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EXECUTIVE SUMMARY

On January 21, 1968, while flying a 24-hour airborne alert mission, B-52G HOBO 28 mysteriously caught fire. All attempts to extinguish the fire failed, and the "bail out" command was given while the aircraft was flying towards Thule Airbase in Greenland for an emergency landing. All seven crewmembers ejected and the aircraft crashed into the sea ice of Wholstenholme Fjord approximately 8 miles west of Thule Airbase. The crash caused the conventional explosives in the four unarmed nuclear weapons to detonate dispersing plutonium and tritium from the ensuing fire in an oval pattern from the impact point.

The response to the incident to find, safeguard, recover, and return weapons contents to the United States, and to assess and mitigate effects on the local populace and ecosystem required over 700 personnel for a period of nine months.

Responding personnel encountered contaminated debris, ice and snow, along with unique and hostile weather conditions. Fortunately, surveys confirmed that most of the plutonium and tritium was confined in a blackened area corresponding to the debris pattern. This significantly reduced the potential for plutonium and tritium residues to become airborne and inhaled by response personnel. Monitoring of personnel, local villagers and the local ecology was performed.

Initial Exposure Evaluation

A comprehensive radiation monitoring and control program was established to assess exposures to personnel. Stringent monitoring of personnel who worked onsite within the control area as well as those involved with debris decontamination and packaging of recovered weapons components were strictly enforced. Air sampