immune system, diabetes).

The health effects of all different types of radionuclides within the human body are not well understood and the biochemical mechanisms are poorly investigated.
Furthermore there is strong empirical evidence that damage also occurs in cells not directy hit by radiation: the so-called non-targeted and delayed effects (e.g. the bystander effect), via unknown mechanisms. Adverse health effects from low radiation doses might be far more serious than previously assumed on the basis of the classic dose-effect models.

A major study (called KiKK) commissioned by the German Government revealed that the leukemia incidence among young children living near nuclear reactors was increased by 120%, and solid cancers were increased by 60%. This result has been affirmed in other studies.

The official exposure standards are based on models and concern only direct exposure to radiation from extern radiation sources. The models do not include:
• biological effects of radionuclides within the living cells, after inhalation and/or ingestion of radioactive materials via air, water and/or food.
• non-targeted and delayed effects.

Empirical evidence proves the dose-effect models to be inadequate to explain observed health effects of routine releases from nominally operating nuclear power plants.

The pathways of tritium and carbon-14 into the human body via drinking water and the food chain are briefly discussed. The biomedical effects of these two biochemically very active radionuclides in the human body are not well understood. Both tritium and carbon-14 are released on daily routine basis in large quantities by nuclear power plants, spent fuel storage facilities and reprocessing plants, under nominal operating conditions.

Health risks of nuclear power are exacerbated by the fact that a number of hazardous radionuclides are difficult to detect, such as tritium, carbon-14 and iodine-129. These radionuclides are routinely discharged into the environment.
But also numerous other hazardous radionuclides in scrap and debris, including some actinides, are hard to detect by commonly used radiation detectors and so these radionucldes can easily enter the public domain.

**Views of the nuclear industry**

The second layer of this study addresses the perspective of the nuclear industry with respect to nuclear health risks. The nuclear industry claims nuclear power to be safe and clean, refering

to a limited number of probabilistic risk analyses (PRAs). This claim is weakly underpinned for two reasons:

• The probabilistic safety analyses done by the nuclear industry cover only a small part of the existing nuclear installations worldwide which have the potential of large-scale accidents.
• Not all events and factors potentially leading to a severe nuclear accident can be analysed or quantified in a PRA. Two unavoidable and unpredictable factors are:
  – degradation of materials and constructions (consequences of the Second Law)
  – human behaviour and economic pressure.

The official radiation exposure standards for individuals are based on computer models, starting from unclear axioms and assumptions, which are not widely understood by scientists outside of the nuclear world, let alone by the public and politicians.

Any computer model has its inherent limitations and specific limitations and may exhibit considerable built-in uncertainties.

The nuclear industry advocates two concepts with regard to the reduction of the radioactivity problem which work out only in cyberspace, namely vitrification and transmutation, because these concepts do not reckon with one of the most basic laws of nature, the Second Law. Vitrification leads to a huge volume increase of the radioactive waste and to massive discharges of radioactivity into the environment. Transmutation is practically unfeasible and even if it would work it will cause a large increase of the amount of anthropogenic radioactivity instead of a reduction.

Information on nuclear matters to the public and politicians originates almost exclusively from institutions with vested interests in nuclear power, for example IAEA, WNA, NEA, NEI, and from the nuclear industry itself, e.g. Areva and EdF.

There are strong connections between the IAEA and UNSCEAR and ICRP and consequently these institutions do not operate independently of each other.

Even the World Health Organization (WHO) cannot operate independently of the IAEA on nuclear matters.

The nuclear industry has a habit of Après nous le déluge by postponing indefinitively the actions required to deal adequately with the human-made radioactivity. The assertion of the World Nuclear Association, representing the Western nuclear industy, that all safety matters are fully under control is in flagrant contradiction to the practice

**Spread of radioactivity into the environment**

Inherently safe nuclear power is inherently impossible.

Only engineered safety exists, which is subject to the Second Law of thermodynamics and to the unpredictable human behavior. Solely dedicated and substantial human effort can prevent large-scale dispersion of anthropogenic radioactivity into the environment, causing extensive and irreversible damage to the public health and well-being.

There are four basic categories of events leading to the spread of radioactivity into the environment:
• authorized routine discharges of radioactive substances by nuclear power plants and other nuclear facilities
• unplanned, unauthorized discharges
• illegal trade and smuggling of radioactive materials and equipment
• large-scale accidents of Chernobyl-type.

The radioactive wastes of uranium mining are dumped into the environment. Risks posed by dust and groundwater contaminated with the radioactive decay daughters of uranium and thorium are poorly or not investigated by the nuclear industry, but affect vast areas. Radioactive dust from uranium mines, containing extremely hazardous radionuclides, is blown by the wind over distances of thousands of kilometers in arid areas, for example in Australia, Namibia, USA.

A nuclear reactor discharges significant amounts of radioactivity into the environment, even when operating nominally. Empirical evidence points to seriously adverse health effects of these 'routine releases', as mentioned above.

Reprocessing plants are extremely polluting. All gaseous radionuclides from spent fuel are released into the air. A great deal of the chemically mobile radionuclides are released into the sea, along with a significant fraction of the uranium, plutonium and other actinides from the spent fuel. Separation processes never go to completion (a consequence of the Second Law), so unavoidably a fraction of the radionuclides from the spent fuel end up in the waste streams of the reprocessing plant.

In addition to the routine releases of radioactivity other, uncontrolled discharges from the nuclear process chain occur. The frequency and the involved amounts of radioactivity of these unplanned and unauthorized discharges are likely to increase with time.

Furthermore the nuclear system hides the potential of severe accidents of extremely large spatial extent and long timescales. Such accidents, which may pale the Chernobyl disaster, are possible even with 'inherently safe' reactors (which do not exist). Several scenarios are conceivable, involving nuclear reactors, spent fuel cooling ponds and reprocessing plants. A number of risk enhancing factors are discussed, some technical, other non-technical.
The chances of severe accidents and the magnitude of the imposed health risks increase with time for three reasons:
• rapidly increasing amounts of human-made radioactive materials in mobile state
• unavoidable deterioration of materials and constructions
• increasing economic pressure.

Nuclear facilities are vulnerable to terroristic attacks. Severe accidents could also be initiated by hostile actions in an armed conflict anywhere in the world. The consequences of a Chernobyl-type accident do not stop at our borders.

The use of MOX fuel in civil nuclear reactors poses a great risk for terroristic use of plutonium in primitive but effective bombs.

**Nuclear health risks and economics**

In the third layer of this study the interactions between economics and health risks are discussed. The current economic paradigm is at odds with nuclear safety. Strong economic forces dominate the views in the political and industrial domains with regard to nuclear power and the perception of its health risks. Two topics are here addressed: the energy debt and the economic pressure to relax safety standards and inspection.

Nuclear power is building up immense energy debts by postponing the immobilization and isolation of the radioactive waste from the biosphere, which is the only way to prevent large-scale accidents affecting vast regions. A physical analysis of the activities required to finish the overdue cleanup of the nuclear heritage points to the consumption of massive amounts of

energy, materials and human resources and consequently to unprecedented economic efforts. The energy debt has a physical basis that will grow with time instead of depreciating with time; the energy debt cannot be discounted nor written off like common monetary debts. The financial consequences of the nuclear debts in countries like France and the UK are estimated to rise to hundreds of billions of euros, several times the final cost of the entire US Apollo moon project.

We may ask ourselves if the future generations will be able to solve the problem we could not. Would the future generations have to their disposal sufficient energy, materials, human resources and economic 'ability to cope' to make their living environment as save as we and they would wish?

Liability of the nuclear industry is passed on to the taxpayer.
Delayed expenses, for example definitive waste storage and dismantling of nuclear power stations, are systematically passed on to the taxpayer: privatising the profits, socialising the costs.
Discussons on lifetime costs, the only method for a fair comparison of different energy supply systems (e.g. nuclear and renewables), are carefully avoided.
Nuclear power is energy on credit.

De-regulation of electricity markets has pushed nuclear utilities to decrease safety-related investments and to limit staff.
The official standards for discharge of radioactive substances into the environment are susceptible to economic pressure. Relaxation of the standards of emissions and of the classification of radioactive materials as radioactive waste occurs on grounds of economic arguments, not on grounds of scientific evidence.
The efficiency and the independency of inspections of nuclear activities are under high economic pressure. The frequency of inspections is lowered to save costs. The nuclear industry urges for simplified and shortened license procedures with elimination of participation of local authorities. independent institutions and the public.

Unambiguous scientific safety standards based on empirical observations are not feasible, other than no radioactive discharges at all. Under economic pressure a trend is observable to relax nuclear safety standards and to limit the inspections and quality contral. A paradigm of short-term profit seeking and living on credit seems to dominate the decision processes with respect to nuclear power. Health risks posed by nuclear power are found to be an economic notion:
* What are we willing to pay for the health of ourselves, our childern and grandchildern and their offspring?
* For what reasons do we think to need civilian nuclear power?

# 1    Introduction

Nuclear power is advocated by the nuclear industry as a clean and safe technology to generate useful energy.
Recent studies indicate that releases of radioactivity which are classified as harmless in the official nuclear health risk models may be not harmless at all.
How reliable are the official nuclear health risk models?
What do we know about other nuclear releases and other nuclear health risk models?

On which empirical evidence has the nuclear industry based the claim of safe and clean nuclear power?

Starting point of this study is formed by the observations that nuclear power irrevocably is accompanied by the generation of immense amounts of human-made radioactivity and that radioactivity cannot be destroyed nor made harmless to man.
What happens to the human-generated radioactivity?
What are the character, amount and lifespan of the human-made radioactivity?
What effects could exposure to human-made radioactivity have?
Which mechanisms could cause exposure of the public to radioactivity in the present practice of nuclear power?

The technical assessment of the nuclear health risks in this study is based on an elaborate life-cycle analysis (LCA) of the complete system of related industrial processes making nuclear power possible from cradle to grave, as published in [1], for a nuclear power station is not a stand-alone system.
Are all actual radioactive releases  known and under control?
Are Chernobyl-type accidents still possible?
Which developments with regard to the nuclear health risks issue may be expected in the near and far future?

Are other factors, such as economic and political interests, the human factor and social issues incorporated into the official nuclear health risk models?
How does the nuclear industry deal with the public health risk issue?
What are the economic consequences of the anthropogenic radioactivity generation in this time and in the future?
How does the current economic paradigm relate to the nuclear health risks issue?

This study aims at revealing knowns and unknowns about health risks posed by civil nuclear power.

Health risks posed by non-radioactive substances released by nuclear power-related processes, for example greenhouse gases, are not assessed in this study to limit its scope.

# 2    Origin of nuclear health risks

## 2.1    The nuclear energy system

A unique feature of a nuclear reactor is the simultaneous and inextricable production of heat and radioactivity by the fission process. The heat from the reactor is converted into electricity by conventional steam turbines; this electricity is the selling point of nuclear power. The generated radioactivity poses a serious threat to public health and this threat is the starting point of this study.

The input of nuclear power plants is nuclear fuel (enriched uranium) and the output consists of electricity and materials containing huge amounts of human-made radioactivity. This is symbolic represented by Figure 1.



nuclear fuel     nuclear reactor     human-made radioactivity
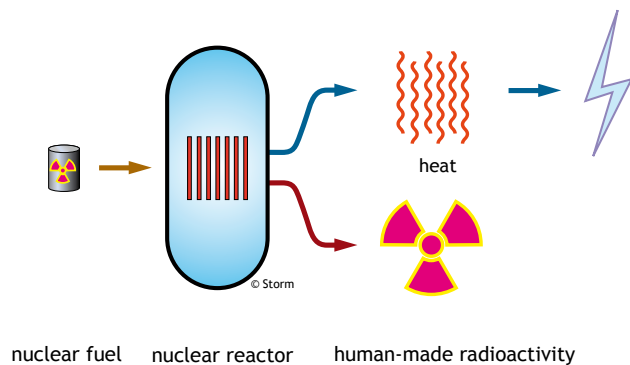
**Figure 1**
A nuclear reactor is a generator of heat *and* radioactivity, simultaneously, inextricably and irreversibly.

Every human activity occurs within the boundaries of the biosphere and so the generation of nuclear power. The materials needed to generate nuclear energy are extracted from the biosphere and all products and wastes end up in the same biosphere. Obviously this holds true for any industrial process.

This chapter starts with a brief description of the nuclear energy system, addressing the questions:
• From where in the biosphere does the nuclear fuel come?
• What happens to the human-generated radioactivity? How and where does it end up, or should it end up in the biosphere?

**Nuclear process chain**

A nuclear power plant is not a stand-alone system, but is part of a chain of industrial processes, each of which is vital for the generation of electricity from uranium ore. The whole complex is coined the 'nuclear process chain' or the 'nuclear energy system' and comprises three main sections: the front end processes, the mid-section and the back end processes.

• Front end section
Nuclear fuel is not found ready to use in nature, like coal or oil, but has to be produced from uranium ore, by means of a number of industrial processes. Jointly these processes – from ore to fuel – form the front end or head of the chain and comprise: mining + milling (extraction of uranium from its ore), conversion of uraniumoxide from the mine into uranium hexfluoride, enrichment and fuel fabrication.

- Mid-section

The mid-section of the nuclear chain encompass the construction of the nuclear power plant plus the operation and maintenance of the plant during its operational lifetime. Maintenance includes refurbishment of the plant. At the end of its operational lifetime nearly all components of the nuclear power plant have been replaced at least once, except the reactor vessel and the reactor building.

- Back end section

The back end processes, also called the tail of the nuclear process chain, comprise all processes needed to effectively isolate the radioactive waste generated by the nuclear energy system from the human environment. The back end processes include cleanup, decommissioning and dismantling of the radioactive part of the nuclear power plant after closedown, and of other radioactive facilities of the nuclear chain.

**Nuclear chain as it ought to be**

A simplified outline of the nuclear chain from cradle to grave is illustrated by Figure 2. A full description of the complete nuclear process chain can be found in Parts B and C of [1].The nuclear process chain starts with the extraction of uranium from the Earth's crusts and ends with the final disposal of the human-generated radioactivity into the biosphere. Disposal of the radioactive wastes in a deep geologic repository is generally considered to be the least risky way of dealing with the anthropogenic radioactivity. Section 2.## addresses in detail the concept of the deep geologic repository.

Like any industrial process chain, the nuclear process chain may be compared with a common, daily chain of housekeeping activities: cooking the meal, enjoying the meal and washing the dishes plus clearing the mess.
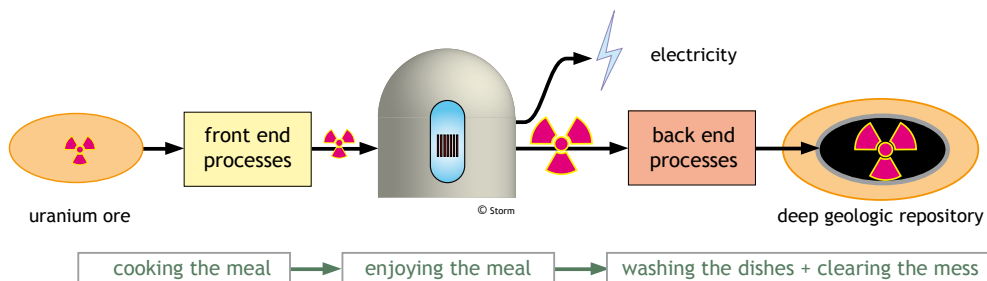


**Figure 2**
Simplified outline of the nuclear process chain, as it ought to be.

The back end processes turn out to be be ill-defined or even non-existent, e.g. the geologic repository. Because of the huge amounts of radioactivity involved, the back end processes pose the majority of the health risks originating from civilian nuclear power. Or, as the old Romans said: *in cauda venenum*.

**Nuclear chain: the current practice**

As common in daily life, nobody likes to do the dishes and clean up the mess. The aftermath of the nuclear meal turns out to be postponed indefinitely. The dirty dishes are piling up in the kitchen and dining room, our living environment. Why do governments, industry and media hide their eyes from this mess?
After more than 60 years of nuclear power the radioactive wastes ever generated are still

awaiting definitive processing, while stored in temporary, above-ground storage facilities, a situation getting more unsafe day by day. Why has not a single piece of the radioactive waste of the nuclear era been effectively isolated from the biosphere?

On closer consideration this question turns out to be not primarily a technical problem, although a demanding task, but a cultural problem. We will return to this issue in the following chapters.
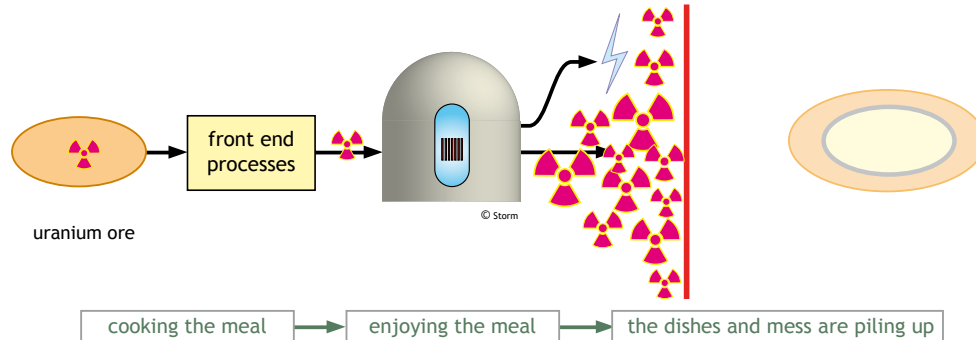


**Figure 3**
The practice: the radioactive waste from more than 60 years of nuclear power is piling up in temporary storage facilities and is still mobile in the human environment. The barrier preventing the human-generated radioactivity from adequate isolation from the human environment is not a technical one, but a paradigmatic one.


## 2.2    Mobilization and generation of radioactivity

The origin of the health risks of nuclear power lays in the irreversible mobilization and generation of immense amounts of radioactivity. These notions are briefly introduced in this section. What happens these amounts of radioactivity? Serious health risks arise by the fact that the nuclear process chain has still an open end, as symbolized by Figure 3.

**Mobilizing natural radioactivity**

Uranium is a radioactive metal found in nature in various chemical forms in uranium ore. In uranium ore strata, uranium and its many radioactive decay daughters are bound in chemically stable minerals. This is not to say uranium-bearing rock is harmless to man, not at all.

When uranium ores are disturbed to extract the uranium, the element is brought out of its geologic confinement into the environment and is chemically mobilized. This process will be explained in detail in section 3.2. The uranium isotopes are chemically separated from their their decay daughters and converted into nuclear fuel. In addition, the separated radioactive daughters of uranium (containing about 85% of the radioactivity in uranium ore) are dumped as uranium mill tailings in huge ponds and spoil heaps. From then on the radioactivity from the uranium ore is mobile.

**Generating radioactivity**

Human-made radionuclides come into being during the fission process in the reactor. Three different groups of the artificial radionuclides are commonly distinguished, according to their origin:

•    Fission products: the light atoms originating from the fission of the heavy uranium and plutonium atoms. Atoms of nearly all chemical elements are present in the mix and a part of the fission products are highly radioactive.

• Transuranic actinides: atoms heavier than uranium, which are formed from uranium atoms by neutron capture. These elements, for example plutonium and americium, do not occur in nature and are highly radioactive and highly toxic.

• Activation products. All non-radioactive materials exposed to neutron radiation from the fission process become radioactive by neutron capture; examples are the nuclear fuel cladding and the reactor vessel itself.

During the fission process the radioactivity of the nuclear fuel increases a factor *billion*. The generation of of these immense quantities of radioactivity is irreversible. Radioactivity cannot be destroyed nor can be made harmless to man. Radioactivity only decreases by natural decay, a process which cannot be controlled by man. The radiation emitted by radioactive substances is hazardous to man, especially when the radionuclides enter the body, via food, water or inhalation. This issue will be addressed in more detail in Chapter 3.

The highly dangerous spent nuclear fuel is unloaded from the reactor and transported to temporary storage facilities, usually on the site of the nuclear power plant. In any case the radioactivity leaving the reactor is physically mobile and mobile radioactivity poses a direct threat to human health.
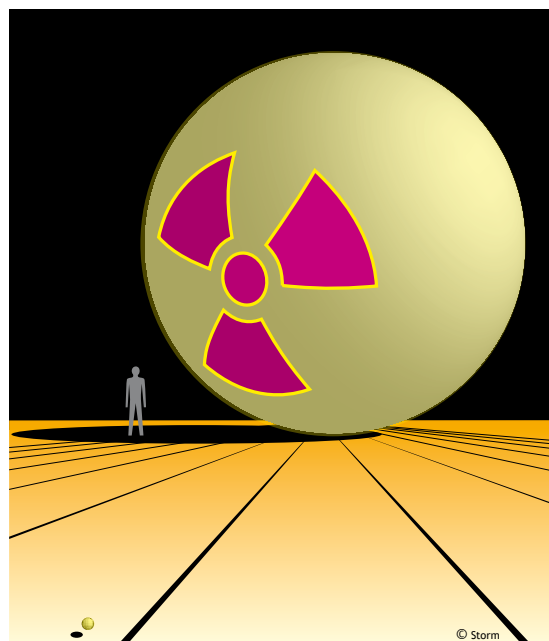


**Figure 4**
As a result of the fission process the radioactivity of the nuclear fuel irreversibly increases a billionfold. The pea in the foreground (diameter 1 cm) represents the original radioactivity of the nuclear fuel, the sphere in the distance with a diameter of 10 meter represents the radioactivity of the same amount of fuel 150 days after shutdown of the reactor. Based on: [2], [3] and [4].

**Nuclear bomb equivalents**

Each nuclear reactor of 1 GWe power produces each year an amount of radioactivity roughly equivalent with 1000 exploded nuclear bombs of 15 kilotonnes, about the yield of the Hiroshima bomb. A nuclear reactor produces relatively more long-lived dangerous alpha-emitting radionuclides than an exploding nuclear bomb, so the radioactivity from a reactor is more dangerous than an equivalent amount from a nuclear explosion.

**Immobilizing radioactivity**

There is only one survival strategy to deal with the reactor-generated radioactivity plus the mobilized natural radioactivity. As radioactivity cannot be destroyed nor can be made harmless to man, it must be immobilized and must be kept out of the human environment for at least a million of years (see also section 3.1).

In other words: the radioactive waste has to be physically immobilized completely and isolated permanently from the biosphere. Such an isolation facility has been coined a *deep geologic repository* in the terminology of nuclear technology. The immobilization and isolation concept will be discussed in more detail in section 2.5.

No such repository is yet available anywhere on the world, nor for high-level waste (spent fuel and reprocessing waste) nor for other radioactive wastes.
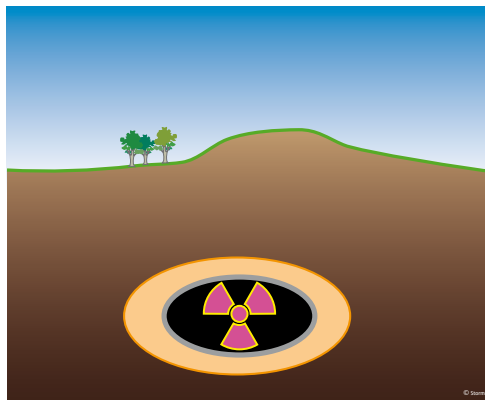


**Figure 5**

Symbolic presentation of a geologic repository. The purpose is to isolate the radionuclides from the biosphere for geologically long periods.
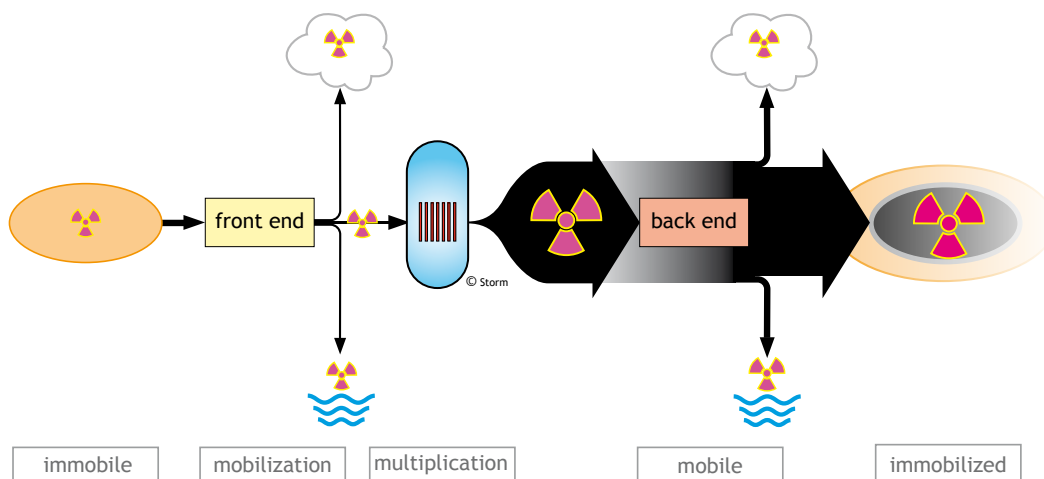


**Figure 6**

Symbolic presentation of the radioactivity flow through the nuclear system. Thw flow starts with the mobilization of natural radioactivity and multiplies a billionfold by generation of radioactivity in the reactor. Unavoidably a part of the mobilized radioactivity will be released into the environment. A safe immobilized end of the nuclear chain still exists only in cyberspace. What quantities of the radioactive materials leaving the reactor will end up in the environment?

## 2.3    Exponential growth of the mobile radioactivity

Ever since the first nuclear reactors started operation in the 1940s, the definitive solution to the radioactive waste problem has been postponed to the future. Spills from corroding storage tanks and waste containers are polluting watersheds, rivers and sea. A systematically underrated aspect of civilian nuclear power is the enormous size of the radioactive waste problem and its exponential growth over time (see Figures 7 and 8).
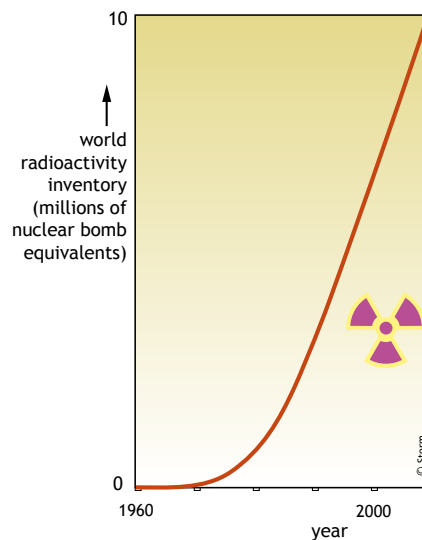


**Figure 7**

Cumulative quantity of the radioactivity generated worldwide by civilian nuclear power, measured in nuclear bomb equivalents. During the 1960s, 1970s and 1980s the quantity of radioactivity increased exponentially. During the last two decades the growth has been almost linearly, for the global nuclear generating capacity leveled off during the 1990s. If the world nuclear generating capacity will increase during the next decades, the world radioactivity inventory would grow exponentially again.
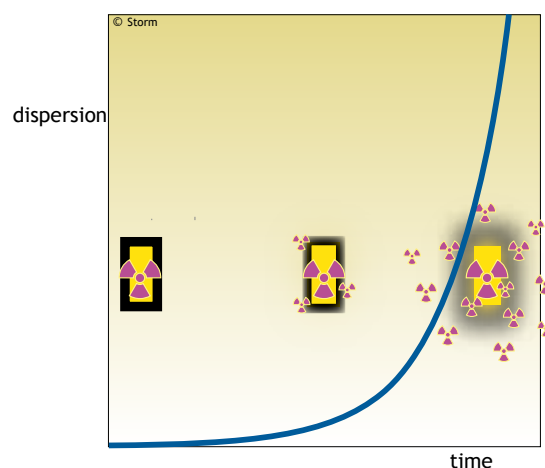


**Figure 8**

Increasing spread of radioactive materials into the environment over time, due to deteriorating containments of the radioactive materials as a consequence of the Second Law. The dispersion rate will increase exponentially, because the corrosion of the containments will progress exponentially. Self evidently the exponential spread rate causes an exponential increase of health risks over time, even if the amount of radioactivity would remain constant.

18

The exponential growth of the radioactivity problem has several causes:
• Each year an amount of radioactivity equivalent to some 370 000 nuclear bomb explosions is added to the world radioactivity inventory, embodied in the spent fuel from civilian nuclear reactors (see Figure 7). Since the 1970s the world inventory has increased with a factor 1000 and the proposed solutions still exist only on paper or in cyberspace.
• The dispersion rate of the anthropogenic radioactivity progressively increases over time caused by the inevitable ageing and deterioration of the materials and constructions of the containments (see Figure 8), which in turn is a consequence of the Second Law (see Box 1). In the next section the notion of engineered safety will be addressed.
• During an economic recession society has a declining ability to cope with nuclear health risks. The safe storage of radioactive waste requires vast amounts of energy, materials an economic effort. Conflicts may surface between short-term economic priorities and and log-term, less visible health effects. We return to the economic aspects in Chapter 6.

**Mobile radioactivity and the Second Law**

Time is a formidable ennemy of the safety of nuclear power. The longer the definitive isolation and immobilization of radioactive waste in a safe geologic repository is postponed, the more likely radioactivity will be spread into the environment and the more efforts will be necessary to prevent severe nuclear accidents. The risks will increase with time due to the progressive and irrevocable loss of quality of materials and structures by spontaneous processes.

An essential property of the curves of Figures 7 and 8 is the growth of the quantities accelerating ever faster. In cybernetic terms: the curves are characterised by a positive feedback mechanism: the growth is proportional to the value of the growing quantity. A positive feedback results in an unrestrained exponential growth, like the curve of Figure 8. When the growth rate decreases with increasing value of the observed quantity, the growth has a negative feedback mechanism, resulting in the well-known S-curve of the logistic growth (see Figure 9).
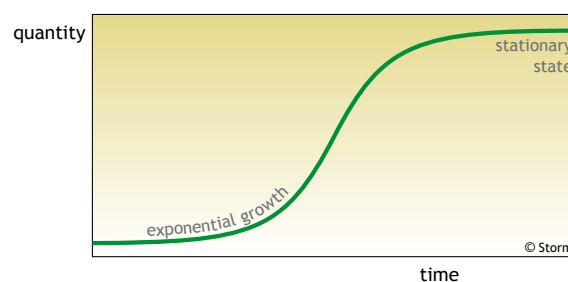


**Figure 9**
Logistic growth: growth of a quantity with a negative feedback mechanism. After a period of exponential growth, the growth levels off and in the long run a stationary state will be reached, in which the numerical value of the quantity no longer increases.

The growth of the cumulative amount of radioactivity (Figure 7) will stop only if all nuclear reactors are shut down. As long as nuclear power continues the cumulative amount of radioactivity will grow.
The dispersion of radioactive materials into the biosphere will follow an exponential growth curve (Figure 8) – even if all nuclear reactors were shut down – unless all existing radioactive materials are isolated definitively from the biosphere (see also next section).
Obviously the growth of both quantities of Figures 7 and 8 are lacking an inherent negative

feedback mechanism. Only dedicated human actions are able to interrupt these exponential growth patterns. The economic marketplace mechanism has definitely no such effect; on the contrary, it enhances the positive feedback and stimulates an ever faster growth.


## 2.4    Engineered safety

No technical system is perfect. In every production plant at any moment something may going wrong: a leaking coupling, a stuck valve, a bad electric contact, or whatever. Generally such bugs can be ironed out without interruption of the production process or without endangering the personel. In a nuclear plant the health risks are much larger than in conventional plants. A small spill, only a nuisance in a conventional plant, may have serious consequences in a nuclear plant. For that reason the quality specifications for materials, control systems and personel in a nuclear plant and other nuclear facilities, such as reprocessing plants, are considerably higher than in non-nuclear plants.

High quality specifications mean a high degree of predictability of the properties and behavior of materials and structures. The higher the specifications the lower the tolerance for random occurrences, for impurities in the materials and for deviation from the dimensional specifications of the structures. High quality standards can be met by stringent control during the production process and by a large input of energy, most of it embedded in materials and specialized equipment. From the Second Law (see Box 1), it follows that the energy inputs exponentially increase with increasing quality specifications of a given amount of material or piece of equipment.

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Box 1

### Second Law

The Second Law of thermodynamics is one of the basic laws of nature. Thermodynamics is the science of energy conversions and lies at the base of all sciences. A basic formulation of the Second Law is:
*With every change the entropy of the universe increases.*

To understand the effect of the Second Law in the context of this study ful comprehension of the notion entropy is not necessary.
The Second Law can be formulated in different ways. Selfevidently all correct formulations are based on the same principle: the dispersion of matter and the randomizing of oriented energy flows by any spontaneous process.
In respect of processes of everydays practice and in the context of this study the following formulation is useful:

*In a system without energy input from the out-side any spontaneous process will increase the disorder of the system and decrease its quality and usefulness.*

Examples of spontaneous processes are: the dispersion of $CO_2$ from burning fuel into the atmosphere, the rusting of steel in the open air and the decay of dead organisms.

The terms disorder, quality and usefulness are related to the basic notion entropy.

A consequence of the Second Law with respect of separation processes is:

*The separation of a mixture of different chemical species never goes to completion. Consequently it is not possible to separate a mixture into its pure constituents without losses. The amount of useful energy required for separation increases with the number of chemical species in the mixture and with the desired purity of the separated constituents.*

A consequence of the Second Law important in the context of nuclear energy generation is:

*The generation of an amount of useful energy from a mineral energy resource (fossil fuels, uranium) inextricably generates more disorder and more loss of quality (= more entropy) of the biosphere than can be compensated for by the produced amount of useful energy.*

**Bathtub hazard function**

The risks for catastrophic breakdown of technical devices, including nuclear reactors, change as the devices age, much like the risks for death by accident and illness change as people get older. There are three distinct stages in the lifetime of a technical system or living organism:
- the break-in phase, also called the burn-in phase or the infant mortality phase,
- the middle life phase, also called the useful life,
- the wear-out phase.

The risk profile, the failure rate as function of the time, for these three phases curves like a bathtub (see Figure 10). The bathtub curve is drawn from statistical data about lifetimes of both living and nonliving things, such as cars, cats or nuclear reactors [5], [6, [7].
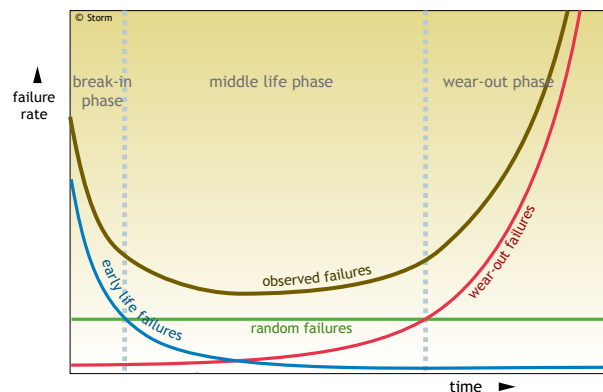


**Figure 10**

Bathtub hazard curve, as the sum of three types of failures rates. The bathtub curve is valid for technical devices, including nuclear installations, as well as for living organisms.

Applied to technical devices only, the bathtub curve may be considered to be the sum of three types of failure rates:
- Early life ('infant mortality') failures, caused by bad design, defective manufacturing, material imperfections, faulty installation, unanticipated interactions, poor workmanship imperfect maintenaince. and ineffective operation. The failure rate of this type decreases with time. The steepness of this curve depends on factors such as the amount of 'pre-flight' testing and the effectiveness of the quality control during manufacturing.
- A constant rate of random failures during working life, caused by accidents and random events. The height of this rate depends on, among other, the quality of the materials, of the design and the professionalism of the operators.
- Wear-out failures, caused by ageing, deterioration of materials, etcetera. The rate increases with time. Wear-out failures are typically the consequences of Second Law phenomena.

Obviously, the boundaries between the three life phases – break-in, useful life and wear-out – are not sharp.

The concepts behind the bathtub curve are playing an important part in space technology. The reliability and predictability of the behavior of each component of a spacecraft or launch vehicle has to be extremely high to achieve a specified reliability of the complex assembly as a whole: the spacecraft or launch vehicle. Extensive testing and screening procedures are applied to pass all components and assemblies through the break-in phase and to eliminate design flaws, manufacturing defects, etcetera. Functional flexibility by redundancy in the design of the spacecraft systems and very high quality standards minimalize the occurence of

random failures and postpone the wear-out failures. Exhaustive screening and pre-flight testing and stringent quality control make spacecraft possible to function unattendedly for a decade or longer. The effort needed to achieve such a level of reliability is exceedingly large, a direct consequence of the Second law. Large efforts mean high input of energy, materials and human resources, and consequently high financial cost.

**Bathtub curve and nuclear technology**

In the commercial nuclear technology no 'pre-flight' testing occurs. A nuclear power plant is assembled at the location chosen by the utility which will operate the plant. Design flaws and manufacturing defects are uncovered during construction and the first several years of operation of the nuclear power plant: the burn-in phase. Historical evidence indicates the burn-in phase of nuclear power plants to be several years. Major failures of nuclear reactors, including Three Mile Island 2 and Chernobyl, occurred during the burn-in phase. As Lochbaum 2004 [8] put it (describing the situation in the USA):

> 'The nuclear power industry's chronic quality control problems during design and construction are legendary, as is the NRC's (Nuclear Regulatory Commission) consistent inability to do anything about it.' (followed by a quote from an NRC report).

How is the situation in other countries?

Exactly the factors contributing to the burn-in phase failures are the cause of massive cost overruns of nuclear power plants and other large technological energy projects, as analyzed by the RAND Corporation [9], [10] . Recent examples of above mentioned habit of the nuclear industry, building before testing, are the troubled construction of the EPRs at Olkiluoto in Finland and at Flamanville in France, causing dramatic cost overruns and time delays.

This report returns to the reactor safety issue in section 4.6 and addresses the economic pressure on reactor safety in section 6.4.

Ageing processes of technical systems are consequences of the Second Law. Ageing processes are difficult to detect because they usually occur on the microscopic level of the inner structure of materials. The consequences are two-fold. Firstly, the number of incidents and reportable events will increase. Secondly, the aging process is leading to the gradual weakening of materials that could lead to catastrophic failures. Most notable among these processes is the embrittlement of the reactor pressure vessel. Failure of the pressure vessel of a PWR or BWR inevitably leads to a catastrophic release of radioactive material to the environment.

No human-made structure can be made absolutely fail-safe during tens of years. In the first place accidents and random events are impredictable by definition. The quality of the properties and the behavior of materials and structures predictably decline with time by ageing, cracking, wear, corrosion and other Second Law phenomena: the rate of wear-out failures predictably increases with time.

*Therefore, inherently safe nuclear power is inherently impossible.*

## 2.5    Immobilization of radioactivity

The only way to prevent serious public health problems is to immobolize the radioactivity from the nuclear chain and to isolate it from the biosphere permanently and stop building more reactors. The flow of radioactivity through the nuclear process chain has been briefly discussed in section 2.2 and is represented by Figure 6.

The radioactivity leaving the reactor must be completely immobilized, to prevent global-scale disasters. Immobilization in the 'natural way', like the radioactive elements in uranium ore (see section 4.2), is not possible for two reasons:

• Quantitatively because the quantities of radioactivity are a billionfold of the original natural amounts. For each tonne of uranium ore used in the nuclear chain a billion tonnes of artificial waste rock would be required.

• Qualitatively because the radioactive waste stream from the reactor contains dozens of different kinds of radionuclides, almost all elements of the Periodic Table are represented, each having different physical and chemical properties. Some radionuclides are volatile, others do not form stable and/or insoluble chemical compounds. Only a limited number of the radionuclides present in the mix could be chemically converted into  stable compounds (see also section 2.6 vitrification).

**Isolation**

The above observations point to the remaining strategy to deal with radioactive wastes: effective and permanent isolation of the radionuclides from the biosphere. The activities required to isolate the radioactive waste resulting from uranium mining are discussed in section 4.2. This section assesses the physical immobilization and definitive isolation of the radioactivity.

The first step to an effective isolation is an appropriate packing of the radioactive material especially the spent fuel. The containers should be resistant to water for long periods, a demanding task, for most materials rapidly deteriorate in the presence of water and strong radiation fields. Spent fuel generates enough heat to melt it, therefore active cooling for dozens of years in cooling ponds is necessary. This so-called interim storage period poses serious public health risks, which will be addressed in section 4.6.



**Figure 11**
The Swedish KBS concept for deep geological disposal of spent fuel. Source: Thegerstrom 2010 [14].

The next step is the permanent disposal of the waste containers. In view of the geologic timescales (millions of years) the waste has to be isolated, the final storage facility should be embedded in a geologically very stable formation, a *geologic repository*. Probably the farthest developed design of a geologic repository is the Swedish KBS-3 concept for permanent storage of spent fuel has already been described in 1993 [11], [12], [13], [14]; during the past 17 years little has changed. This concept is envisioned as a system of galleries in a granitic formation

some 500 meters below the surface. The spent fuel elements would be packed in containers of cast iron, clad by a thick layer of very pure copper. The designers assume this combination of materials to be resistant to (sea)water for thousands of years. However this assumption may be quite optimistic in view of the elevated temperatures and the presence of nuclear radiation.

The spent fuel in the containers generates heat for long periods after removal from the reactor, so each spent fuel container has to be placed into a separate hole in the floor of a gallery to avoid melting and cracking. Each hole is filled up with bentonite. When the holes of one gallery are occupied, which has to be done with robotic equipment because of the high radiation fields, the gallery itself is back filled with bentonite and permanently closed. Bentonite is a clay mineral that swells by absorption of water and so forms a poorly permeable mass. Ion migration through bentonite is very slow. Corrosion proceeds fast at elevated temperatures in the presence of water and of nuclear radiation. The bentonite is for retarding the migration of radionuclides leaking from corroded containers.

The construction of a geologic repository is anything but a simple task. A repository with a capacity of 20000 tonnes of spent fuel, about the current world annual production, should comprise some 100 kilometers of galleries and tunnels at a depth of about 500 meter below surface. Each year the world would need a new repository of this capacity.
A similar underground storage facility could be envisioned for categories of radioactive waste that do not produce heat at an appreciable rate. As there are no melting risks, these wastes can be stacked in large quantities in underground caverns. As the waste containers contain equally hazardous radionuclides as spent fuel, albeit in lower concentrations, the caverns should also be backfilled with bentonite. The cost of excavating one such repository will amount to billions of euros.

Which geologic formations are best suited to accomodate a geologic repository? Each country seems to answer this question on its own way, dependent on the geologic options present and the political situation of the moment. For example, in the Netherlands and in Germany salt domes are discussed, in Belgium and France old clay formations, in the USA a volcanic formation (recently cancelled, without naming a new option) and in Sweden, Finland and Switzerland granitic formations.


## 2.6    Solutions from cyberspace

In its communication with politicians and the public the nuclear industry advocates several solutions of the radioactivity immobilization problem, one of them the geologic repository discussed in the previous section. Two other solutions are based on sophisticated technical concepts to deal with the human-made radioactivity: vitrification and transmutation. According to a popular opinion within the nuclear industry each of these technical concepts could reduce the high-level waste problem to a routine job, nothing to worry about, see for example MacKay [15]. Both concepts may seem plausible at first sight, but, on closer examination, prove to be in conflict with one of the most basic laws of nature: the Second Law (see Box 1).
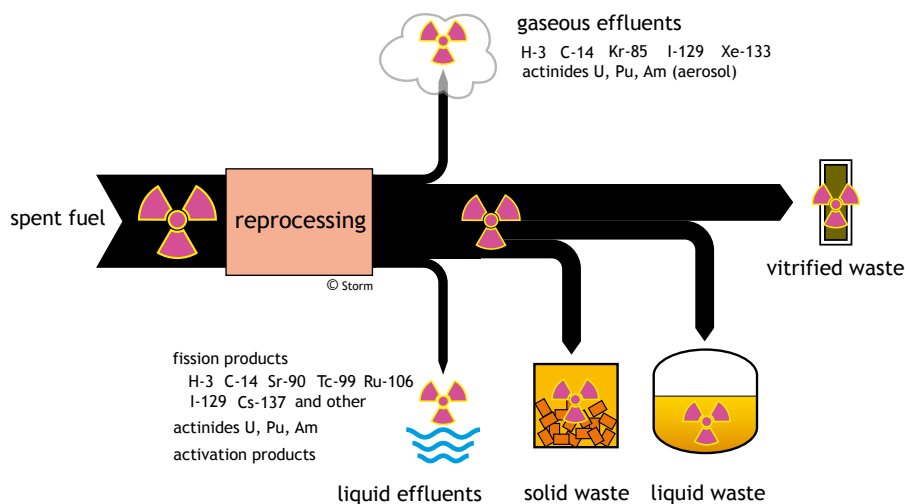
**Vitrification**

Vitrification is advocated as a means of a significant volume reduction of radioactive materials removed from a nuclear reactor. According to this concept the dangerous radionuclides from spent fuel would be chemically immobilized in a matrix of borosilicate glass. To this end the radionuclides first have to be separated from the non-radioactive components of spent fuel,

this separaton process is called reprocessing.

Civilian reprocessing has been developed during 1970s and 1980s to retrieve the plutonium from spent fuel (formed by neutron capture of unfissionable uranium-238 atoms) to start up the envisioned breeder system. The breeder has proved to be technically unfeasible for several reasons, one of them being the inherent imperfections of reprocessing. Apparently to justify the extremely expensive reprocessing industry from being closed down, reprocessing is presently advocated by the nuclear industry as a means of reduction of the radioactive waste volume. This is a serious fallacy, as will be explained below.



**Figure 12**

Outline of the radioactive waste streams from reprocessing of spent fuel. Significant amounts of radionuclides are discharges into the environment. Only a part of the radionuclides from the spent fuel can be vitrified.

In the reprocessing plant the spent fuel is chemically treated to separate it into several fractions: unfissioned uranium, newly formed plutonium, fission products and actinides. The radioactivity, in the spent fuel present in a very condensed form, is during the reprocessing spread over large volumes of liquids and solids. All gaseous fission products, such as tritium, carbon-14, the radioactive noble gases and a significant part of iodine-129 are released into the air. Complete separation of a mix of different species into its pure consituents is a delusion, a consequence of the Second Law (see Box 1). Separation processes always proceed incompletely – the more so the greater the number of constituents and the higher the radioactivity of the mix. This follows from the Second Law. Consequently a significant fraction of the radionuclides is discharged from the plant with the waste water into the sea. Not by chance the European reprocessing plants (La Hague in France and Sellafield in the UK) are located at the sea coast.

As pointed out above spent fuel contains many tens of different kinds of elements and only a limited number of these elements has the appropriate properties to be chemically immobilized. This vitrifiable fraction, minus the unavoidable separation losses, is confined into a matrix of borosilicate glass (vitrification). The volume of this glass is smaller than the volume of the spent fuel it is made from, due to a higher concentration of the vitrifiable radionuclides in the glass. The nuclear industry does not mention a single word about the large volumes of the remaining waste, nor about the releases of substantial quantities of radioactivity into the biosphere. Nothing is said about the massive volumes of radioactibe wastes, resulting from the decommissioning and dismantling of the reprocessing plant at the end of its operational lifetime: debris and scrap heavily contaminated with all kinds of radionuclides.

**Transmutation**

Transmutation is advocated by the nuclear industry as a means of 'destroying' long-lived radionuclides. Transmutation is a theoretical concept in which long-lived radionuclides from the spent fuel would be converted by intense neutron irradiation into other radionuclides with shorter half-lives. After this treatment the radioactive waste from nuclear power would remain dangerous for 'only' a few centuries, instead of hundreds of thousands of years, according to the advocates of the transmutation concept.

As a means of nuclear waste reduction transmution is a utopia for several reasons, among other:
• Not all long-lived radionuclides can be transmuted into short-lived ones [16]. A number of important long-lived fission products cannot be transmuted in this way, on nuclear physical grounds.
• Complete separation of spent fuel into its pure constituents, without losses, is a conditio sine qua non. This condition is impossible based on the Second Law, as pointed out in the previous section.
• Even with a perfectly operating transmutation system it would take centuries (!) to reduce the quantity of long-lived radionuclides to 10% of the original quantity, in a given amount of spent fuel [16].
• The transmutation system, consisting of a reactor, a reprocessing plant and a fuel fabrication plant, would generate more long-lived radionuclides than it woud convert into short-lived.
• The energy consumption of a transmutation system would be prohibitive: the system would consume more energy than could be generated by the nuclear power plant producing the spent fuel to be transmuted.

Essentially a working transmutation system has to treat individually each atom from the spent fuel. One kilogram of spent fuel contains some $10^{24}$ atoms: a million times billion times billion. One reactor of 1 GWe produces each year some 30000 kilograms of spent fuel. The world has about 370 GWe nuclear generation capacity.

The health risks of a (hypothetical) transmutation system would be enormeous and, worse, uncontrollable. The total amount of radioactivity per unit useful energy delivered to society would increase exponentially. In addition these amounts would be chemically and physically very mobile, in gaseous effluents, in liquids and in solids, with exceedingly high risks of dispersion into the environment.

# 3    Radioactivity and health

## 3.1    Radioactive decay of human-made radioactivity

Spent fuel contains fission products, newly-formed actinides, activation products and unfissioned uranium. During the first year after shutdown of the fission process, the radioactivity per kilogram falls with a factor of hundred, after that much more slowly, see Figure 13.
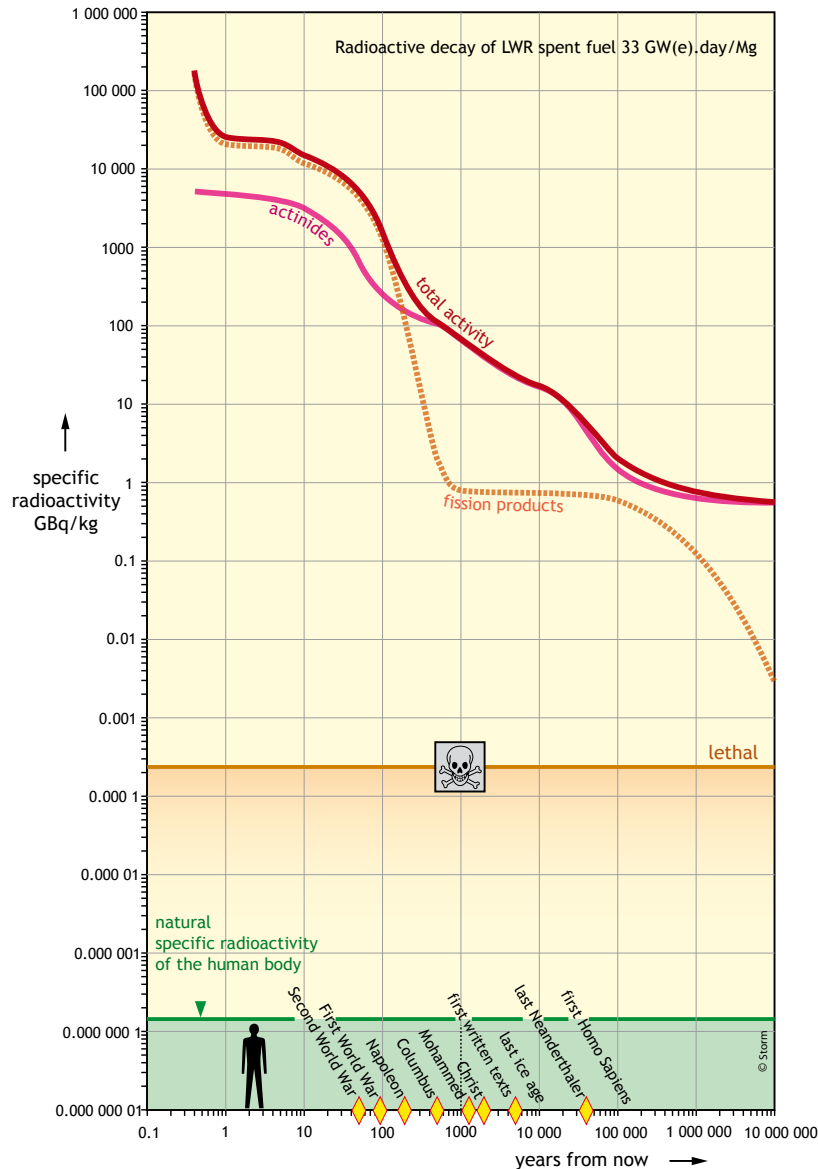


**Figure 13**

The specific radioactivity, in gigabecquerel per kilogram (GBq/kg), of spent fuel. Nuclear fuel from the new types of nuclear reactors has considerably higher burnup than the fuel this diagram is based on and so is its specific radioactivity. The contributions of activation products, including tritium, carbon-14, are not included in these curves. Note that both axes have logarithmic scales. Each scale division denotes a factor ten. With a linear time scale the horizontal axis would be about 100 kilometers long.

On the horizontal axis a reverse historic timescale is indicated, to give an idea of the time frames involved. The green line indicates the natural radioactivity of the human body (143 Bq/kg). For more details see text. Sources: [2], [3], [4], [17].

The decay of the radioactivity of spent fuel is represented for a period of ten million years in Figure 13. To bring the time intervals within human perspective, some important dates are given, looking back in time as far as the decay will take into the future.

The numbers on the vertical scale of Figures 13 are in gigabecquerel per kilogram mass (GBq/kg, 1 Bq = 1 desintegration per second) a measure of specific radioactivity, which may have little meaning without a reference value. The obvious standard is the human body itself, which has a natural specfic radioactivity of about 143 Bq/kg, mainly due to potassium-40 (86 Bq/kg) and carbon-14 (57 Bq/kg), two naturally occurring radioisotopes. The average lethal amount of radioactivity in the human body is roughly 25000 times the natural activity [17]. which is indicated in Figure 13, but this amount strongly depends on the types of radionuclides.

The curves of Figure 13 do not include the activities of tritium and carbon-14, nor the activity of the radionuclides in the cladding hulls of the fuel. The contributions of these nuclides may be significant after a cooling period of 10 years.

Box 2

## Nuclear radiation

Radioactive atoms (radionuclides) have unstable nuclei, which turn spontaneously into stable nuclei. This process is coined radioactive decay and cannot be controlled by man. Radioactive decay is accompanied by the emission of radiation from the nucleus. There are three main types of nuclear radiation: $\alpha$ (alpha), $\beta$ (beta) and $\gamma$ (gamma) rays.

Alpha rays consist of the bare nuclei of helium-4, which are ejected from the decaying nucleus with high energy. Due to their electric charge and high speed, the interaction of alpha particles with normal matter is very strong. As a result of the strong interaction the range of $\alpha$-rays within solid matter is very short: they are blocked by a heavy sheet of paper. Consequently $\alpha$-rays do not penetrate deeply into the skin.

Beta rays consist of electrons which are ejected at high speed from the decaying nucleus. The interaction of $\beta$-rays with matter is less strong than of $\alpha$-rays and consequently their range is longer. Beta particles are stopped by 1 mm aluminum.

Gamma radiation is a kind of electromagnetic radiation, more energetic than X-rays. Gamma emission occurs usually in combination with alpha- or beta emission. Gamma rays have a weaker interaction with matter than $\alpha$- and $\beta$-rays and are very penetrating, they can pass through thick layers of metal and concrete.

During interaction with the atoms and molecules of normal matter the majority of the energy of the nuclear radiation is given off to electrons, which are knocked loose from the atoms. The energy of these secondary electrons is 1-2- eV (electronvolt), about the energy range of visible and ultraviolet light, is enough to cause chemical reactions. An atom which looses one or more electrons becomes a positively charged ion, a chemically very reactive species. For reason of the generation of ions in matter, nuclear radiation is often called ionising radiation.

Alpha- and beta-rays from a source outside of the body do not penetrate far into the skin. If however radionuclides are absorbed by the body, e.g. by inhalation or ingestion, the emitted rays pass through unshielded tissue and cause biological damage. Alpha particles are more devastating than beta- and gamma-rays, due to their high electric charge and higher energy. On its short path through living tissue an $\alpha$-particle from a decaying uranium atom generates about 16000 secondary electrons. Each of these electrons can initiate a chemical reaction. For reason of the high number of secondary electrons and the high LET value (Linear Energy Transfer = the amount of energy dissipated per unit path length) $\alpha$-emitters are classified as the most harmful type of radionuclides in living organisms.

Spent fuel contains relatively large amounts of $\alpha$-emitters in the form of actinides. In addition to the dangerous $\alpha$-emission, several of the actinides, e.g. americium and curium, exhibit spontaneous fission. As a result spent fuel also emits neutrons, which are biologically very dangerous. Neutrons are not ionising directly, they don't have an electric charge, but interact with organic molecules via activation reactions. The penetrating power of neutrons is very high. The biologically harmful effects of fast neutrons are assumed to be ten times as high as those of gamma-radiation.

## 3.2    Radioactivity in the human body

**Effects**

There are stochastic and non-stochastic effects of nuclear radiation. Non-stochastic effects occur at very high doses within a short period and are due to cell killing on a massive scale. The effects become evident within hours or days. A clear relationship exists between the effects and the magnitude of the received dose. Non-stochastic effects are important in case of nuclear explosions and large nuclear accidents.

Stochastic effects occur at random and concern mainly cancer and genetic effects. A common wisdom is that a larger received dose means an increased chance of cancer or other effects. The classical radiobiology assumes a linear relationship between dose and adverse effects. However it not certain if an individual will develop a cancer or other adversed effect. If a large number of individuals receive the same dose, one can predict the number of individuals  who will develop an adverse effect, but not which individuals. With regard to stochastic effects there is no threshold of the received dose below which adverse effects certainly will not occur, apart from zero dose.
Radiation-induced effects comprise, among other, chronic diseases such as leukemia, other forms of cancers and diabetes, but also premature births, low birth-weight, infant mortality and congenital defects.

Quantification of the relationship between low radiation doses and the effects is a real problem. Usually it is hardly possible to prove unambiguously the relationship between a once contracted dose of radiation and the carcinogenic, mutagenic and teratogenic effects many years later, for a number of reasons, such as:
• long incubation periods
• stochastic character of the biological effects
• interference with other factors, such as chemical pollution, life style, diseases, smoking
• uncertainties of the actually received dose
• low doses during a long period or higher doses during a shorter period
• which nuclides are involved
• basic biomedical unknowns.
In addition the kind of exposure is important: did the individual get radiation from nuclides extern to his body, or internally from nuclides within his body? In which form have the nuclides entered the body, by inhalation of dust and gas, or by ingestion via food and drinking water? In which chemical form did the radionuclide enter the body: as a free element, as an inorganic species or as an organically bound species?

Due to the complexity of the dose-effect relationship the only way to obtain reliable empirical data on the health effects of radioactivity are extensive epidemiological inquiries, involving large cohorts of individuals. Such inquiries should be performed by independent scientific institutions without direct or indirect financial connections with the nuclear industry. However, epidemiology studies are not without problems, see for example [18].

**Biochemical aspects of radioactivity**

The relationship between irradiation of living cells and health risks is exceedingly complex. Available knowledge is based on experiments with bacteria, mouses and other animals and often comprises little more than mathematical models based on theoretical assumptions. The standards for the public exposure to nuclear radiation were (and probably still are) based on

the experience with diagnostic X-rays and gamma rays from external sources and originate from the early 1950s. Not included in the early models are the fact that the adverse effect of radiation is 10s to 100s of times more serious for the developing infant in the mother's womb and young childern than for adults studied following medical X-ray exposures [19].

Not until the early 1970s it was discovered that protacted radiation exposures as from long-lived radionuclides accumulating in the body, is much greater than from the same total dose received in a short X-ray exposure.

A number of radionuclides has been investigated to some extent, other nuclides (e.g. carbon-14) practically not. The empirical database on effects in the human body seems to be very small. Synergistic effects are unknown basically. What are the effects of several radionuclides together in a biological system?

Some radionuclides have a specific biological behaviour and tend to cumulate in a special organ or tissue. In that case, the radioactivity is not evenly distributed among the body and doubling of the radioactivity of the body as a whole, means locally a sharp increase in radiation. The chemical properties of an element are not affected by the radioactivity of its atoms. For example, the biochemical machinery of the human body cannot distinguish between a normal water molecule $H_2O$ or a water molecule with one or two tritium atoms (HTO respectively $T_2O$). As a consequence the biochemical behaviour of radionuclides in the human body is identical to that of their non-radioactive isotopes.

High concentrations of a specific radionuclide in a specific organ are possible as a consequence of its biochemical properties. Radioactive iodine atoms ($^{129}I$ and $^{131}I$) for example, seek out the thyroid gland, together with its non-radioactive sister atoms, and damage the production of key growth hormones and cause thyroid cancer. Strontium-90 and plutonium tend to cumulate in the bones, where they irradiate the bone marrow, causing leukemia in newly forming red blood cells as well as damage to crucial white cells of the immune system that fight cancer cells and bacteria. Cesium-137 collects in soft tissue organs, such as the breasts an reproductive organs of females and males, leading to various types of cancer in the individuals and their childern as well as in later generations [19].

When in the human body a radioactive atom decays, an atom of another element comes into being. This change of identity will cause a chemical reaction. The nuclear radiation from the decay will generate large numbers of secondary ions, each of which will cause also chemical reactions. Chemical bonds will be broken and new ones will be formed. Existing molecules can be destroyed and new molecules can be formed.
Several factors are important in judging the biological hazards of radioactive substances in the human body, such as:
• biochemical behaviour of the radioisotope itself and of its decay product
• biochemical reactions initiated by the ionizing radiation of the radioactive decay, via primary and secondary ions
• biochemical reactions initiated by the energy transfer of the decay (recoil) and of the secondary electrons.

**Non-targeted and delayed effects**

Relatively recent studies proved the existence of 'non-targeted' and 'delayed' radiation effects. Probably these effects had been observed in earlier studies but they had been unrecognised as they fell outside the then accepted paradigm of radiation effects. Non-targeted effects, which

arise as a result of damage/changes to unknown areas if the cell, are termed 'non-targeted' because they mainly do not cause damage/changes to DNA or chromosomes, heretofore believed to ne the main site for radiation's lesions. Non-targeted effects include, according to [20]:

• genomic instability (effects occurring up to 20-30 generations later in the progeny of an irradiated cell),

• bystander effects (effects in unirradiated cells situated close to irradiated cells),

• clastogenic effects (causing chromosome disruption or breakages in blood plasma that result in chromosome damage in non-irradiated cells), and

• heritable effects of parental irradiation that occur in succeeding generations.

The classical explanation for radiation's effects was that they were mostly caused by structural DNA damage (i.e.single- and double-strand DNA breaks) which resulted in mutations in the cell's genetic information that, without repair or elimination, would end eventually in cancers. This is the target theory of radiation effects, the target being specific sequences in DNA and chromosomes.

The doses causing non-targeted effects are too low to cause structural DNA damage. The dose-response curve of these effects is often not linear, with substantial increases at very low doses followed by a levelling off at higher doses. Presently there is no mechanical explanation for how the non-targeted effects actually occur [20]. The target for radiation damage is greater than the initial tissue volume irradiated [21]. A historical overview is given, among others, by [22]. The observed phenomena pose many fundamental questions to be answered and result in a paradigm shift in the understanding of radiation biology.

## 3.3 Tritium, carbon-14 and krypton-85

The three radionuclides tritium, carbon-14 and krypton-85 are routinely released into the human environment by nominally operating nuclear power plants. According to the classical dose-risk paradigm, as discussed in the previous section, these discharges would have negligible public health effects and so were (and still are) permitted. This assumption turns out to be untenable based on the evidence of non-targeted and delayed adverse radiation effects, discussed in the previous section.

Of special importance are the radionuclides tritium and carbon-14, $^{14}C$. As pointed out above these radionuclides are biochemically indistinguishable from their non-radioactive isotopes, normal hydrogen H, respectively normal carbon (mainly $^{12}C$). Carbon and hydrogen are two of the six primary building blocks (C, H, O, N, S, P) of proteins and DNA. A possible complication is that both radionuclides are always discharged simultaneously.

**Tritium**

Tritium, symbol: $^{3}H$, H-3 or T, is the radioactive isotope of hydrogen with a half-life of 12.32 years and a specific activity of 358 TBq/g. Chemically, tritium is indistinguishable from ordinary hydrogen H, or the other isotope deuterium ($^{2}H$, H-2 or D). Ordinary hydrogen and deuterium are stable isotopes, of which H is the most abundant: H 99,985% and D 0,015%. In nature tritium is formed in the upper atmosphere, due to cosmic radiation. The generation rate of tritium by nuclear installations surpasses its natural generation rate [23]. Tritium decays to helium-3 with the emission of low-energy beta radiation (electrons).

Tritium is discharged into the environment as tritiated water HTO and relatively small amounts of hydrogen gas HT or $T_2$. Tritium atoms, like ordinary hydrogen atoms, are very mobile in the

aquatic system and as a consequence in the biochemical system. They are readily incorporated into biomolecules, which may enter the food chain. Direct ingestion via drinking water, prepared from river water, is another pathway.

Hydrogen atoms bound to the N, O or S atoms in biomolecules of a living cell are easily exchanged with hydrogen atoms from the water molecules in the cell. In a living cell this exchange process goes on continuously. When tritiated water HTO enters a cell, normal hydrogen atoms in the biomolecules are exchanged with tritium atoms. By this process biomolecules with built-in radioactive hydrogen atoms are formed. In this way tritium enters the food chain, for example in milk and vegetables. In the body organically bound tritium (OBT) is slowly formed by metabolic reactions. Once it is formed it stays in the body for much longer periods (20 to 30 times longer) than HTO [24].

Tritium can enter the body via food as OBT and via drinking water containing tritiated water HTO. The biological half-life of OBT in the human body is much longer than of HTO. Normal hydrogen atoms in the DNA molecules are exchanged for tritium via OBT and HTO. The exposure of DNA to the radiation from tritium comes from within the DNA molecules themselves and from biomolecules and HTO adjacent to the DNA molecules. Despite the short-range of the β-radiation, its effects can be significant. See also [25], [26], [27], [28].
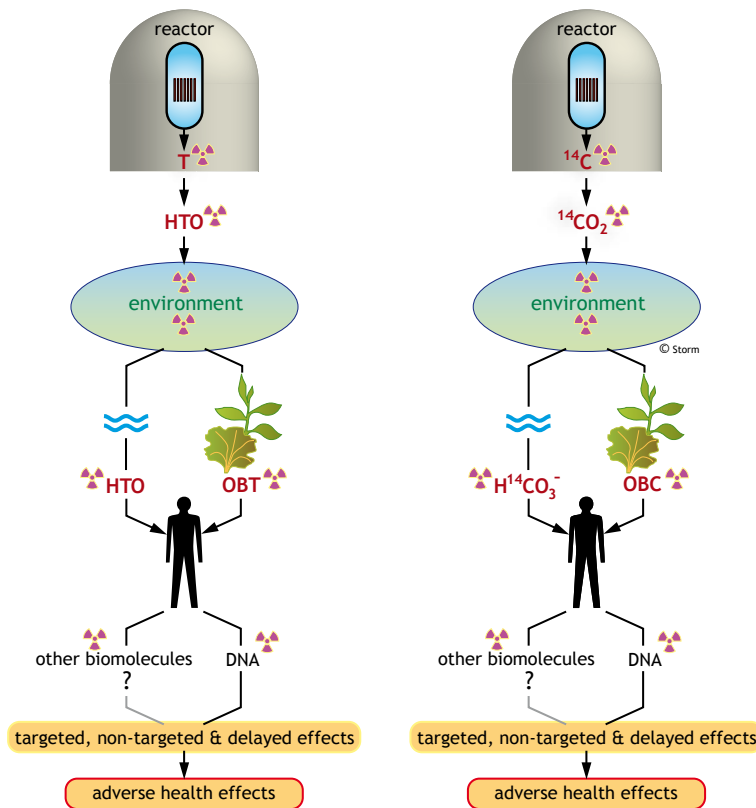


**Figure 14**

Pathways of radioactive hydrogen (tritium) and carbon-14 into the human metabolism. Both radionuclides are routinely released into the environment by operating nuclear power plants. The pathways are similar. It is generally assumed that damage to DNA molecules cause adverse health effects. Cell damage is not limited to the cells directly hit by radiation, due to the bystander effect (see text). It is not known if radiation damage to other biomolecules could cause adverse health effects.

If a tritium atom decays during its stay in a DNA molecule it transforms into a stable helium-3 atom, a noble gas, while emitting a beta-particle. The helium atom does not form any chemical bonding and is ejected from the DNA molecule. The emitted beta particle causes additional ionisations and broken bonds in the vicinity of the decay event. Obviously such an event may cause a mutation or lesion in the DNA molecule.

Studies in the 50's, 60's and 70's of the 20th century concluded that deleterious effects of tritiated water from nuclear installations were unlikely at its (then present) levels. This is not to imply that tritium at higher concentrations would be not carcinogenic or mutagenic [26]. Apparently no fundamental, biochemical reaction mechanisms initiated by tritium decay (interaction of bèta radiation with chemical bonds, transmutation and recoil effects) in living organisms have been thouroughly experimentally investigated. Experimental research in mice and rats of biological effects of tritium is reported, but extrapolation to human health effects is difficult. Little direct evidence of tritium effects in humans exists, according to [29].

The radiotoxicological classification of tritium is based on theoretical computations, starting from the relatively weak beta radiation of this nuclide [26]. Indications are found that under certain circumstances the biological activity of tritium is higher than predicted [28], [29], [30]. These findings may point to non-targeted and delayed affects.

**Carbon-14**

Carbon has two stable isotopes, of which $^{12}$C or C-12, ordinary carbon, is the most abundant (98,9%), the other stable isotope is $^{13}$C (1.1%). The element has an important radioactive iso-tope, $^{14}$C or C-14, with a half-life of 5730 years. The specific activity is 0.165 TBq/gram.

Carbon-14 is emitted by a nuclear power plant as $^{14}CO_2$ and $^{14}CH_4$ and some higher alkanes [28]. In air the alkanes are slowly oxidized to $^{14}CO_2$. Carbon-14 atoms are chemically identical with stable carbon atoms and enters the biosphere mainly as $^{14}CO_2$. Carbon dioxide slightly dissolves in (rain) water and a chemical equilibrium is established in which bicarbonate ions are formed. Carbon-14 can be bound in the bones of animals and humans via bicarbonate ions in drinking water.
Via photosynthesis in plants, $^{14}CO_2$ can be bound into biomolecules: the built-in C-14 atoms are called organically bound carbon, or OBC. Via the food chain OBC can enter the human body and become incorporated into DNA molecules (see also Figure 14). A combination with tritium is possible. Near all nuclear power plants, both isotopes are present, because tritium and carbon-14 are usually the highest discharges.

By the end of the second growing season, most food plants will be nearly at equilibrium with the atmospheric $CO_2$. The time delay for most foodstuff of plant origin to reach maximum concentration of $^{14}$C is not more than one year [31].
Soft tissues in animals (and humans) seem to lag behind the tropospheric $^{14}C/^{12}C$ ratio by about one to two years. Since some tissues or body compartments have long turnover times, approaching the life span, total body carbon in the adult subjected to a change in $^{14}C/^{12}C$ intake ratio may not approach equilibrium for decades.
Fetal tissues will more nearly reflect the current $^{14}$C composition of the food available to the mother.

Male sperm cells are produced from spermatogonia continuously in the adult male and consequently the $^{14}$C specific activity in the nuclear material must resemble that of the food with a lag time of one or two years.

Female oocytes are laid down in the fetus before birth and thereafter remain dormant until they ripen just before being shed. It is uncertain how much of the adjacent tissue may be subject to turnover and renewal but, in any case, none of the DNA of the ovum, except the small fraction renewed by repair processes would contain $^{14}C$ of the current specific activity. There will, therefore, be a delay of 16-40 years in the human female for expression of the genetic effects of a given $^{14}C/^{12}C$ ratio. Calculation of the genetic effect to the current generation of an added increment of $^{14}C$ to the atmosphere using a lag time of 1-2 years, therefore, is conservative according to [31].

Damage to DNA molecules occurs in a similar manner as by tritium. A carbon-14 atom decays into a stable nitrogen-14 atom by emitting a beta particle. The chemical properties of nitrogen differ widely from carbon and the beta particle causes secondary ionisations and lesions.
Some DNA molecules in the human body may remain practically unchanged for decades, for example in egg cells, so the medical consequences of carbon-14 ingestion may have long incubation times.

Experiments proved beta-particles (electrons) with remarkably low energy to be able to destroy vital parts of DNA and RNA molecules [32]. Up until about the year 2000 the common opinion was that DNA and RNA molecules could be damaged only by electrons with an energy of more than 10 eV. Experiments proved that electrons with energies as low as 3 eV can break both strings of the DNA double helix. There is evidence of a lower energy limit well below 1 eV.
The DNA repair mechanism is able to repair a single lesion, but complex and multiple lesions may result in misrepair, ie mutations may occur.

Sparse data are available to base on estimates of genetic hazards associated with $^{14}C$-labelled nucleic acid precursors, according to [26], [30]. This is confirmed by [31], which mentiones only a few studies with theoretical calculations, concerning the dispersion of $^{14}CO_2$ in air.

**Krypton-85**

Being chemically inert, krypton and the other noble gases are not usually involved in biological processes. They are, however, absorbed into the tissues of the body via inhalation and dissolution in body fluids and tissues. Xenon has been shown to combine with specific sites with certain protein molecules. Krypton is characterized by low blood solubility, high lipid solubility and rapid diffusion in tissue.
Exceptions to the biologically inert characterization of inert gases have been noted by numerous studies, according to [33]. A comparatively high uptake of krypton by the adrenal gland has been reported. These phenomena are not understood.

On global scale the genetic and overall carcinogenic effects from Kr-85 are calculated to be small as compared with other possible sources of deleterious effects.
The possible interaction of radiation from krypton-85 and solar ultraviolet (UV) should be mentioned. In order to understand better the implications of long-term $^{85}Kr$ releases to the atmosphere, epidemiological and laboratory studies should be undertaken to define the nature and degree of interaction, if any, of UV radiation with ionizing radiation in the induction of skin cancer [33].

## 3.4      The KiKK study

One of the very few independent epidemiological inquiries of the relationship between nuclear power and health risks is the German Epidemiological Study on Childhood Cancer in the Vicinity of Nuclear Power Plants (*Epidemiologische Studie zu Kinderkrebs in der Umgebung von Kernkraftwerken* (KiKK-Studie)) of 2007 [30]. The report was published on the web in 2008. The study was commissioned by the German government and carried out by the Deutsches Kinderkrebsregister DKKR (German Childhood Cancer Register) during the years 2003-2007. The validity of the study has been accepted by the German government.

The KiKK study includes all the cases of childern reported to the German Childhood Cancer Register diagnosed with cancer during 1980-2003, who were under 5 years of age at the time, and living in preassigned regions the vicinity of the 16 German nuclear power plants (1592 cases). Controls of equal sex and age in the year of the onset of the disease were chosen randomly for each case (4735 controls).

With regard to the incidence of cancers with childern before their 5th birthday, living within a distance of 5 km from a nuclear power plant, the KiKK study concluded:
• 1.2x increase in child leukemias
• 0.6x increase in child solid cancers
• strong association with proximity to a nuclear reactor.

The KiKK study was unable to pronounce which biological risk factors could expain the results of the study. Existing models of the relationship between the incidence of cancers and low radiation doses are generally based on adults and solid cancers, not on children and blood cancers. These models cannot explain the results of the KiKK study. We return to the issue of the use of models in the section 5.2.
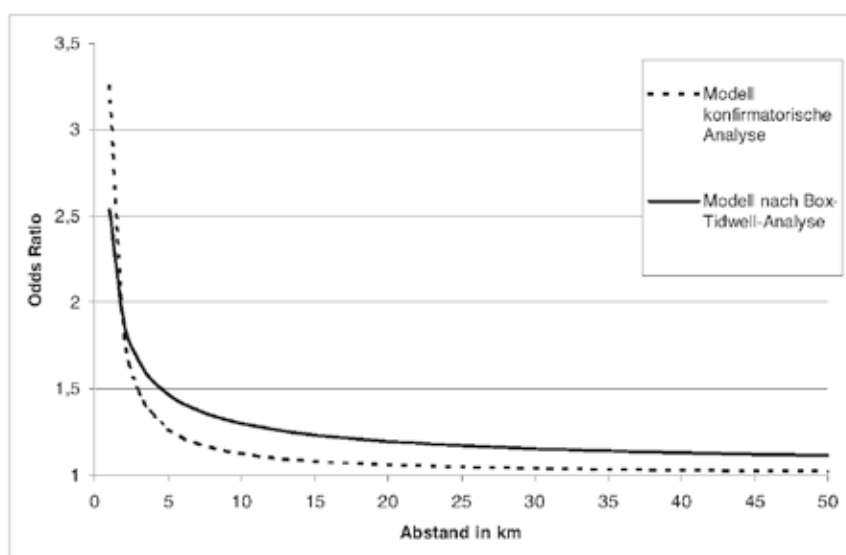


**Figure 15**
KiKK's regression analysis showing the statistical relationship between the incidence of cancer with children under 5 years of age and distance to the nearest nuclear power plant. The closer to a reactor, the greater the risk of childhood leukemia and solid cancers. Source: KiKK 2008 [30].

The increased risks as observed by the KiKK study do not seem to be explained by the radiation from nuclear power plants, as official estimated doses from NPPs appear to be too low. The radioactive releases of nuclear power plants, mainly tritium and carbon-14, exhibits spikes when the reactor is shut down and opened for removing spent fuel and exchanging it for fresh fuel.

To explain the results of the KiKK study the following hypothesis has been suggested [35]. The spikes in the radioactive releases may result in the labeling of the embryos and foetuses of pregnant women living nearby at high concentrations. Such high radionuclide concentrations could occur in long-lived cells and could result in large exposures to radiosensitive tissues en subsequent cancers. Some foetal tissues *in utero* may be exceedingly radiosensitive. Fairlie [36] observes the absence of essential knowledge with regard to radiation risks for embryos and foetuses.

According to Fairlie, vulnerable people, in particular pregnant women and women of child-bearing age, should be advised to move away from nuclear facilities as a precautionary step. Also local residents should be advised not to eat products from their gardens or wild foods, as the food pathway is the largest contributor to local doses.

# 4 Pathways of nuclear health risks

## 4.1 Releases of radioactivity into the environment

Adverse health effects are to be expected as soon as radioactive substances are released into the environment. To assess nuclear health risks knowledge is needed on the frequency and extent of possible discharges, on the amounts of radioactivity involved and on the biomedical characteristics of the released radionuclides. This chapter briefly discusses the following discharges, sources and mechanisms.

No technical system is perfect, as explained in section 2.4. Inevitably radioactive substances will leak out of the technical systems and disperse into the environment. Leakages can be curtailed by application of high quality standards of the technical systems and a stringent inspection regime. Due to ageing, corrosion and wear the quality of the materials and equipment will decline, and consequently the magnitude of spills and discharges tends to increase over time. In view of the immense amounts of radioactivity involved in the reactor operation and in the downstream processes, even the escape of a tiny fraction could involve large amounts of radioactivity with serious public health consequences.

**Routine releases**

The nominally operating nuclear process chain discharges routinely radioactive substances into the environment, in the upstream processes, during the reactor operation as well in the downstream processes. A part of these operational releases is hardly avoidable from a technical point of view, but another part is accepted for economic reasons (see also Chapter 6). This chapter briefly addresses the authorized routine discharges from the following processes:
• uranium mining
• upstream processes (front end)
• reactor operating
• downstream processes (back end).

**Unauthorized discharges**

Besides the above mentioned routine discharges of radioactivity from the nuclear process chain inadvertent releases occur. Apart from the accidental spills from any nuclear facility, which are in fact unavoidable, there are releases from little known and practically 'invisible' sources. Some of these uncontrolled and unauthorized discharges occur occasionally, other frequently. Here we briefly address:
• depleted uranium
• discarded nuclear-related components and materials (orphan sources)
• decommissioning and dismantling of nuclear facilities.

**Severe accidents**

In addition to the routine and unauthorized discharges large-scale accidents are possible, involving spread of massive amounts of radioactivity over vast (inhabited) areas. Potential sources of Chernobyl-like accidents are:
• reactor
• interim storage of spent fuel
• reprocessing plants

A separate threat is posed by terrorism involving nuclear explosives made from commercial MOX fuel (uranium-plutonium fuel).

**Risk-enhancing factors**

Accidental and inadvertent releases of radioactivity into the environment, including large-scale accidents, can be brought about by different mechanisms, such as:
- ageing, wear, corrosion
- accidents
- human factor
- illegal trade, criminality
- transport
- terrorism
- armed conflicts

Economic pressure must be deemed as a serious risk enhancing factor; this issue will be addressed in Chapter 6.

**Cumulation effects**

The amounts of radioactive substances routinely discharged in a given year into the environment may perhaps seem relatively insignificant, however, year over year the released radionuclides can regionally build up to significant concentrations in groundwater and soil. Moreover a number of long-lived radionuclides accumulate in the food chain to high concentrations, even in a medium at very low concentrations of radionuclides (e.g. seawater).
Cumulation of radionuclides into the food chain greatly amplifies the health risks of routine or accidental discharges of radionuclides. This mechanism is not addressed in detail in this study, to limit the scope.


## 4.2     Uranium mining

Uranium is a radioactive metal, which decays by alpha and gamma emission into other elements, called the decay products or 'daughters'. The decay products are also radioactive, most of which are potent alpha-emitters. The final decay product is stable lead. Consequently uranium bearing rock contains a number of radioactive elements. In the natural condition the radionuclides are confined in more or less insoluble minerals in the rock of the uranium ore deposit. Uranium ores are generally very old geologic formations, with ages of billions of years.

In spite of its old age uranium-bearing rock is anything but harmless, for the rock emits gamma radiation and the dust of it contains dangerous alpha emitters. One of the decay products is the radioactive noble gas radon-222 that escapes into the air. When groundwater enters an ore deposit, the radioactive minerals may slowly disintegrate and as a result the groundwater will be contaminated with radioactive species. By far the most uranium deposits of the world are located in sparsely inhabited and often arid areas, for example in Australia, Namibia, Kazakhstan and USA.

To obtain uranium it has be extracted from uranium ore by physical and chemical separation processes. At the uranium mine the ore is mined, then milled (ground to powder) and finally chemically treated to extract the uranium. The other radionuclides in the ore, the decay products of uranium, remain in the tailings (waste stream) of the extraction process. The mill

tailings have the appearance of a watery mud and consist of the ore powder, chemicals and large volumes of water. The radioactive mud is stored in large ponds (see for example Figure 17).

A part of the water from the mud will evaporate and the other part, including the dissolved radionuclides, drains into the ground. When the mill tailings go dry, the remaining fine powder will be easily spread by the wind. This situation occurs when one pond is filled up and a new one is taken into operation and after the mine has been mined out and is abandoned.

Satellite photo's show dust from the Sahara desert crossing the Atlantic Ocean under certain conditions. An indication how far dust, and so radioactive dust, can be transported by the wind.
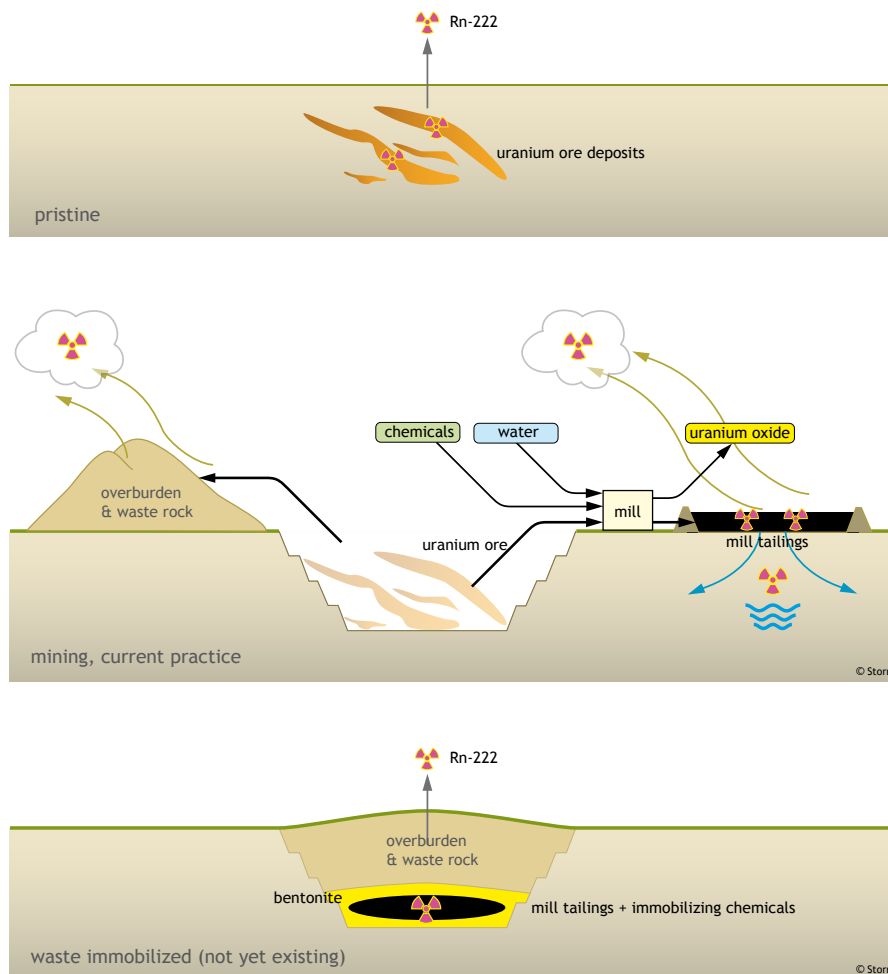


**Figure 16**

Outline of uranium mining, the first step of the nuclear process chain. The area directly disturbed by the mining operations of a large uranium mine may come to some 100 km$^2$. The indirectly disturbed area, by wind blown dust and contaminated groundwater, may run into hundreds of thousands of square kilometers. When the ore is exhausted, the dangerous mill tailings should be immobilized and the mine and its surrounding area should be restored to the original situation, a process called mine reclamation, see text.

Apart from the remaining uranium isotopes (U-238, U-235, U-234) in the mill tailings – the extraction yield or recovery always is less than 100% – the mill tailings contain the uranium decay daughters, see Table 1. Some uranium ores contain a significant fraction of Th-232 and its decay products. The activity of some nuclides in mill tailings are given in Table 1, taken from [37] and [38].

**Figure 17**

Satellite photo of the Ranger uranium mine in Australia, a medium-sized and one of the cheapest operating uranium mines in the world. The large green geometric pond on the lower left is the mill tailings pond. The light colored areas are the overburden and waste rock dumps. The active mining pit is the one at the upper right, partially flooded. The round dark object at the lower center is a former, mined out, pit which is fully flooded. The extraction plant (mill) is on the far right, barely discernable. Note the scale bar in the lower left corner. Source photo: Google Maps.

The dangerous decay products of the uranium isotopes are physically and chemically mobilized. The dust blown off the mill tailings contains highly radiotoxic elements, such as Ra-226, Pb-210 and Po-210. The lethal dose of polonium-210 is some 50 nanogram. Inhalation of the dust is a dangerous contamination pathway, for most of the radionuclides are potent alpha emitters. The decay products can also enter the body via drinking water, as the groundwater at large distances from the mining area may be contaminated with soluble compounds of the radionuclides, seeping from the mill tailings. By the way, the escaping radon-222, a noble gas, from uranium bearing rock offers one of the methods to localize uranium ore bodies.

All radionuclides present in the tailings pose a serious long term environmental risk [16], [39], [40], all the more so because the elements are chemically mobile after the milling process. The publication of Blanchard [41] deepens that worries. Health risks from uranium mining are also addressed by Diehl [38].

A recent study [42] found that uranium can also damage DNA as a heavy metal, independent of its radioactive properties. When cells are exposed to uranium, the uranium binds to DNA and the cells acquire mutations.

**Table 1**
Activity of the radionuclides of the U-238 decay series in mill tailings (in terabecquerel TBq), set free per GWe.a electricity production by LWR nuclear power plants. The second column is from INFCE-7 1980 [37]. The third column gives figures in Bq/g from Diehl 2006 [38], valid for ore at a grade of 0,1% U (about world average in 2010) and an extraction yield of 90%. In the fourth column the figures of Diehl are converted into TBq/GWe.a, to make them comparable with the figures of INFCE-7. Assuming the model reactor (see [1] PartB2) consumes 198 Mg (metric tonnes) natural uranium per GWe.a, the mass of the mill tailings is 220000 Mg/GWe.a.

| nuclide | activity TBq/GWe.a [33.] | activity Bq/g [34.] | activity TBq/GWe.a [34.] + [1] | decay mode |
|---------|--------------------------|---------------------|-------------------------------|------------|
| U-238   | 1.3  | 1.2  | 0.27 | alpha-emitter |
| Th-234  | -    | 1.2  | 0.27 | beta-emiiter |
| Pa-234m | -    | 1.2  | 0.27 | beta-emiiter |
| U-234   | 1.3  | 1.2  | 0.27 | alpha-emitter |
| Th-230  | 25.2 | 12.3 | 2.7  | alpha-emitter |
| Ra-226  | 26.6 | 12.3 | 2.7  | alpha-emitter |
| Rn-222  | -    | 12.3 | 2.7  | alpha-emitter |
| Po-218  | -    | 12.3 | 2.7  | alpha-emitter |
| Pb-214  | -    | 12.3 | 2.7  | beta-emiiter |
| Bi-214  | -    | 12.3 | 2.7  | beta-emiiter |
| Po-214  | -    | 12.3 | 2.7  | alpha-emitter |
| Pb-210  | 26.6 | 12.3 | 2.7  | beta-emiiter |
| Bi-210  | -    | 12.3 | 2.7  | beta-emiiter |
| Po-210  | -    | 12.3 | 2.7  | alpha-emitter |

INFCE-7 [37] does not specify the ore, extraction yield and natural uranium consumption per GWe.a the table is based on. It is not clear why the activities of other radionuclides are not given by INFCE-7, neither why their figures are higher than those of Diehl [38] by a factor ten.

Strikingly the dangers from uranium mining get little attention in the media. One reason may be the fact that by far the most uranium mines are located in sparsely inhabitated areas, most of which have an arid climate. So it can happen that people in Sydney and Melbourne in Australia inhalate radioactive dust from the Olympic Dam mine, the largest uranium mine in the world. Mine reclamation (see next para) is never included in the cost pictures of nuclear energy, nor in the published energy balances of the nuclear chain, except in [1]. The authors of an Australian [43] considered mine reclamation, although a hot item in Australia, to be outside the scope of their study.

**Mine reclamation**

Mine reclamation comprises the actions needed to restore the mining area to a habitable one again. The chemically mobile radionuclides in the mill tailings should be immobilized again and put back in the mining pit, as deep as possible. To prevent remobilization by groundwater flows, the mill tailings must be shielded from the groundwater by an effective barrier.

The authors of [1] proposed the following concept to limit the health effects of uranium mining. The mill tailings are mixed with immobilizing chemicals, for example sodiumphosphate, for most phosphates are highly insoluble in water, and the resulting mass is put back into the mining pit between thick layers of bentonite (see also Figure 16). Bentonite is a clay mineral with special properties: it swells by the uptake of water, effectively closing fissures and microchannels, and has strong ion-exchange properties, resulting in a very low migration rate of nuclides other than hydrogen ions and some alkali metal ions.

In view of the exceedingly large masses of the mill tailings (often tens of millions of tonnes at each uranium mine), above concept seems reasonable. As said before, it is a hypothetical concept, for it has never been tried in practice. To our knowledge no other study ever included a concept of mine reclamation.

Nowhere in the world, as far as known, the impact on the environment by uranium mining has been compensated for in a way that can be considered ecologically adequate and safe to the local inhabitants. Uranium mining companies leave the mill tailings unshielded in the mining area. After the last kilogram of uranium has been removed from the site, the lights are turned off and the gate is closed.

## 4.3 Routine releases of the nuclear chain

**Front end**

The front end of the nuclear chain, sometimes also called the upstream processes, comprise:
* uranium mining and milling (addressed in the previous section)
* conversion of the mine product ('yellow cake') into very pure uranium hexafluoride $UF_6$
* enrichment
* fuel element fabrication

For more details see also [1] Parts B5 and E1.

Little data are available on the operational releases of the front end of the nuclear chain, Table 2 is based on data from [40]. As the processes have little changed during the past decades, the data from [44] may give a fairly good impression. Even less data are available on the health risks of the operational releases.

Locally the health effects of the releases of the front end processes may be more significant then Table 2 might suggest, as there are only a few facilities in the world, each of them processing the nuclear fuel for dozens nuclear power stations a year.

**Table 2**
Activity of the radionuclides in the effluents of the front end of the nuclear chain, in GBq/GWe.year. Source: [44]. Very little data on his subject have been published.

| process | gaseous effluents | liquid effluents | remarks |
|---|---|---|---|
| conversion | 2.3 | 11 | sum U, Th-230, Ra-226 |
| enrichment | 1.1 | 0.074 | U |
| depleted uranium | | | 2.08 TBq/GWe.a, 0.2% U-235 |
| fuel element fabrication | 0.7 | 0.007 | U |
| sum | 4.1 | 11.81 | |

Health risks posed by depleted uranium, the waste of the enrichment process, will be addressed separately in section 4.4.

**Reactors**

IDuring the fission process in the nuclear reactor tens of different kinds of radionuclides come into being in the fuel, in the coolant and in the construction materials. Operating reactors release in the liquid and gaseous effluents some fission products and activation products, such as tritium, carbon-14, noble gases (mainly krypton-85) and iodine-129 [16]. The fission products originate from leaking fuel pins and uranium contamination on the outside of the pins. The activation products are produced by neutron reactions on light elements in the cooling water and on corrosion products.

Data on operational discharges of nuclear power plants are scarce and incomplete; very little direct measurements have been published. In Table 3 some discharges of radionuclides (gaseous plus liquid effluents) are listed.

**Table 3**

Approximate discharge limits of radionuclides in the liquid effluents into rivers and sea of one LWR nuclear power plant in Europe in 2000. Source: OSPAR 2002 [45].

| radionuclide | discharge limits TBq/yr | remarks |
|---|---|---|
| tritium H-3 | 20 - 70 | |
| other nuclides | 0.02 - 0.4 | not specified |
| gross alpha | 0.0002 | only given for Borssele  (NL) |
| gross beta, excl tritium | n.a. | not published for LWR |

Some small quantities of $^{129}$I are undoubtedly present in gaseous and liquid effluents from power reactors, but it measurement is difficult because of high concentrations of other fission and activation products [46].

Few if any data have been published on the concentrations of fission products and activation products in the effluents. A certain fraction of each nuclide in the fuel escapes, dependent on the properties of the nuclide. The ratio of the cerium-144 release rate in liquid effluent to the generation rate in the reactor core  has been estimated to be $4\times10^{-10}$, among the lowest values for any fission product measured. This is due to the low volatility of cerium compounds and their low solubility in aqueous solvents near neutral pH [47].

As about 17 MCi/GW(e).a $^{144}$Ce is generated in an LWR, above ratio implies a discharge in the liquid effluent of an average LWR of 0.000252 TBq/GW(e).a. Likely the activities of other radionuclides in the liquid effluent will be higher.

Large amounts of carbon-14 are generated in nuclear reactors, due to neutron-induced reactions of oxygen (in $UO_2$ and $H_2O$) and nitrogen and carbon which may be present as components of coolant, moderator, structural materials, fuel, or as impurities.

It is assumed that most $^{14}$C in cooling water is released at the reactor site and is discharged in the gaseous effluent, less than 1% in the liquid effluent. Very few results of measurements of carbon-14 emissions are published [48]. In [45] not a single measurement of C-14 emission is listed. In [31] one German publication from 1982 is mentioned, which reported an annual

release of 0.21 TBq/GW(e).a for PWRs and 0.50 TBq/GW(e).a for BWRs. The experimental data from which the estimates are made are limited.

If the fuel is reprocessed, the $^{14}$C in the fuel will be emitted as $^{14}CO_2$ at the reprocessing plant. Some of the radionuclides generated during the fission process can hardly be confined within the system of the reactor and associated components and will escape into the environment, particularly tritium, carbon-14 and krypton-85.

**Table 4**

Discharges of some radionuclides in the effluents of PWR nuclear power plants in TBq/GWe.a. Sources: NEA 1980 [48], Pigford et al. 1973 [44] and various NCRP reports. n.m. = not mentioned

| radionuclide | NEA | Pigford 1973 | NCRP | remarks |
|---|---|---|---|---|
| H-3 | 37 | 18.5 | 31 | NCRP-62 1995 [25] |
| C-14 | 0.3 - 0.4 | n.m. | 0.37 - 0.52 | NCRP-81 1993 [31] |
| Kr-85 | 10 | – | < 110 | NCRP-44 1975 [33] |
| Kr + Xe | – | 259 | – | |
| I-131 | n.m. | 0.030 | – | |
| I-129 | n.m. | n.m. | 0.000018 ? | NCRP-75 1983 [46] * |
| other nuclides | n.m. | 0.185 | – | |

\*     Assumed 0.1% of fission products escape from leaking fuel pins
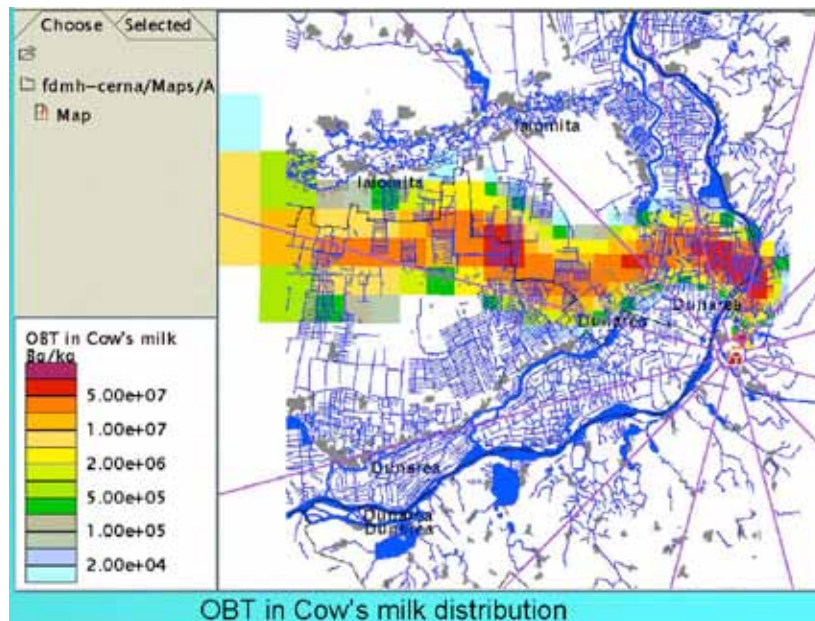


**Figure 18**

The spread of organic bound tritium (OBT) in cow's milk as result of tritium discharges from a nuclear power plant. This map comes from a Rumanian study and is one of the few published results of tritium measurements in the vicinity of a nuclear power plant. Source: RODOS 2007 [49].

Tritium generated in the nuclear fuel diffuses slowly through the zirconium cladding of the fuel and comes into the water cooling the fuel elements. In addition tritium is also generated directly in the primary cooling water by neutron capture reactions. Tritium diffuses much easier through steel and so ends up the secondary cooling water, which is released into the environment, as titriated water (symbols: HTO or $^3$HOH). Carbon-14 is generated also in the primary coolant and

is released into the air as radioactive carbon dioxide $^{14}CO_2$ or alkanes, mainly methane $^{14}CH_4$. The biomedical effects of tritium, carbon-14 and krypton-85 have been discussed in section 3.3. Figures 18 and 19 represent the results of two studies of the routine spread of tritium from nominally operating nuclear power plants.
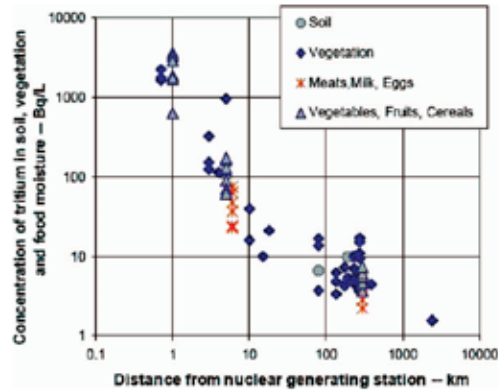


Figure 2. $^3$H concentrations in vegetation and food moisture near NPPs. Source: Reproduced with permission from the Canadian Nuclear Safety Commission from *Tritium in the Canadian Environment: Levels and Health Effects*. Report RSP-0153-1. Prepared for the Canadian Nuclear Safety Commission under CNSC contract no. 87055-01-0184 by Ranasara Consultants and Dr Richard Osborne. Data from Health Canada (2001) Environmental Radioactivity in Canada. Radiological Monitoring Report, Ottawa, Government of Canada.

**Figure 19**

The concentration of tritium in vegetation and food moisture in relationship to the distance from a nuclear power station. These data come from a Canadion study and refer to CANDU reactors. CANDU reactors are moderated by heavy water and release considerable more tritium per unit electricity than light-water reactors, so the values on the vertical axis would be lower from LWRs. Source: Fairlie 2007 [27].

Examples of undetected spillages of radioactive material are the large and prolonged undetected tritium leaks at the Vermont Yankee and 12 other nuclear power plants in the USA [50].

**Interim storage of spent fuel**

After removal from the reactor spent fuel elements have to be stored in water-filled cooling ponds for a long period, this is called interim storage. Due to the radioactive decay of the fission products and actinides the spent fuel generates so much heat, that fuel elements will melt within a short time if not effectively cooled. After some 30 years interim storage in cooling ponds the heat production has decayed sufficiently to handle the fuel elements for further processing.
Interim storage may become a source of inadvertent emission of radioactivity. During the storage 80-90% of the tritium in the fuel will diffuse from the fuel and released into the environment. Other nuclides are released into the cooling water from leaking fuel pins. The number of leaks will rise over time, due to ageing, corrosion and deterioration of the materials.

Operation and maintenance of the interim storage facilities are expensive. The water in the pools has to be actively cooled and decontaminated during een period of at least 30 years. The spent fuel of the new generation of reactors, such as the EPR, has to be cooled for a period of at least 60 years. The basins deteriorate and may go leaking, as happened at several occasions in the past, and have to be replaced. These activities do not generate financial profits for the company which operated the nuclear power plant during its productive life. Does that company still exist 30-60 years after closedown of the plant? We'll return to this issue in Chapter 6.

**Reprocessing plants**

Reprocessing plants discharge large quantities of radioactive materials into the environment, as pointed out in section 2.6. All gaseous fission and activation products from the processed spent fuel are routinely released into the atmosphere: radioactive noble gases krypton and xenon, tritium, carbon-14 and iodine $^{129}$I and $^{131}$I. Substantial amounts of chemically mobile radionuclides, which do not easily form stable and/or insoluble compounds are discharged into the sea via the waste water streams, notably $^{90}$Sr, $^{99}$Tc, $^{106}$Ru and $^{137}$Cs. As separation processes never go to completion, significant amounts of actinides are released, in addition to the discharged soluble or gaseous fission products. The release standards of permitted are dimensioned in such way that the reprocessing plants are permitted to discharge into the environment all radionuclides which are difficult to retain.

**Table 5**
Discharge limits of radionuclides the effluents from reprocessing plants to the sea in 2000. Source: OSPAR 2002 [45]. These figures prove the incompleteness of the separation processes. n.a. = not available

| radionuclide | discharge limits La Hague TBq/yr | discharge limits Sellafield TBq/yr |
|---|---|---|
| tritium H-3 | 37000 | 25000 |
| total alpha | 17 | 1 |
| total beta | 1700 | 400 |
| plutonium | n.a. | 0.70 |
| uranium | n.a. | 2000 kg/yr |

**Table 6**
Discharge limits of radionuclides of the reprocessing plant at La Hague. Source: Malherbe 1991 [51]. n.a. = not available

| radionuclide | gaseous effluents TBq/yr | liquid effluents TBq/yr |
|---|---|---|
| tritium H-3 | 2200 | 37000 |
| Kr | 480000 | - |
| halogens | 0.11 | n.a. |
| aerosols | 0.074 | - |
| total alpha | n.a. | 1.7 |
| total beta | n.a. | 1700 |
| of which Cs-137 + Sr-90 | | 220 |

On several locations in the Irish Sea (Sellafield, UK) and in the vicinity of La Hague (Normandy, France) seafood may be contaminated with radionuclides to such extent that consumption is not safe anymore.
Dilution of radioactive waste streams with uncontaminated water cannot be continued forever. Besides, a number of long-lived radionuclides tend to accumulate to high concentrations in the food chain, e.g. $^{14}$C, $^{129}$I, Pu, $^{90}$Sr, $^{137}$Cs.

In 2005 a large leak (83 m$^3$) of a liquor containing dissolved spent fuel at the THORP (THermal

Oxide Reprocessing Plant) reprocessing plant at Sellafield in the United Kingdom went undetected for more than eight months. The leaked solution contained some 19 Mg of uranium and 190 kg of plutonium and minor actinides. The fluids collected in a secondary containment. The fact that a shortfall in the amount of plutonium, enough for some 30 nuclear bombs, did not arouse concern for so many months, suggests that the theft of a significant amount of plutonium could also go undetected [52].

**Table 7**
Discharges of radionuclides in the liquid and gaseous effluents of a reprocessing plant in TBq/GWe.a. Sources: NEA 1980 [48.], Pigford et al. 1973 [44.] and various NCRP reports. n.m. = not mentioned

| radionuclide | NEA 1980 | Pigford 1973 | NCRP | remarks |
|---|---|---|---|---|
| H-3 | 630 | 885 | 555 - 925 | NCRP-62 1995 [25] |
| C-14 | 0.4 - 0.6 | n.m. | 0,74 | NCRP-81 1993 [31] |
| Kr-85 | 14000 | 13800 | 11000 | NCRP-44 1975 [33] |
| Ru-106 | - | 136 | - | |
| I-129 | 0.05 | 0.022 | 0.042 | NCRP-75 1983 [46] |
| other fission products | - | 0.340 | - | |
| transuranics | - | 0.185 | - | |

## 4.4   Other sources of radioactive contamination

**Depleted uranium**

In the enrichment process natural uranium, with a fissile U-235 content of 0.71%,  is separated into two fractions: a small mass fraction of enriched uranium, containing 2-5% U-235, and a larger mass fraction of depleted uranium, containing 0.2 - 0.3% U-235. For each kilogram of enriched uranium 6-7 kg depleted uranium (DU) are left. Depleted uranium is stored as uranium hexafluoride $UF_6$ – the chemical form needed in the enrichment process – in steel vessels lined up in sheds or in the open air. World-wide more than a million tonnes of depleted uranium are stored, an amount growing each year by some 50000 Mg.

During storage the radioactivity of depleted uranium steadily increases due to cumulation of radioactive decay products of U-238 and remaining U-235 [16]. Uranium hexafluoride is chemically a reactive compound, easily reacting with water and moist air. All uranium compounds are highly toxic: in addition to its chemical toxicity, comparable with lead, uranium is a dangerous alpha emitter. The element tends to cumulate in bones and kidneys.

Health risks posed by depleted uranium are threatening during peacetime when the uranium hexafluoride containers go leaking. This will happen sooner or later as result of the unavoidable deterioration of the containers, due to corrosion and other causes.

**Orphan sources**

Lost or uncontrolled sources ('orphan sources') are a major subject of concern to the metal recycling industry in terms of potential economic loss and to the general public in terms of public health impact.
Inadvertently melting radioactive scrap metal or devices containing sealed radioactive sources

are frequently found in construction and demolition debris, especially from industrial facilities; the frequency increases each year [53]. Gamma-emitting nuclides, such as $^{137}$Cs, $^{60}$Co and $^{241}$Am are those most commonly detected. The nuclides are detected in the off-gas, slag and/ or furnace dust of steel mills. Inadvertent meltings have also occurred at mills naking metal products from recycled aluminium, carbon, copper, nickel, lead, zinc and gold. Sometimes sources containing nuclides such as $^{3}$H, $^{90}$Sr or $^{85}$Kr are found by spotting warning labels or signs on scrapped equipment.

International trade in recycled metals and finished products made from recycled metals is complicating the controllability of radioactive scrap metals. Not all countries are equally meticulous in their regulations and control.

Volatile beta-emiters, such as $^{3}$H and $^{14}$C, may escape detection and be discharged from the mills into the environment undetected. What is known about other hardly detectable radionuclides?

**Cleanup, decommissioning and dismantling of nuclear plants**

Each nuclear power plant has to be decommisioned and dismantled after closedown. The main part of the buildings and equipment (e.g. turbines and generators) are not radioactive, if the plant has operated nominally during its technical life. The reactor vessel and associated equipment, piping, pumps, etcetera, have become highly radioactive as a result of neutron radiation and contamination with radioactive materials (CRUD: corrosion residuals and unidentified deposits). Restoration of the site of a given nuclear power plant to habitable greenfield conditions again requires a sequence of very costly activities over a period of a 100 years or even more.

The activities related to the decommissioning and dismantling of a nuclear power plant can be divided into four stages, known under different names in the literature:
• plant cleanout, decontamination or decommissioning
• safe-guarded cooling period, safe enclosure or 'safestor'
• dismantling, demolition of the structures
• site clearance, including packing of the debris and scrap, followed by removal and definitive storage of the containers in a repository.
More details on cleanup, decommissioning and dismantling of nuclear plants can be found in Part F6 of [1].

Other nuclear facilities are also to be dismantled at a given time. Due to ageing, cracking, wear, corrosion and other deteriorating mechanisms any facility processing radioactive material will become increasingly contaminated with radioactive material. When the radiation doses for the personel become irresponsible or when the safety is at issue as a result of unreliable equipment, a nuclear plant has to be closed down.

The radioactive inventory of the reactor with connected systems and shielding materials increases with operational lifetime of the reactor, by activation reactions, depending on the neutron flux. Based on model computations the radioactive inventory of a light-water reactor (LWR) after 20 full-power years is estimated at some 0.1 - 0.6 EBq (exabecquerel, 1 EBq = $10^{18}$ desintegrations per second), one year after final shutdown, excluding spent fuel and control rods.

The radioactive inventory also rises during the operational years by progressive contamination of the system, despite of chemical and mechanical decontaminating activities during operation of the reactor.

Not just the radioactivity in Bq, but also the kind of the radionuclides contaminating the system has consequences for the way of demolition and handling the wastes. With longer operating times, the chances on contamination with fission products and actinides increase.

Contamination is extensive in a reprocessing plant. Dismantling of the huge buildings will generate large volumes of heavily contaminated wastes. Costs will be high, because large parts of the construction are contaminated with dangerous long-living radio-nuclides and alpha wastes. Experiences with dismantling the West Valley reprocessing plant (which operated during the period 1966-1972) and some minor DOE plants, are not encouraging.

Dismantling of a reprocessing plant will be an exceedingly demanding task. Reprocessing plants are among the largest industrial complexes in the world. The hot areas, the compartments in which radioactive materials are processed, are strongly contaminated with radionuclides representing almost the entire Periodic Table of the Elements, including the transuranic actinides. The volume and mass of the radioactive debris and scrap resulting from the dismantling of a reprocessing plant will be a multiple of those from a nuclear power plant.

The radioactive strucures of the nuclear power plants and reprocessing plants have to be cut in small pieces, packed in steel or concrete containers and definitively stored in a safe geologic repository. How much dust and leaked liquids containing radionuclides will be dispersed into the environment? Who controls which piece is not radioactive and which one is?
The demolition debris contain large amounts of many different long-lived radionuclides and not all radionuclides are easily detectable. As pointed out before, there is no relationship between the biomedical activity of a radionuclide and its detectability by common radiation counters. As yet little actual measurements, if any, of the radioactive content of dismantling debris have been published.
The health risks of decommissioning and dismantling may seem remote, for they are not very visible at this moment. No commercial nuclear power plant nor any reprocessing plant has completed the dismantling sequence. The large volumes of waste and the long lead times

Box 3

**Radionuclides in dismantling scrap and debris of a nuclear power plant**

Activation products present in the structures to be dismantled are, among others:
in steels and equipment parts:
$^3$H, $^{14}$C, $^{54}$Mn, $^{55}$Fe, $^{57}$Co, $^{60}$Co, $^{59}$Ni, $^{63}$Ni, $^{65}$Zn, $^{94}$Nb and $^{108m}$Ag
see: [53], [31], [54]
and in concrete [55]:
$^3$H, $^{14}$C, $^{36}$Cl, $^{41}$Ca, $^{152}$Eu and $^{154}$Eu

For short-living nuclides, an equilibrium between activation and decay will be reached after 10-20 full power years. According to the study of Watzel et al. 1978 [56], equilibrium will be reached in about 20 years. In their study only $^{55}$Fe and $^{60}$Co are taken into account, as in most other studies. For long-living radionuclides, no equilibrium will be reached and the radioactive inventory of the reactor will grow with the operating life of the reactor.
The inventory of activation products increases with the neutron flux [57].

The radioactive inventory caused by fission products from leaking and contaminated fuel pins and by activated corrosion products, CRUD (Corrosion Residuals & Unidentified Deposits), will be a function of the full power operating time. The contamination of the cooling system reaches saturation after about 5-6 years operation of the reactor [56]. Broadly, this supposition has to be empirically confirmed. The inventory of contamination products a large PWR or BWR at equilibrium may be in the order of 1-5 PBq.

Some fission products to be expected in the scrap metal and dismantling debris are:
$^{90}$Sr, $^{99}$Tc, $^{110m}$Ag, $^{129}$I, $^{134}$Cs, $^{137}$Cs, $^{144}$Ce.
Small amounts (less than 1% of total activity) of transuranic nuclides are present, e.g.
$^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Am, $^{243}$Am, and $^{244}$Cm,
and these may dominate the hazard if an inhalation or ingestion pathway is significant [53].

involved greatly enhance the chances of inadvertent releases of considerable amounts of radioactive materials into the environment.

## 4.5      Extent of large-scale accidents
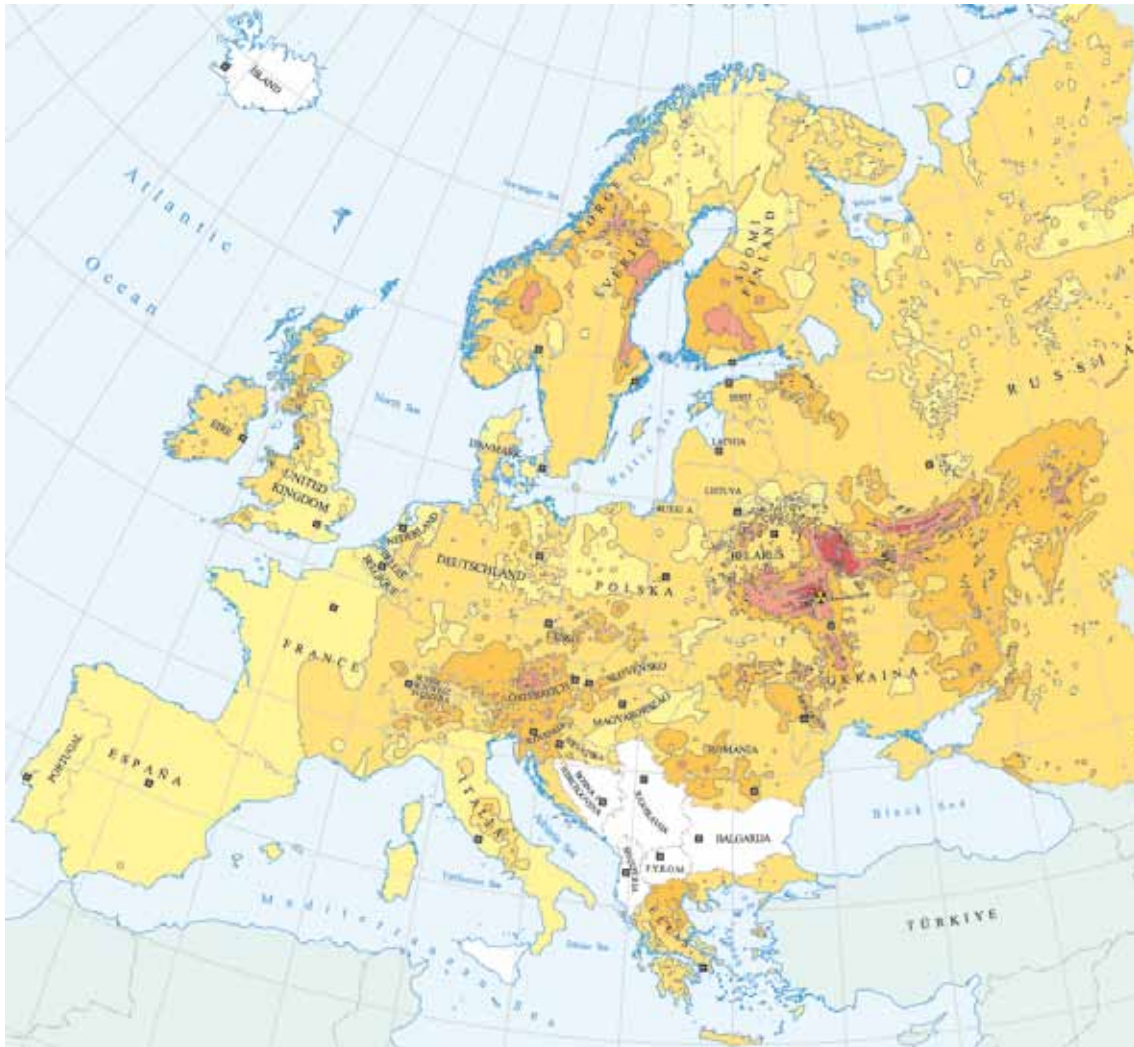


**Figure 20**
The spread of caesium-137 (Cs-137), a fission product, after the Chernobyl disaster in 1986. The darkest colored areas have become in fact inhabitable due to radioactive contamination. In the blanc areas insufficient data were available. The lightest colored areas did not get an appreciable radioactive deposition. Source: UNSCEAR [58].

Accidents with radioactive materials in the downstream part of the nuclear fuel chain, particularly spent fuel and reprocessing waste, may have far-reaching consequences, because of the immense quantities of radioactivity present in these materials. As pointed out before, one reactor of 1 GWe generates each year a 1000 nuclear bomb equivalents of radioactivity. The temperary storage facilities of the highly radioactive waste deteriorate over time and are vulnerable to accidents and terrorism. A geologic repository still does not exist.

Substantial fractions of the cumulated nuclear bomb equivalents – often tens of thousands at a temporary storage facility – may get released into the environment, if something goes wrong. Severe accidents in which thousands of nuclear bomb equivalents may be released into the

biosphere are not completely stochastic events, for they are becoming increasingly predictable if no massive and adequate actions are taken to prevent them. We only do not know where and when exactly.
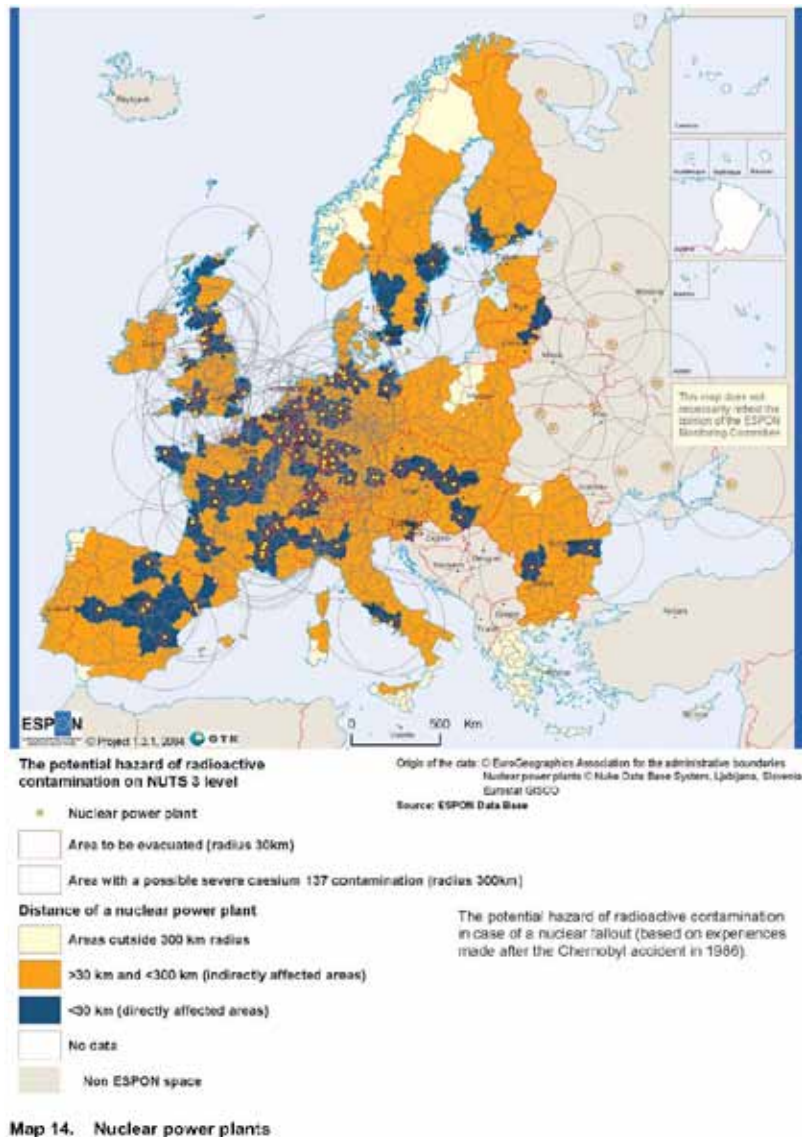


Map 14.   Nuclear power plants

**Figure 21**

Chart with the nuclear power plants of Europe. The darkest colored areas are within 30 km of an NPP and are the areas to be evacuated in case of an accident releasing nuclear fuel. The risks posed by accidents involving the interim storage of spent fuel might be greater than reactor accidents. Most interim storage facilities are located at the reactor site. Source: ESPON [59].

The consequences of a severe accident would be devastating. Figure 20 shows the spread of cesium-137, an easily detectable fission product, after the xplosion of Chernobyl. Apparently it is assumed that the spread of the other radionuclides from the exploded reactor would follow the same pattern as $^{137}$Cs. This assumption  may be invalid for reason of the widely different physical and chemical properties of the radionuclides from the reactor. Important to note is that not all radionuclides are easily detectable, including some of the dangerous actinides. Therefore it may be very well possible that the spreads of hardly detectable, but nevertheless dangerous, radionuclides would exhibit patterns quite different from $^{137}$Cs.

The spatial extent of the Chernobyl disaster is illustrated by Figure 20. The human suffering and economic damage can only be guessed from that chart. The IAEA and the WHO (see also section 5.3) insist that only 32 people died from radiation exposure at Chernobyl. Likely the IAEA counted only those persons who died immediately after the explosion, due to direct exposure to radiation from the wrecked reactor. Victims caused by ingestion and inhalation of radionuclides afterwards were not counted. The IAEA is anything but an independent organisation, for its mission statement is promoting civilian nuclear power (see also section 5.3).

Obviously the consequences of a Chernobyl-like explosion in the densely inhabited parts of Western Europe would be disastrous. Imagine a situation in which the fallout from Chernobyl represented by the darkest colored parts of the chart in Figure 20 would be deposited a 2000 kilometers more to the West. A major accident in a light-water reactorcan lead to radioactive releases equivalent to several times the release at Chernobyl and about 1000 times that released by a fission weapon. Relocation of the population can become necessary for large areas (up to 100 000 km$^2$). The number of cancer deaths could exceed 1 million [60].

According to the local authorities of Russia, Belarus and the Ukraine the Chernobyl death toll amounts to hundreds of thousands of people in each of these three countries, not counting the innumerable sick people, childern with serious congenital physical defects and miscarriages. One may ask with respect to the Chernobyl death toll: who is more trustworthy? An organisation with vested interests in nuclear power, dominated by countries outside of the contaminated area, or the local authorities who have to deal with the affected people?

A major study [61], based on 5000 scientific papers published in Russian, mentiones a death toll of the Chernobyl disaster worldwide of 985000 people. Some 400 million people have been affected by the Chernobyl fallout. The IAEA bases its estimate on 300 exclusively Western papers.

## 4.6    Conceivable sources of large-scale accidents

**Reactor**

Serious accidents with nuclear power plants are very well possible, despite of reassuring statements of the nuclear industry. The probabilistic safety studies of the nuclear industry do not cover all events which could cause a severe reactor accident, as will be discussed in section 5.1. Such an accident could involve a meltdown of the core and a violent explosion, which would sever the reactor vessel and the containment building. Consequently the barriers between the radioactive content of the reactor and the environment would be disrupted, resulting in a Chernobyl-like disaster.

In the commercial nuclear technology no 'pre-flight' testing occurs, as pointed out in section 2.4. A nuclear power plant is assembled and tested at the location chosen by the utility. Design flaws and manufacturing defects are uncovered during construction and the first several years of operation of the nuclear power plant, a period called the burn-in phase. Major failures in the past, including TMI-2 and Chernobyl, occurred with reactors still in their burn-in phase.

New reactor designs incorporate features to make the plants safer and more economical. As Lochbaum [8] put it:

'These features, however, are largely untested in the field or have very limited operating experience. Other new reactor designs have operated only in cyberspace and have never experienced the trials

and tribulations of real-world operation. The gremlins hiding in their designs have not yet been exposed, let alone exorcised.'

Leaked papers from the Electricité de France (EdF) report serious safety problems, which could cause a Chernobyl-like accident, with the French reactors, including the flagship EPR [62].

A comprehensive study [60] concluded:
• All operational reactors have serious inherent safety flaws which cannot be eliminated by safety upgrading.
• Many countries are planning to extend the lifetime of their reactors beyond the original design lifetime. This leads to degradation of critical components and the increase of severe accidents. The age-related degradation mechanisms are not well understood and difficult to predict.
• Utilities are upgrading their reactors by increasing reactor pressure and operational temperature and the burn-up of the fuel. This accelerates ageing and decreases safety margins. Nuclear regulators are not always able to fully cope with this new regime.
• Reactors cannot be sufficiently protected against terrorist threat. There are several scenario's – aside from a crash of an airliner on the reactor building – which could lead to a major accident.
• Climate change impacts, such as flooding, sea level rises and extreme droughts, seriously increase nuclear risks.

The US Nuclear Regulatory Commission (NRC) recently revised its licensing process to virtually eliminate public participation [63]. In the UK and in France similar regulations seem to exist. How is the situaton in other countries? The lack of public input could drastically curtail discovery of important areas of safety improvements.

Inherently safe nuclear power is inherently impossible, as has been explained in section 2.4.

**Spent fuel storage**

Section 4.3 briefly discussed the interim storage of spent fuel after removal from the reactor. If the cooling of a storage basin fails beyond a critical period, the pond can boil dry and the spent fuel elements will melt. At high temperatures the zirconium cladding starts reacting with the remaining water, generating large volumes of hydrogen. In addition the zirconium is highly flammable at elevated temperatures. A powerful explosion seems unescapable. The same scenario will roll out when a cooling pond is drained by whatever cause. The fuel elements will heat up and the zirconium cladding will ignite, causing the fuel to melt.

The explosion may result in the dispersion of huge amounts of radioactive fission products and actinides over vast areas. As the radioactive inventory of a cooling pond may be 20 times as high as the inventory of a reactor core, the consequences of a cooling pond explosion may turn out considerably worse than the Chernobyl disaster.

A major American study of MIT [64] sees no problems in the USA with the temporary storage of spent fuel during the next decades or even a century:
    'Scientifically sound methods exist to manage spent nuclear fuel.'

reactor containment

cooling pond spent fuel
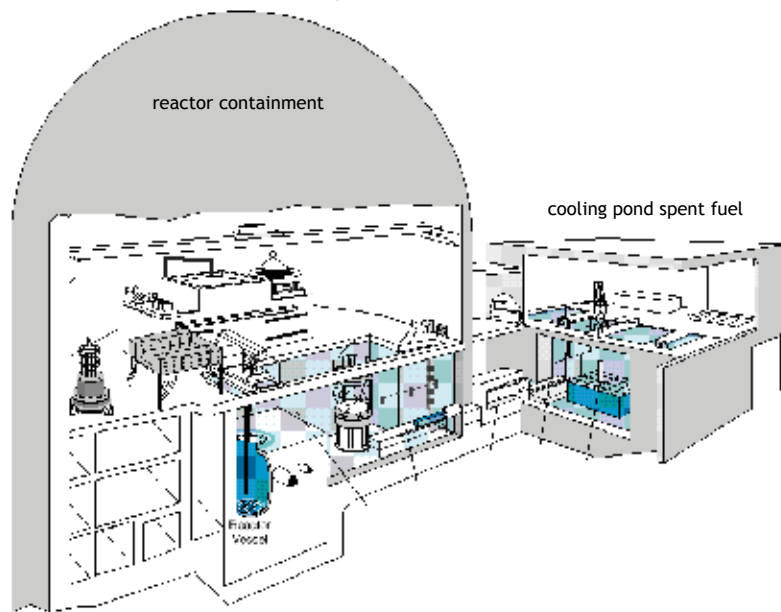
Reactor
Vessel

**Figure 22**

Cross-section of a modern PWR nuclear power plant (Sizewell B in Great Brittain). For reloading the reactor with fresh fuel, the head of the reactor vessel is removed, shielded by many meters of water. The spent fuel elements are hoisted out of the reactor core and transported by robotic equipment to the spent fuel storage basin outside of the reactor containment building. Then the fresh fuel elements are placed into the reactor core, the head of the vessel is replaced and the reactor is restarted.
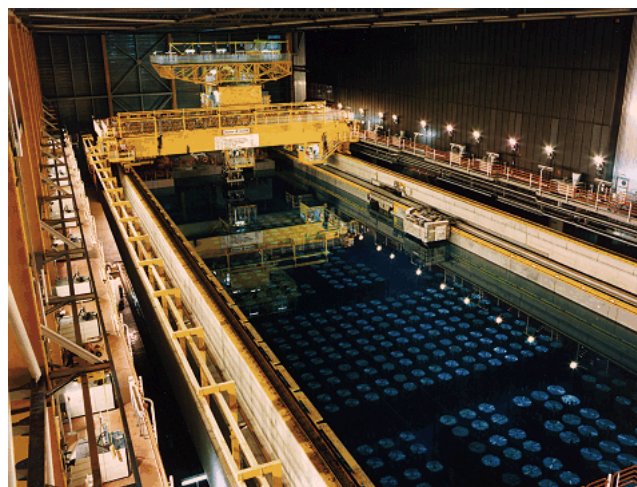


**Figure 23**

Storage basin for spent fuel in the British reprocessing plant THORP at Sellafield. The basin is filled with demineralised water, which has to be cooled and purified continuously. The spent fuel elements give off a blue glare caused by the interaction of the nuclear radiation with water (Cherenkov effect). The cooling ponds of nuclear power plants have a similar construction, but are smaller. Photo WNA.

**Reprocessing waste**

A special category of nuclear installations are the reprocessing plants, in Europe at La Hague (France) and Sellafield (UK). As pointed out in section 2.5, reprocessing of spent fuel is the reverse of immobilization: the radioactivity from the spent fuel is spread over large volumes of solids and liquids and all geaseous radionuclides are released into the air. The liquid waste

streams contain significant amounts of radionuclides which are released into environment as well. Only a certain fraction of the radioactivity can be chemically immobilized in borosilicate glass. This is not to say the glass does not pose health risks anymore.

At a reprocessing plant large quantities of spent fuel are stored in the cooling basins, probably many tens of thousands nuclear bomb equivalents of radioactivity. This is necessary to let decay the radiation to a level at which chemical treatment is possible.
In addition vast amounts of radioactivity are stored in the large volumes of liquid and solid wastes originating from the separation processes. The storage tanks of these wastes have to be cooled and these too have the potential of Chernobyl-like disasters.

**Geologic repository**

The nuclear industry considers a deep geologic repository to be a safe method to dispose of the human-made radioactivity. A European industrial platform, IGD-TP [65] states:
> 'Our vision is that by 2025, the first geological disposal facilities for spent fuel, high-level waste. and other long-lived radioactive waste will be operating safely in Europe.'

And:
> 'These will not only be the first such facilities in Europe but also the first in the world.'

These statements strongly suggest that the European concepts for geological disposal are the farthest developed of the world. Despite the reassuring statements, the IGD-TP recognizes, in the most carefully-worded manner, the existence of some 'specific challenges' [66].

How safe are the proposed solutions to the radioactive waste problem, amounting to many millions of nuclear bomb equivalents? After dozens of years of studies and research there still remain a number of questions:
- How long will this isolation and physical immobilization last?
- How well are the geologic properties understood of the formation in which the repository will be excavated?
- To what extent will the choice of the location be on scientific grounds and to what extent will it be a political choice? A political choice may lead to a location less than optimal from a geologic and scientific point of view. The cancelled Yucca Mountain project in the USA (cost $10bn) is an example of a political choice, which proved to be incompatable with scientific observations.
- What are the risks during the period the waste is being placed into the repository and the facility is still open and accessible?

Water ingression and the formation of fast transport channels (fissures, porosity of barriers) are the principal enemmies of a stable isolation of radioactive waste in a repository. After the galleries and shafts of the repository have been filled up with bentonite, the migration of radionuclides from leaking canisters will be slow, provided that no unexpected water flows are present in the geologic formation and that the only transport mechanism of radionuclides is diffusion. Because of the exceedingly large amounts of long-lived dangerous radionuclides in the repository, the migration of the radionuclides to the human environment, for example via the accessible groundwater, has to be exceedingly slow.

According to a recent study [67] has the confident view of the European IGD-TP [65] a meagre scientific basis. The study indentified a number of phenomena that could compromise the containment barriers, such as:
- High likelihood of interpretative bias in the safety assessment process because of:
  - lack of validation of models (see also section 5.2)

- commercial interests (see also Chapter 6)
- pressure to implement existing roadmaps despite important gaps in knowledge
- lack of independent scrutiny of data and assumptions.

• Question of wether site selection and characterisation processes can actually identify a large enough volume of rock with sufficiently favourable characteristics to contain the expected volume of wastes. As pointed out in section 2.5, each year one deep repository comprising about 100 kilometers of tunnels has to be openened to dispose of the world production of spent fuel.

• Potential for significant releases of radioactivity through a variety of mechanisms, involving the release of radioactive gas and/or water due to the failure of the near-field and/or far-field barriers.

During the period of construction and operation, which probably will take tens of years, the repository is open to the surface. Other risks are posed by mishaps with the robotic equipment needed to place the containers with the highly radioactive materials into the galleries or caverns of the repository.

In addition to the geologic and technical uncertainties there is the human factor. How could we prevent future, ignorant generations from reopening an underground waste repository, or from drilling holes into it from the surface for whatever reason?

In view of the many uncertainties and unknowns, the cost of a deep geological repository likely will escalate beyond the first estimates. This poses the risk that less effective but cheaper solutions will be declared safe enough.

## 4.7 Terrorism and MOX

Increasing amounts of mobile radioactive materials also increase the chances of malicious spread of radioactivity into the environment. Matter of concern are, among other:
• MOX fuel
• dirty bomb
• attacks on nuclear power plants and vulnerable facilities with large radioactive inventories, such as spent fuel storage facilities and reprocessing plants [68].

MOX is the acronym of Mixed OXide fuel, nuclear fuel with plutonium instead of U-235. MOX fuel is relatively little radioactive and can be handled without specialized equipment. The fuel can be separated into uranium and plutonium using simple chemical techniques every chemistry student knows. The so-called reactor-grade plutonium from the MOX fuel can be used in a crude nuclear bomb, despite its less than optimal isotopic composition. Such a bomb might be not very reliable, and its explosive yield might be relatively low, but these drawbacks might be irrelevant to suicide terrorists planning an attack in the center of a large town [69], [70], [71]. This is the reason why so many scientists all over the world are strongly opposing reprocessing of spent fuel and the use of MOX fuel in civilian reactors.

A dirty bomb is understood to be a conventional explosive used to disperse an amount of any hazardous radioactive material.

## 4.8 Risk enhancing factors

The probability of unnoticed releases of radioactive materials, but also of severe accidents involving large amounts of radioactivity, increases with time, due to the ever increasing amounts of mobile radioactive material and the progressive ageing and deterioration of the temporary

storage facilities, as pointed out in section 2.4. This situation is worsened by a number of risk enhancing factors, some of which are briefly discussed in this section, such as:

• human factor
• illegal trade, smuggling and criminality
• transport
• terrorism (see previous section)
• armed conflicts
• economic arguments. We return to the issue of economic pressure in Chapter 6.

**Human factor**

Even if the engineered safety measures of nuclear power (see also section 2.4) work according the design criteria, which of course is not always the case, risks are introduced by the human factor. Routine tasks such as operation and maintenance are susceptible to errors, sloppiness, laziness, poorly educated personel and incompetention. Any company and organisation may have to deal with this kind of factors, but in the nuclear industry the safety margins are small and the consequences may be disproportionally large and irreversible.

Problem identification and resolution programs – how plant owners find and fix safety problems – are often flawed or even dysfunctional. Violation of the Technical Specifications, part of the operating license issued by the NRC to the owner of each power reactor in the USA, is another problem [8]. How is the situation in other countries?

Bad management, shortage of funds and qualified personel, shifting priorities, matters of prestige and cognitive dissonance will lead to less than optimal control and consequently to enhancement of risks. Financial interests may entice people to make choices based on a belief in unproved technology, in the economy of the marketplace or in security measures which may seem perfect only on paper or in cyberspace, while arguing away the contra-indications.

**Illegal trade, smuggling and criminality**

The nuclear industry uses large masses of expensive high-grade metals, alloys and other materials. After replacement of equipment or dismantling of nuclear facilities these materials may enter the market as used materials. Who controls the sorting of radioactive from non-radioactive scrap? Who safeguards the batches of high-value scrap which are not released for free use? Illegal trade, smuggling and criminality are already worrisome at this moment. Too often pulses of radioactivity are observed in the flue gases of metal smelters and recycling plants of special materials (see also section 4.4 orphan sources).

Radioactive scrap and metal components can be smuggled out of a port or country relatively easily [72]. Detectors, if present at all, have limited detection possibilities. Detection of many radionuclides in scrap metal or concrete rubble is very difficult if alpha emitters (uranium and transuranics) or low-energy beta-emitters (e.g. $^3$H and $^{14}$C) are involved; low-energy gamma emitters may escape detection as well [53]. The absence of easily detectable radionuclides, such as the $\gamma$-emitting radionuclides $^{137}$Cs and $^{60}$Co, in no way warrants the absence of other dangerous radionuclides. So, when scrap metal or rubble is cleared for unrestricted use after superficial screening with a radiation detector, how sure we are wether all nuclides present in the materials have been measured and accounted for? Or, are the clearance standards based on just a few easily detectable nuclides?
Besides, it is relatively easy to shield radiation sources in a container from detection by non-radioactive scrap. In addition the human factor may play a part. How reliable are the inspectors?

Up until 1993 large amounts of radioactive waste has been dumped at sea, including discarded ship reactors. A 1993 amendment to the London Dumping Convention halted the ocean disposal of all radioactive waste. From 1979 on ships loaded with wastes have been wrecked under questionable circumstances in the Mediterranean at an increasing rate, 20 of these wrecks are considered extremely suspicious with regard to radioactive waste. Serious engagement by magistrates and politicians to investigate the wrecks and their cargo has been lacking [73]. How is the situation elsewhere at the world's seas?

Surges in illegal trade of radioactive scrap metal may be expected in the future when large nuclear power plants are dismantled, for massive amounts of high-value metals at various levels of radioactivity are released during dismantling. Preliminary estimates of these amounts – empirical evidence is still not existent – amount to the following figures for one 1 GWe nuclear power plant (from [1] Part F6, Table F.22):
• 1600 Mg (metric tonnes) of high-grade steel, stainless steel and special alloys
• 10000 Mg steel
• 500 Mg non-ferrous metals
• 3000 Mg other materials
• 30000 Mg concrete rubble.
In addition some 5000 Mg decontamination waste is generated, which is highly radioactive and likely will have no commercial value.

## Transport

The various processes of the nuclear chain are at widely spaced locations, often on different continents. Nuclear power involves many transports over long distances, up to tens of thousands kilometers. For example Japanese spent nuclear fuel has been transported from Japan to Sellafield in the UK for reprocessing, and the recovered plutonium has been transported back to Japan. Every transport of nuclear material enhances the risk of dispersion of radioactive material into the biosphere.

## Armed conflicts

An armed conflict with convential weapons has the potential to cause severe nuclear accidents, if nuclear power plants or storage facilities are hit by bombs and/or penetrating projectiles, intentionally or by accident. Although storage facilities are safeguarded, all are vulnerable to wartime activities. Even nuclear power plants with heavy containment buildings are not able to withstand attacks with conventional weapons.

A forced shutdown of nuclear power plants of the adversary of a belligerent party may be an atractive option. Nuclear power plants are generally large units, 1000-1600 MW, and by cutting out one or more of these large units the energy supply of the adversary, and with it its economy, is dealt a heavy blow.

Armed conflicts may seem a remote possibility in Western Europe and in the USA, but how about other nuclear countries in the world? The consequences of a severe nuclear accident do not stop at our borders. Chernobyl proved how far-reaching those consequences can be.

# 5　Views of the nuclear industry

## 5.1　Safety studies of the nuclear industry

The first major study on reactor safety was the 'Rasmussen Report' of 1975 [74]. This report has been updated in 1990 [75] and is at present being updated in the State-of-the-Art Reactor Consequence Analyses (SOARCA) by the US Nuclear Regulatory Commission NRC. Up until today only LWRs (light-water reactors) in the USA have been analysed. Internationally the results of the US nuclear safety studies seem to be adopted as standards for other safety studies.
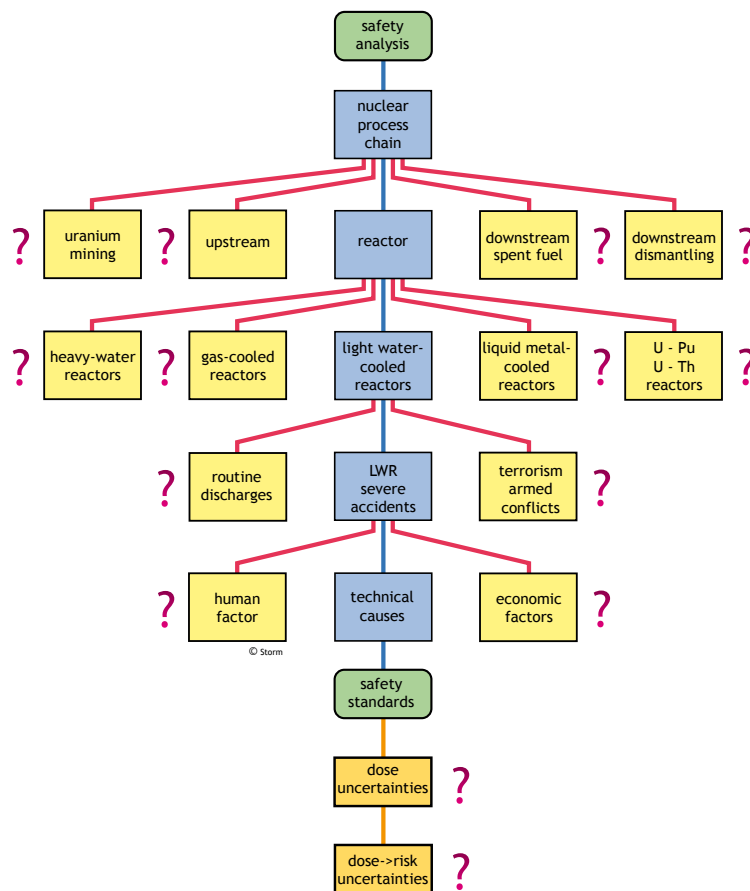
**Figure 24**
Decision tree of the analysis of the safety of nuclear power. Only a fraction of the processes comprising the worldwide nuclear energy system turns out to be examined in detail, for the safety analyses focus on nuclear reactors, in particular light-water reactors from Western vendors. The majority of the nuclear safety issues (see the queries in above diagram) may never have been investigated, at least not as thouroughly as the technical LWR safety issue.

The official safety studies are Probabilistic Risk Analyses (PRAs), which have a limited scope:
• 　the PRA methodology does not cover all kinds of events which can cause a severe reactor accident [68],
• 　ageing and other Second Law effects are difficult to include,
• 　unpredictable human behavior cannot be quantified.
What do we know about other reactor types (gas-cooled reactors, heavy water reactors, liquid metal-cooled reactors) and, equally important, about reactors from vendors in Russia, China,

India, Japan, Korea? The consequences of a severe nuclear reactor accident do not stop at our borders. Chernobyl proved how far-reaching those consequences can be.

In the USA the Nuclear Regulatory Commission (NRC) is found to be highly reliant on information from licensee risk assessments. There are no PRA standards, no requirements for licensee's PRAs to be updated or accurate, and that the quality of the assessments varies considerably among licensees [76].

Another limitation of the official safety studies is the fact that the other processes comprising the nuclear chain are marginally or not mentioned, see the queries in Figure 24. After unloading from the nuclear power plant the generated billion-x amounts of radioactivity are passed on to the downstream processes. How safe are these downstream processes?
The emphasis on the reactor safety may also be prompted by the high public visibility to the of nuclear power plants and by the accidents with Three Mile Island-2 in 1979 and Chernobyl in 1986. The other industrial processes of the nuclear chain are practically invisible to the public, but not less important with respect to health risks. The amounts of radioactivity present at a given location of one of the downstream processes may be a hundredfold of the inventory of an operating nuclear reactor.

The safety of nuclear power is a very complex issue comprising a lot more contributing factors than the chance of a severe nuclear accident in a nuclear reactor. Besides, that chance is not determined only by the technical safety standards of the reactor, for non-technical factors could initiate such accidents as well. These possibilities will be discussed in the following chapters.


## 5.2 Reliance on models

**Uncertainties in dose estimates**

In official publications the radiation doses to individuals near nuclear power stations are invariably very low, in the range of $10^{-3}$ to $10^{-4}$ mSv/year. These values are estimates and are not based on measurements. How these estimates are derived is not widely understood by scientists, and not at all by members of the public [36].
The methodology is very complicated as it based on at least four kinds of computer models in sequence:
• Models for the generation of fission and activation products in reactor cores. The emission data published by utilities are derived from these models.
• Environmental transport models for radionuclides, including weather models.
• Human metabolism models to estimate radionuclide uptake, retention and excretion.
• Dose models which estimate radiation doses from internally retained radionuclides.

Each model has its inherent limitations so the result of each model has an uncertainty range. The uncertainties of each model have to be treated together to gain an idea of the overall uncertainty in the final dose estimate. Further uncertainties are introduced by 'unconservative' radiation weighting factors, dose rate reduction factors, and tissue weighting factors in the official models [36]. The cumulative uncertainty in dose estimates could be very large as recognized by the report of the UK Goverment's CERRIE Committee [77].
In view of these uncertainties one should not dismiss radiation exposure as a possible cause of the observed results of the KiKK study on the ground of low official dose estimates without first carefully examining the dose estimates.

**Uncertainties in risk estimates**

Risk models are used to estimate the likely level of cancers. The risk models have their inherent imperfections and uncertainties as well as the dose estimate models. The current official risk models are mainly based on studies of the Japanese survivors of the nuclear bombs in 1945. How reliable are the official risk models? Uncertainties are introduced by a number of factors, such as:

• The Japanese bomb survivor study was started five years after the bomb blasts, so the deaths in the first five years were not counted.

• The risks estimated from a sudden puls of gamma rays and high-energy neutrons are not applicable to environmental releases which result in chronic, slow, internal exposures to often low-range beta radiation (e.g. T and C-14, see section 3.2).

• Application to adults only.

• Application of age and gender-averaged risks.

• Arbitrarely halving the risks to take account of cell studies suggesting lower risks from low doses and low dose rates.

For the discussion of these uncertainties see [77].

**Troublesome detection of radionuclides**

An impediment for sound health risks assessments is the fact that a number of dangerous radionuclides, e.g. tritium, carbon-14, iodine-129 and a number of alpha emitters, are hard to detect with commonly used radiation counters.

As a result of the difficult detectability, severe radioactive contamination with these radionuclides may escape notice during prolonged periods. Not every spill or release contains 'marker' nuclides which are easily detectable, such as $^{137}$Cs or $^{90}$Sr.

Examples of 'unnoticed' releases are the routine releases of nuclear power plants under nominal conditions. For that reason it would be advisable to check on regular occasions food and drinking water on the presence of those troublesome radionuclides, even if no direct threat seems apparent. Risk estimates based on models likely will not come up to the mark.

**Limited significance of models**

Any model in physics, economics or other field, inevitably has two kinds of limitations: inherent limitations and the specific limitations resulting from the choice of input data: constants, variables and other data.

*Inherent limitations*

A model is a simplified description of the reality, the practice, and is based on a number of axioms and assumptions. Models are widely used in science to describe specified phenomena in nature and to build a theory wich enables scientists to predict the occurrence of such phenomena under conditions different from the investigated ones. As a result of the simplification of the reality a model is only valid within specific system boundaries and has a limited application range. The wider the system boundaries of a model, the more complicated its structure. Bouchaud [78] put it as follows:

> 'If empirical observation is incompatible with a model, the model must be trashed or amended, even if it is conceptual beautiful or mathemathecally convenient.'

Two examples of scientific models used in chemistry may illustrate this statement. The simple model of atoms and molecules formulated by Dalton in the 19th century is able to describe

some basic chemical phenomena. To explain why water has the formula $H_2O$ and not $H_3O$ and to predict chemical compounds not yet found, one needs the greatly more complicated atom model of Bohr. However, not all chemical phenomena can be explained by the Bohr model.

*Specific limitations: the choice of input data*
The results of an investigation by means of a model are determined by the input data, such as physical constants, variables and properties of the entities of the model.
How reliable are the axioms the model is based on and the input data? Are they experimentally verified and are they widely accepted by the scientific community? How large are the uncertainty ranges of the numerical input data and how do these uncertainties propagate into the results? How sure can we be that the investigator's choices of the input data of his model were not biased, wittingly or unwittingly?

**About the radiological models used by the nuclear industry**

Which assumptions form the basis of the currently used radiological models? Which phenomena are included in the models and which are not?
What was the original purpose of the models? To estimate the acute radiological risks for military personel in wartime, or to estimate the health risks for the public posed by chronic exposure to a number of radionuclides from civilian nuclear power?

More than ever the time has come to base health risk estimates on published and verifiable empirical facts, not on computer models originating from the closed nuclear industrial complex and based on secret data. The KiKK study [34] proved that the existing exposure and health risk models are unable to explain the empirical observations of that study, so the models must be revised.

## 5.3 Entanglement of interests

Information on nuclear matters to the public and politicians originates almost exclusively from institutions with vested interests in nuclear power, such as: International Atomic Energy Agency (IAEA), World Nuclear Association (WNA), Nuclear Energy Agency (NEA), Nuclear Energy Institute (NEI), Areva, Electricité de France (EdF), the latter two being 90% state-owned.

How independent are the reports on the consequences of radioactive contamination for the local inhabitants, for example after the disaster of Chernobyl? According to an agreement between the International Atomic Energy Agency and the World Health Organization (UN Res. WHA12-40, 28 May 1959) the WHO cannot operate independently of the IAEA on nuclear matters. The IAEA ranks higher in the UN hierarchy than the WHO. Bertell [79] also reports on the strong connections between IAEA and UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) and ICRP (International Commission on Radiological Protection).

# 6 Health risks and economics

The chances of large-scale nuclear accidents, with irreversible consequences affecting vast areas of inhabited land, may greatly increase if the nuclear industry keeps approaching the radioactive waste problem from the current short-sighted economic views.

This chapter addresses some aspects of the long-term economic burden of unprecedented size, character and timescales inflicted to the present anf future generations by nuclear power. These economic problems, ensuing from the back end part of the nuclear process chain, cannot be handled by the current way of economic thinking and will persist for the next century, even if the world's nuclear power stations are all closed down today.

## 6.1 Energy on credit

In the downstream part of the nuclear process chain some activities have extremely long lead times, up to many decades or even a century. As pointed out in Chapter 2, the downstream processes are of crucial importance for the survival of the society as we know it today. After all nuclear power plants are not a purpose, they are nothing more than a technical means to deliver useful energy, to let florish our society, and not to burden society and future generations with untold hazards. Incompetent actions may cause serious and irreversible consequences.
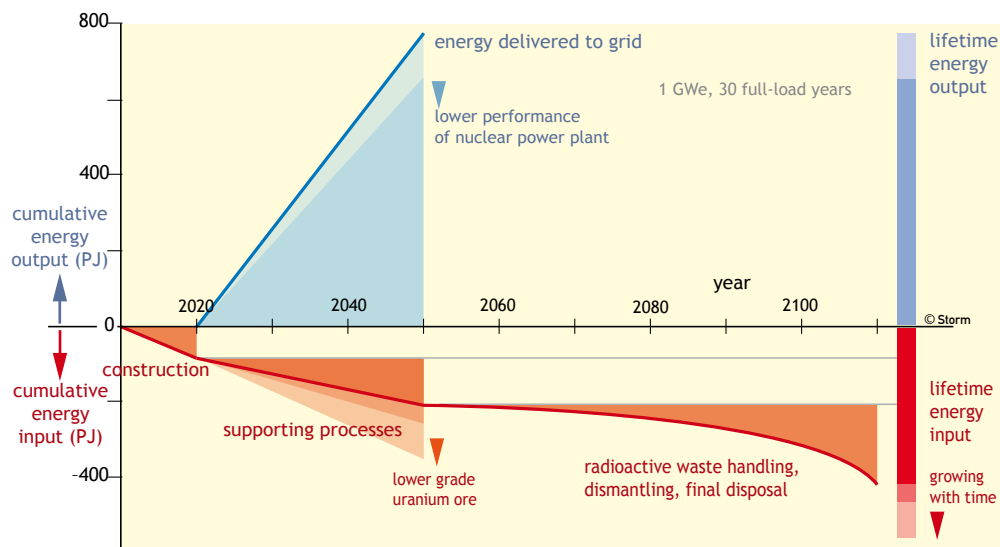


**Figure 25**
Dynamic energy balance of the nuclear energy system. The vertical scale has energy units, the horizontal scale the year from 2010 on. The reactor is assumed to operate continuously on full power for 30 years (average load factor 100%). No reactor in the world ever reached this production. The graph is roughly at scale. The lifetime net energy production will decrease with time, because of the increasing energy input of the front end part due to the decreasing quality of uranium ores. For details see Part G6 of [1].

Adequate completion of the downstream processes of the nuclear chain will require high investments of energy, materials and human resources. Notably the decommissioning of nuclear power plants and reprocessing plants, the definitive packaging and storage of spent fuel and the construction of the required geologic repositories, will absorb massive amounts of energy and materials. The fulfilment of the downstream processes involve large-scale industrial activities,

requiring massive amounts of energy, high-grade materials and human resources: this debt is called the energy debt.

The energy debt can be roughly estimated by a physical analysis of the processes needed to handle safely the radioactive materials generated during the operational lifetime of the nuclear power plant. The energy debt built up during construction of the nuclear power plant is repaid during the first years of the operational lifetime (see Figure 25).

The energy- and material debt will increase over time, for the radioactive waste has to be cooled and safeguarded during many decades and the temporary storage facilities have to be maintained during that period. The increase of the debt is exacerbated by the unavoidable deterioration of the materials and structures confining the radioactive materials. In addition a geologic repository has to be constructed. Jointly the activities associated with one nuclear power plant will cover a period of at least 100 years and probably longer.

Figure 23 represents a dynamic energy balance of the full nuclear process chain, from cradle to grave. For a comprehensive analysis of the energy balance of nuclear power see [1].

## 6.2      Monetary debt

Obviously an energy debt and a material debt correspond with a monetary debt. The first, preliminary cost estimates by the British Nuclear Decommissioning Authority [80] amount to over €7bn per GWe for nuclear power plants, or 100-200% of the original construction cost. The final cost will undoubtly be higher.

The cost of the decommissioning and dismantling of a reprocessing plant will rise to astronomical values. For the reprocessing plant at Sellafield (UK) these costs are preliminarily estimated at about GBP38bn (€45) [81] to GBP50-100bn (€60-120bn) [82] and will take some 130 years. Studies by the RAND Corporation [9], [10] proved that the cost of large projects involving new technology are always estimated too low. The causes of the cost overruns observed by the RAND studies perfectly apply to the present nuclear projects, see also section 2.4.
Cost overruns are the rule in the nuclear industry.

Compare the preliminary cost estimate of decommissioning Sellafield with the final cost of the American Apollo project, which succeeded in putting the first man on the moon (Apollo 11) and landing five crews thereafter. The final cost of the entire Apollo project, which started essentially from scratch, were less than €100 bn in €(2009).

The conclusion is that the decommissioning and dismantling of the Sellafield reprocessing plant, will cost the same or even more than the entire, inspiring Apollo project (1961-1975), with its huge technological spinoff.

The decommissioning and dismantling of the US West Valley reprocessing plant, which operated from 1966-1972 and reprocessed 640 tonnes of spent fuel, will cost, from 2007 on, at least €(2009) 4bn and will take another 40 years to complete. Very likely the final cost will be considerably higher. Up until 2007 several billions of dollars already have been spent on West Valley [83]. The total cost will amount to more than 40 times (!) the construction cost of the plant. If all goes according to the current plans, the decommissioning and dismantling of the US West Valley reprocessing plant would have taken a period of 70 years. In the meantime the radioactive pollution of the groundwater and creeks in the vicinity of the plant is still going on and so the health risks of the local inhabitants.

The final cost of the complete sequence of spent fuel handling – interim storage, packing

through definitive storage in a geologic repository – are unknown. A preliminary estimate of the lifetime cost may come to billions of euros per reactor.

The World Nuclear Association (WNA), presenting itself as representative of the nuclear industry, asserts [84] :
> "Nuclear power is the only large-scale energy-producing technology which takes full responsibility for all its wastes and fully costs this into the product."

This WNA statement is in direct conflict with the facts and arguments presented in this paper and also with the following remarks.
• In the USA the federal administration is automatically responsible for the definitive storage of the spent fuel in a geological repository. Most likely the American taxpayer has also to pay for the decommissioning and dismantling of the nuclear power plants.
• In the UK the closed down nuclear power plants are sold for a symbolic amount to the government, who gets the responsibility of the cleanup, decommissioning and dismantling of the discarded radioactive facilities. Most likely the British taxpayer has also to pay for the construction of a geologic repository plus the packaging and definitive storage of the nuclear waste.
• In France a special situation is existing. All nuclear activities in France are managed by two state-owned companies: Areva and Electricité de France (EdF). Who pays the bill?

How is the situation in other countries, for example Russia, China, India, South Korea, Japan?


## 6.3      Economic challenge

The monetary debt ensuing from the energy debt and material debt has a character completely different from the monetary debts economists are used to. Present economic concepts are invalid to handle the problems and risks posed by the nuclear heritage, in view of the following characteristics:
• Energy is a conserved quantity. The energy debt is not discountable and cannot be written off as uncollectable.
• Energy units do not depend on place and time, nor on politics, nor on economic concepts.
• The size of the energy debt is of unprecedented size in history. Each nuclear power plant leaves behind an energy debt as large as about one third of its lifetime energy production. During the next decades this debt fraction will rise considerably, as result of the decline of the quality of the required nuclear-related mineral resources.
• The timescale of the tail of the nuclear chain, over a 100 years, is unprecedented in history.
• The massive investments of energy, materials and human resources do not contribute to the improvement of the economic infrastructure and must be considered to be pure losses. As the investments are used to isolate the radioactive wastes including their packing from the human environment, they will vanish from the economic system forever.
• The energy debt is not subject to monetary-like depreciation, on the contrary, it will increase with time, for reason of inevitably deteriorating materials and constructions, following from the Second Law (see Box 1). The longer the adequate actions will be postponed, the more energy, high-quality materials and economic effort will be required to achieve a given level of safety.

Any country with an appreciable number of nuclear power plants, such as France, Great Brittain and the United States, should reckon on economic efforts of Apollo project size, many hundreds of billions of euros, to keep their territory (and of the neighbour countries) habitable. Would

the decision makers foster such efforts, or does the world need another Chernobyl disaster? The current way of economic thinking, pursuing only short-term profit goals, is not quite reassuring.

With respect to radioactive waste problems and health risks the nuclear world seems to foster a culture of downplaying and concealing risks and of an unrealistic belief in unproved and unfeasible technical concepts, exacerbated by an attitude of postponement which may be best described as an *après nous le déluge* attitude.

Usually this attitude is based on questionable arguments and fallacies, such as:

'Technology advances with time and future generations will be richer than our generation, so they will have more economic means and better technological possibilities at their disposal to handle the waste problem.'

Or, as John Broome put it [85]:

> 'How should we – all of us living today – evaluate the well-being of future generations, given that they are likely to have more material goods than we do?'

**Misconception**

The view that the solution of the radioactive waste problem is just a matter of advanced technology is a misconception, for the immobilization of radioactivity is a Second Law problem. It will not be possible to prevent the spread and dispersion of radioactivity into the environment by less effort than it would require at this moment by use of advanced, yet to be developed, technology. Spread can only be limited by dedicated human efforts, involving massive amounts of useful energy and materials. As useful energy and materials are becoming increasingly scarce with time, the chances of solving the radioactive waste problem adequately can only decline with time.

## 6.4     Economic pressure

Apart from the energy debt and its potential health risks in the near future, economic pressure as present today is enhancing the health risks of nuclear power. Safety measures are vulnerable to economic pressure and short-sighted actions: the standards, the quality control and the independency of inspections. These three issues are briefly addressed in this section.

**Price-Anderson Act**

The Price-Anderson Act was enacted in the USA in 1957 as a supplemental 'insurance policy' for nuclear power plants. With this act, providing equal liability protection regardless of risk, the cost of additional safety features becomes a financial impediment for a nuclear plant owner. New nuclear reactors must be excluded from liability protection under the Price-Anderson Act [8]. Lochbaum:

> 'If new reactors are truly so safe that the public need not be protected from technological disaster, then they are also so safe that their owners need not be protected from financial disaster'

This kind of liability protection may be seen as a disincentive for safety, preventing safety upgrades from being incorporated into new reactor designs.

How is the situation in other countries?

The problems with the reactors in France (section 4.6) point to a similar liability protection in France. This assumption sounds plausible, because the reactor operator EdF and the reactor vendor Areva both are state companies.

**De-regulation**

De-regulation (liberalisation) of electricity markets has pushed nuclear utitlities to decrease safety-related investments and limit staff [60].

**Relaxation of exposure and activity standards**

The high and continually escalating costs of waste management and disposal may provoke undesirable developments and hazardous situations. Standards in regulations may be relaxed to admit higher concentrations of radionuclides in materials for clearance, because of economic reasons. Clearance is the controlled release of materials into the public domain; once released the materials are no longer subject to regulation.

The IAEA [55] proposes to dilute radioactive materials with non-radioactive and to use concrete rubble as landfill or road paving. 'Weakly' radioactive steel scrap – however defined and measured – could be remelted with fresh steel and used for 'special purposes'. Reuse of 'low-activity' contaminated and/or activated steel and concrete by diluting it with fresh steel or concrete, as proposed by the IAEA, is very risky in our view, for several reasons:
• the unknown but potentially hazardous isotopic composition of the scrap and rubble
• the unknown biological behavior of the radionuclides
• problematic detection of a number of radionuclides (see also section 4.8).
• uncertainties with regard to standards, inspection and control (see section below)
• the high risk of uncontrolled trade in radioactive materials (see section 4.8).

Findings of the National Council of Radiation Protection and Measurements (NRCP) [53], concerning potentially radioactive scrap metals, are indicative of an urgent and problematic situation in the USA:
  'There is an urgency to establish consistent national/international policies and standards.'

In Europe, with its many different countries, the situation is far more complex and probably more problematic. In case of the waste released by dismantling nuclear power plants and other nuclear facilities, it would be wise to avoid shipments and trade of radioactive scrap metal and debris as much as possible by packing the materials at the source: the reactor being dismantled.

Economic arguments may also lead to relaxation of the standards of the routine emissions of radioactive materials. An example is the proposal of the US Environmental Protection Agency (EPA) to dramatically raise permissible release levels. The new standards permit public exposure to radiation levels vastly higher than EPA had previously deemed unacceptably dangerous [86], [87]. EPA increased permissible public exposure to radiation in drinking water with factors of 1000 to 100000 involving the nuclides $^{90}$Sr, $^{131}$I (what about $^{129}$I?) and $^{63}$Ni. In the most extreme case the new standard would permit radionuclide concentrations 7 million times more lax than permitted under the Safe Drinking Water Act. Other aspects of the new EPA proposal are lax cleanups and higher exposures to other sources, such as relaxed dirty bomb standards.
EPA made not clear on base of what physical and medical evidence the standards could be relaxed. In view of the reliance on models within the nuclear industry (see section 4.2) and the ease to adapt models to changing needs of the nuclear industry, any relaxation of standards should be based on verifiable empirical evidence.

The strained relationship between economics and nuclear safety and health risks is clearly expressed in the French Roussely report [88]:
  'La question du risque nucléaire acceptable, ou plus généralement du risque technologique acceptable,

est un débat de société à part entière pour lequel la ou les réponses à donner sont naturellement du rôle du Politique. Force est néanmoins de constater que la notion même de compétitivité du nucléaire et l'hétérogénéite des règles de sûreté selon les Etats renforcent l'actualité de ce débat et la nécessité de préciser certaines exigences de sûreté. La seule logique raisonnable ne peut pas être une croissance continue des exigences de sûreté.'

In English translation:
'The question of what is an acceptable nuclear risk, or more generally an acceptable technogical risk, is a debate that concerns the entire society and for which the answer(s) to provide belong evidently to the political domain. However, one must note that the concept itself of competitiveness of nuclear power and the heterogeneity of the security rules according to the each country reinforce the relevance of this debate and the need to specify certain security requirements. The continued increase of security requirements cannot be the only reasonable rationale.'

## Standards and quality control

On base of what scientific and medical evidence would the qualifications be defined such as: 'weakly' radioactive, 'low-activity' and 'special purposes'? Who controls the sorting of the materials into the categories: 'free release', 'to be diluted' and 'waste'? How are 'special purposes' defined and how is 'restricted reuse' controlled? Which radioisotopic composition has the radioactive component of the debris or scrap? Has that composition been measured or has it been estimated based on models from the early 1970s? What is known about the biomedical activity of the radionuclides in the debris and scrap? Another problem is the problematic detection of a number of hazardous radionuclides.
In view of the large problems already existing with regard to illegal trade and smuggling, great risks are looming here, even without relaxing of the standards. Large volumes and masses of debris and scrap, sometimes of high value on the free market, are involved in decommissioning and dismantling, as pointed out in section 4.4. Experiences in the past with waste handling by private companies are not always encouraging in this respect.

If the handling and management of radioactive debris is left to private companies, profit seeking may prevail over of safety and health. Financial motives for short-term 'solutions' may be backed by financial constructions which leave the liability for failures and mishaps at the customer, in case the taxpayer. Such financial constructions seem to be involved in the contracts for decommissioning and dismantling of the Sellafield reprocessing plant under the authority of the British Nuclear Decommissioning Authority NDA [80].

## Independency of inspections

Economic arguments may also lead to reduced quality controls by official inspectors. Several incidents at nuclear power stations in the USA during the past years point to such a development. In a number of countries the nuclear industry urges simplified and shortened license procedures to speed up the construction of new nuclear build, with minimalisation or even elimination of the participation by the local authorities and the public.
It is conceivable that even the independency of the controlling institutions would be liable to suffer under economic pressure. The above described relaxation of the exposure standards by the US EPA points in that direction. How is the situation in other countries?

The Roussely report [88] calls for a reduction of the scope, and so for a reduction of the independency, of the French Safety Authority ASN (Autorité de Sûreté Nucléaire):
'En France, il convient que l'État définisse un modus vivendi équilibré avec l'Autorité de Sûreté,

c'est-à-dire réaffirme le rôle régalien qu'il ne devrait pas abandonner à une autorité indépendante.

... Il convient d'éviter que des événements de portée très limité conduisent à jeter une suspicion injustifiée sur l'ensemble d'une technologie.'

In English translation:

'In France, the government must define a balanced modus vivendi with the Safety Authority, that means to re-establish sovereignty which it should not relinquish to an independent authority.

... It must be avoided that events with very limited effects result in unjustified suspicion of a technology as a whole.'

Which independent authority judges an event, e.g. an incident or design error, to have 'very limited effects' not only at the moment of discovery but also in the long run?

For what reasons could an 'event with very limited effects' cast suspicion on a technology as a whole, in case nuclear technology?

The decision process on nuclear power in France is controlled by the president and the Corps des Mines (a technocratic elite), effectively without the participation of the parliament [89].

## 6.5    Health risks of nuclear power: an economic notion

Inherently safe nuclear power is inherently impossible, as has been explained in section 2.4, and there are no unambiguous nuclear health and safety standards possible based on unambiguous scientific and medical empirical evidence. This observation and the issues addressed in this study are pointing to the following conclusion:

Nuclear safety is an economic notion and so are the health risks posed by nuclear power.

Two questions really matter:
•    What are we willing to pay for our health and the health of our childern, our grandchildern and of future generations?
•    For what reasons do we think civilian nuclear power to be necessary?

# Conclusions

1   The physical origin of nuclear health risks is the mobilization of natural radioactivity and the anthropogenic generation and mobilization of a billionfold of the natural radioactivity.

2   Routine releases of radioactivity by nominally operating nuclear power plants, which are classified as harmless by the nuclear industry, proved to be harmful. Within a radius of some 30 km an increasing occurrence of childhood cancer with decreasing living distance from a nominally operating nuclear power plant is proved to exist.

3   Computer models from the nuclear industry fail to explain empirical observations of health effects of nuclear power. These models do not include health effects of radionuclides within living cells, nor non-targeted and delayed effects.

4   A number hazardous radionuclides are hard to detect with common detectors, enhancing health risks.

5   In nuclear technology only engineered safety exists, which is subject to economic pressure, to human behavior and to the basic laws of nature, particularly the Second Law of thermodynamics.

6   *Inherently safe nuclear power is inherently impossible*.

7   Severe accidents are possible, involving a radioactive inventory of thousands of nuclear bomb equivalents. The extent and consequences of such accidents could pale the Chernobyl disaster. The risks of such large-scale accidents originate from the reactors as well as from the interim storage of spent fuel and from reprocessing plants.

8   The only way to prevent disastrous exposure of the public to human-made radioactivity on unprecedented scale is to immobilize the radioactive waste physically and to isolate it from the biosphere in deep geologic repositories, lasting at least a million of years.
    To deal with the global radioactive waste at the current rate of generation about every year a new large deep geological repository has to be opened, at an estimated cost of at least €10bn each. To dispose of the existing radioactive wastes from the past dozens of deep geologic repositories would be required.

9   The health risks of nuclear power are growing with time as a result of:
    • Increasing amounts of mobile radioactive material piling up in temporary storage.
    • Unavoidable deterioration of materials and structures of the temporary storage facilities, as a consequence of the basic laws of nature.
    • Increasing economic pressure.

10  Ever since the beginning of the nuclear era the activities necessary to effectively immobilize and isolate the human-made radioactivity from the biosphere have been postponed to the future. This behavior has generated, and is still generating, an immense debt in terms of energy, materials, human resources and economic effort. A habit of living on credit and '*après nous le déluge*' seems to dominate the present attitude of politicians and the nuclear world.

11  *Nuclear power delivers energy on credit*.

12 Information on nuclear matters to the public and politicians originates almost exclusively from institutions with vested interests in nuclear power, for instance the International Atomic Energy Agency IAEA.
The institutions United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Commission on Radiological Protection (ICRP) and World Health Organization (WHO) cannot operate independently of the IAEA on nuclear matters.

13 Health risks of nuclear power are greatly enhanced by economic pressure, as a result of:
  • decrease of safety-related investments and staff at the utilities
  • relaxation of official exposure standards
  • decrease of the efficiency and independency of inspectors and regulators.

14 *Health risks posed by nuclear power are an economic notion.*

15 The basic questions the public and politicians are confronted with are:
  • What are we willing to pay for the safety and health of ourselves, our childern and grandchildern and of future generations?
  • For what reasons do we think civilian nuclear power to be necessary?

# References and endnotes

[1]     Storm & Smith 2008
Storm van Leeuwen J W & Smith Ph B,
*Nuclear power - the energy balance*,
Chaam, Netherlands, February 2008
www.stormsmith.nl

[2]     Bell 1973
Bell M J,
*ORIGEN, the ORNL isotope generation and depletion code*,
ORNL-4628,
Oak Ridge National Laboratory, Oak Ridge, Tenn, 1973.

[3]     Hollocher 1975
Hollocher T C,
Storage and disposal of high-level radioactive wastes, in:
*The Nuclear Fuel Cycle*,
Union of Concerned Scientists,
MIT Press, Cambridge, Mass., 1975.

[4]     JPL-77-69 1977
*An analysis of the technical status of high-level waste and spent fuel management systems*,
JPL-77-69,
Jet Propulsion Laboratory, Pasadena, CA, December 1977.

[5]     Sheldon 2009
Sheldon D,
*Reliability considerations*,
California Institute of Technology, 2009,
filename: NSREC for MAPD 2009.ppt
http://nepp.nasa.gov

[6]     Stancliff et al. 2006
Stancliff SB, Dolan JM & Trebi-Ollenu A,
Mission reliability estimation for repairable robot teams,
*International Journal of Advanced Robotic Systems*,
Vol.3, No.2 (2006).
filename: 10.1.1.68.5695.pdf
http://citeseerx.ist.psu.edu

[7]
See for example:
www.tutorialsweb.com/reliability/reliability1,2,3.htm
www.itl.nist.gov/div898/handbook/apr/section1/apr124.htm
www.weibull.com/hotwire/issue21/hottopics21.htm

[8]     Lochbaum 2004
Lochbaum D,
*US Nuclear plants in the 21st century. The risk of a lifetime*,
Union of Concerned Scientists, May 2004,
http://www.ucsusa.org/assets/documents/nuclear_power/nuclear04fnl.pdf

[9]     RAND 1981
Merow E W, Philips K E & Myers C W,
*Underestimating cost growth and perfomance shortfalls in pioneer process plants*,
RAND/R-2569-DOE,
prepared for US Department of Energy,
RAND Corporation, Santa Monica, CA., September 1981.

[10]    RAND 1979,
E.W. Merow, S.W. Chapel & C. Worthing,
*A review of cost estimation in new technologies*,
RAND-2481-DOE,
prepared for US Department of Energy,
RAND Corporation, Santa Monica, CA., July 1979.

[11]    Papp-1 1998
Papp, R.,
Technische und geologische Barrieren bei der Endlagerung, (in German),
*ATW* 43, Jg 1998a, Heft 4, April, pp. 252 255.

[12]    Papp-2 1998
Papp, R.,
Untersuchung unterscheidlicher Endlagerwirtsgesteine,
*ATW* 43, Heft 4, April, pp. 249 251.  Jg 1998b.

[13]    IAEA-349 1993
*Report on radioactive waste disposal*,
Technical Report Series No 349,
International Atomic Energy Agency (IAEA), Vienna, 1993,
ISBN 92-0-100393-5

[14]
Thegerstrom 2010
filename: jrc_aaas2010_waste_thegerstrom.pdf
http://ec.europa.eu

[15]    MacKay 2009
MacKay DJC,
*Sustainable Energy – without the hot air*,
UIT Cambridge Ltd, 2009.
free downloadable file: sewtha.pdf
www.inference.phy.cam.ac.uk/
or   www.withouthotair.com/download.html

[16]    NRC 1996
Rasmussen N C (chair) et al.,
*Nuclear Wastes. Technologies for separations and transmutation*,
National Research Council, NRC
Washington DC: National Academy Press, 1996.

[17]    Charpak&Garwin 2002
Charpak G & Garwin RL,
'The DARI'
Europhysics News (2002) Vol 33 No.1
www.europhysicsnews.com/full/13/article4/article4.html

[18]    Koppe et al. 2006
Koppe JG, Bartonova A, Bolte G, Bistrup ML, Busby C, Butter M, Dorfman P, Fucic A, Gee D, Van Den Hazel P, Howard V, Kohlhuber M, Leijs M, Lundqvist C, Moshammer H, Naginiene R , Nicolopoulou-Stamati P, Ronchetti R, Salines G, Schoeters G, Tusscher GT, Wallis M, Zuurbier M.
'Exposure to multiple environmental agents and their effect',
*Acta Paediatr Suppl.* (2006) Oct;95(453):106-13.

[19]     Sternglass 2009
Sternglass EJ,
letter to Dr Steven Chu, Secretary of Energy, Febr 7, 2009,
www.radiation.org/reading/090423_ejs_to_doe.html

[20]     Fairlie 2010
Fairlie I,
Commentary on UNSCEAR 2006 Report: Annex C – New effects of radiation,
Letter,
*Radiat Prot Dosimetry*, 2010 Febr; 138 (2): 190-3

[21]     Morgan & Sowa 2005
Morgan WF & Sowa MB,
Effects of ionizing radiation in nonirradiated cells,
*PNAS*, October 2005, vol.102 no 40, pp 14127-14128.
www.pnas.org/cgi/doi/10.1073/pnas.0507119102

[22]     Mothersill & Seymour 2006
Mothersill C & Seymour CB,
Radiation-induced bystander effects and the DNA paradigm: An "out of field" perspective,
*Mutation Research* 597 (2006) 5-10.
www.sciencedirect.com

[23]     Dworschak 1993
Dworschak H,
'Characteristics, origin, production, applications', in:
F. Mannone (ed.),
*Safety in Tritium Handling Technology*,
EUR 15144 ECSC, EEC, EAEC, Brussels/Luxembourg, 1993,
Dordrecht: Kluwer, 1993.

[24]     Fairlie 2008
Fairlie I,
The hazards of tritium – revisited,
*Medicine, Conflict and Survival*,
Vol 24:4. October 2008. pp 306 -319.

[25]     NCRP-62 1995
*Tritium in the environment*,
National Council on radiation Protection and Measurements,
NCRP Report 62,
Washington DC, January 1995,
(reprint of 1st edition 9 March 1979 and 2nd edition 15 May 1989).

[26]     NCRP-63 1979
*Tritium and other radionuclide labelled organic compounds incorporated in genetic material*,
National Council on Radiation Protection and Measurements,
NCRP Report 63,
Washington DC, 30 March 1979.

[27]     Fairlie 2007
Fairlie, I,
*Tritium hazard report: pollution and radiation risk from Canadian nuclear facilities*,
Greenpeace, June 2007,
file: tritium-hazard-report-pollu.pdf
www.greenpeace.org/canada/en/documents-and-links/publications/

[28]     AGIR 2007
*Review of Risks from Tritium*,

Report of the independent Advisory Group on Ionising Radiation (AGIR),
Documents of the Health Protection Agency, Radiation, Chemical and Environmental Hazards, RCE-4,
Oxford. United Kingdom, November 2007,
filename: RCE_Advice_on_tritium.pdf
http://www.hpa.org.uk/web/HPAweb&HPAwebStandard/HPAweb_C/1197382220012.

[29]     Straume 1991
Straume T,
*Health risks from exposure to tritium*,
UCRL-LR-105088,
Lawrence Livermore National Laboratory,
University of California, Livermore, CA, February 22, 1991.

[30]     NCRP-89 1987
*Genetic effects from internally deposited radionuclides*,
NCRP Report 89,
National Council on Radiation Protection and Measurements,
Bethesda, MD, December 1, 1975.

[31]     NCRP-81 1993
*Carbon-14 in the environment*,
National Council on Radiation Protection and Measurements,
NCRP Report 81,
Bethesda, MD, 15 May 1985, first reprinting April 30 1993.

[32]     Collins 2003
Collins G P,
Fatal attachments. Extreme low-energy electrons can wreck DNA,
*Scientific American*, September 2003, pp14-15.

[33]     NCRP-44 1975
*Krypton-85 in the atmosphere. Accumulation, biological significance and control technology*,
National Council on Radiation Protection and Measurements,
NCRP Report 44,
Washington DC, July 1, 1975.

[34]     KiKK 2007
Kaatsch P, Spix C, Schmiedel S, Schulze-Rath R, Mergenthaler A & Blettner M,
*Epidemiologische Studie zu Kinderkrebs in der Umgebung von Kernkraftwerken (KiKK-Studie)*,
Vorhaben StSch 4334 (in German),
Im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit und des Bundesamtes für Strahlenschutz, Germany, 2007,
4334_KiKK_Gesamt_T.pdf
www.bfs.de/de/bfs/druck/Ufoplan/

[35]     Fairlie 2010
Fairlie I.
Hypothesis to Explain Childhood Cancer near Nuclear Power Plants
*Int J Occup Environ Health* 16:341–350 (2010)

[36]     Fairlie 2009
Fairlie I,
Childhood cancers near German nuclear power stations:

hypothesis to explain the cancer increases,
*Medicine, Conflict and Survival*, 25:3, pp206-220,
online publication July 2009,
http://dx.doi.org/10.1080/13623690902943396

[37]     INFCE-7 1980
*Waste management and disposal*,
Report of the INFCE Working Group 7,
International Nuclear Fuel Cycle Evaluation,
IAEA, Vienna, 1980.

[38]     Diehl 2006
Diehl P,
*Environmental consequences of uranium mining*,
Seminar Kernenergie "ja mits" of "nee, tenzij",
Amsterdam, 9 november 2006,
www.tegenstroom.nl

[39]     Andriesse 1994
Andriesse C D,
*Comment on prospects for nuclear power, Energy
technologies to reduce CO2 emissions*,
OECD/IEA, Paris, 1994.

[40]     Lipschutz 1980
Lipschutz RD,
*Radioactive waste: politics, technology and risk*,
A report of the Union of Concerned Scientists,
Ballinge Publishing Company, Cambridge, Mass, 1980
ISBN 0 8 8410 621 7.

[41]     Blanchard et al. 1982
Blanchard RL, Fowler TW, Horton TR & Smith JM,
Potential health effects of radioactive emissions from
active surface and underground uranium mines,
*Nuclear Safety*, Vol 23 no 4, July-August 1982.

[42]
http://www4.nau.edu/insidenau/bumps/2006/2_22_06/
uranium.htm

[43]     ISA 2006
*Life-Cycle Energy Balance and Greenhouse Gas Emissions
of Nuclear Energy in Australia*,
A study undertaken for the Department of Prime Minister
and Cabinet of the Australian Government,
ISA, The University of Sydney, 3 November 2006,
www.isa.org.usyd.edu.au/publications/reports.shtml

[44]     Pigford et al. 1973
Pigford Th J, Keaton MJ & Mann BJ,
*Fuel cycles for electrical power generation,
prepared for the Standards Research Branch*, Office
of Research and Monitoring, Environmental Protection
Agency,
EPA No 68-01-0561,
Teknekron Report No EEED-101,
Teknekron Inc., California, January 1973.

[45]     OSPAR 2002
*Liquid discharges from nuclear installations in 2000*,
Radioactive Substances Series,
OSPAR Commission 2002,
ISBN 0 946956 91 X
www.ospar.org

[46]     NCRP-75 1983

*Iodine-129: evaluation of releases from nuclear power
generation*,
NCRP Report 75
National Council on Radiation Protection and
Measurements,
Bethesda, MD, July 1, 1975.

[47]     NCRP-60 1978
*Physical, chemical and biological properties of
radiocerium relevant to radiation protection guidelines*,
NCRP Report 60,
National Council on Radiation Protection and
Measurements,
Washington DC, 15 December, 1978.

[48]     NEA 1980
*Radiological significance and management of Tritium,
Carbon-14, Krypton-85, Iodine-129, arising from the
nuclear fuel cycle*,
Report by the NEA Group of Experts
Nuclear Energy Agency (NEA),
OECD, Paris, April 1980.

[49]     RODOS 2007
Slavnicu D, Galeriu D, Gheorghiu D & Melintescu A,
*Tritium model in RODOS system*,
8th Meeting of the EMRAS (IAEA) Working Group on Tri-
tium and C-14,
Bucharest, Romania, May 30–June 1, 2007.
file:     TRITINRODOS.ppt
http://www.nipne.ro/emras/

[50]
Beyond Nuclear, 19 April 2010, www.beyondnuclear.org

[51]     Malherbe 1991
*Nuclear science and technology. Management of
radioactive waste from reprocessing including disposal
aspects*,
Commission of European Community, Directorate-General
Science, Research & Development,
EUR 13116 EN
cataogue nr CD-NA-13116-EN-C
Brussels-Luxembourg, 1991.

[52]     Gronlund et al. 2007
Gronlund L, Lochbaum D & Lyman E,
Nuclear power in a warming world,
*Assessing the risks, addressing the challenges*,
Union of Concerned Scientists, 2007.
www.uscusa.org

[53]
NCRP-141 2002
*Managing potentially radioactive scrap metal*,
NCRP Report 141
National Council on Radiation Protection and
Measurements,
Bethesda, MD, November 2002.

[54]     Woollam 1984
Woollam P,
Five years of European research into decommsissioning,
*Nuclear Engineering International*, August 1984, pp 15-18.

[55]     IAEA 293 1988,

*Factors relevant to the recycling or reuse of components arising from the decommissioning and refurbishment of nuclear facilities,*
Technical Report Series No 293,
International Atomic Energy Agency (IAEA), Vienna, 1988,
ISBN 92-0-125888-7.

[56]    Watzel et al. 1978
Watzel GVP, Essmann J, Lukacs G & Thalman G,
*Decommissioning study for nuclear power plants with light-water reactors - First results,*
ENS/ANS International Topical Meeting on Nuclear Power Reactor Safety,
Brussels, 16-18 October 1978,
INIS-mf-4769.

[57]    IAEA 389 1998
*Radiological characterization of shut down nuclear reactors for decommissioning purposes,*
Technical Report Series No 389,
International Atomic Energy Agency (IAEA), Vienna, 1998.

[58]
United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), www.unscear.org/unscear/en/chernobyl.html

[59]
European Spatial Observation Network (ESPON):
www.gtk.fi/projects/espon/Nuclear.htm
www.espon.eu

[60]    Hirsch et al. 2005
Hirsch H, Becker O, Schneider M & Froggatt A,
*Nuclear  Reactor Hazards. Ongoing dangers of operating nuclear technology in the 21st century,*
Report prepared for Greenpeace International, April 2005
www.greenpeace.org/international/en/publications/reports/nuclearreactorhazards.pdf

[61]    Yablokov et al. 2010
Yablokov A, Nesterenko V & Nesterenko A,
*Chernobyl: Consequences of the catastrophe for people and the environment,*
Annals of the New York Acadamy of Sciences, Volume 1181.
www.nyas.org/publications/annals/

[62]
*Nouvelles révélations d'une source interne à EdF sur le dangerosité de l'EPR,*
www.sortirdunucleaire.org/dossiers/EPR-revelations2.html
4 October 2010

[63]    NRC 2004
Nuclear Regulatory Commission,
'Final rule: Changes to Adjudicatory Process',
*Federal Register* 69(9), January 14, 2004.

[64]    MIT 2010
*The Future of the Nuclear Fuel Cycle.*
*An Interdisciplinary MIT Study,*
Massachusetts Institute of Technology, Cambridge MA, USA, 2010
ISBN978-0-9828008-1-2
http://www.mit.edu/press/2010/nuclear-report-release.
html

[65]    IGD-TP 2009a
*Vision Document. Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP),*
European Commission, European Research Area, Euratom, 24 October 2009,
EC Publications Office, ISBN 978-92-79-13622-1
file: VisionDoc_final_Oct24.pdf
www.igdtp.eu

[66]    IGD-TP 2009b
Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP),
*From Vision to Implementation,*
Launching Event, Brussels, 12 November 2009.
file: IGDTP_2001112.pdf
www.igdtp.eu/

[67]    Greenpeace 2010,
Wallace H,
*Rock Solid? A scientific review of geological disposal of high-level radioactive waste,*
GeneWatch UK Consultancy report, for Greenpeace International, September 2010,
http://www.greenpeace.org/raw/content/eu-unit/press-centre/reports/rock-solid-a-scientific-review.pdf

[68]    Hirsch 2006
Hirsch H,
*Hazards of new reactor types,*
presentation at WISE Seminar, Amsterdam, November 9, 2006.
www.tegenstroom.nl/pdf/seminar/hirsch.pdf

[69]    Barnaby 2005a
Barnaby F,
Factsheet 1 – *Security and Nuclear Power*
Oxford Research Group, November 2005
www.oxfordresearchgroup.org.uk/publications/briefing_papers

[70]    Barnaby 2005b
Barnaby F,
Factsheet 2 – *Effective Safeguards?*
Oxford Research Group, November 2005
www.oxfordresearchgroup.org.uk/publications/briefing_papers

[71]    Barnaby 2006
Barnaby F,
*The Nuclear Renaissance and the Spread of Nuclear Weapons,*
Seminar Kernenergie in de 21ste eeuw. Realiteit en beloften,
Greenpeace, WWF, IEW, Bond Beter Leefmilieu & Voor Moeder Aarde,
Brussels, Federaal Parlement, 19 Oktober 2006.
www.uitstapkernenergie.be/

[72]
*Nature,* 4 March 2010, pp 26-27

[73]
*Scientific American,* February 2010, p.8-9

[74]    WASH-1400 1975

Rasmussen NC et al.,
*Reactor safety study. An assessment of accident risks in US commercial nuclear power plants*,
Report to the US Nuclear Regulatory Commission,
WASH-1400/NUREG-75-014,
US Government Printing Office, Washington DC, USA,
October 1975.

[75]     NUREG-1150 1990
*Severe accident risks: an assessment for five US nuclear power plants*,
US Nuclear Regulatory Commission,
Washington DC, USA, December 1990.
available on http://www.nrc.gov

[76]     NRC 2002
Nuclear Regulatory Commission,
'*Review of NRCs Significance Determination Process*',
Office of Inspector General, OIG-02-A-15, August 21, 2002
Online at:
www.nrc.gov/reading-rm/doc-collections/insp-gen/2002/02a-15/02a-15.pdf

[77]     CERRIE 2004
*Report of the Committee Examining the Radiation Risks of Internal Emitters*,
Health Protection Agency, October 2004,
file: cerrie_report_e-book.pdf
www.cerrie.org

[78]     Bouchaud 2008
Bouchaud J-P,
Economics needs a scientific revolution,
*Nature*, vol 455, 30 October 2008, p 1181.

[79]     Bertell 2002
Bertell R,
Avoidable tragedy post-Chernobyl,
*Journal of Humanitarian Medicine*,
Vol II, nr 3, pp21-28, 2002,
International Institute of Concern for Public Health,
Toronto, Canada.
www.iicph.org/chernobyl

[80]     NDA 2006
*NDA Strategy*,
Nuclear Decommissioning Authority,
NDA-Final-Strategy-published-7-April-2006.pdf
www.nda.gov.uk
See also *Nature*, 23 November 2006, p.415.

[81]     NDA 2009
NDA report 020409.pdf
www.wcssg.co.uk/documentstore/

[82]
*Nature*, 23 November 2006 p415.

[83]     UCS 2007
*A brief history of reprocessing and cleanup in West Valley, NY*
Factsheet,
Union of Concerned Scientists, December 2007.
www.uscusa.org

[84]
www.world-nuclear.org/info/inf04.html

[85]     Broome 2008
Broome J,
The ethics of climate change.
*Scientific American*, June 2008, pp 69-73.

[86]     PEER 2009
*Radiation exposure limits weakened in departing Bush move*,
Public Employees for Environmental Responsibility (PEER),
News release, January 21, 2009.
www.peer.org/news

[87]     PEER 2009a
*Suit to air internal EPA protests on radiation exposure plan*,
Public Employees for Environmental Responsibility (PEER),
News release, October 28, 2009.
www.peer.org/news

[88]     Roussely 2010
Roussely F,
*Synthèse du rapport. Avenir de la filière Française du nucléaire civil*,
16 Juin 2010,
file: Synthese-ROUSSELY.pdf,
www.elysee.fr/president/les-actualites/rapports/2010/synthese-du-rapport-sur-l-avenir-de-la-filiere.9375.html
English translation (not very accurate):
www.psr.org/nuclear-bailout/resources/roussely-report-france-nuclear-epr.pdf

[89]     Schneider 2008
Schneider M,
*Nuclear power in France. Beyond the myth*,
Commissioned by the Greens-EFA Group in the European Parliament,
December 2008,
www.greens-efa.org/cms/topics/dokbin/258/258614.pdf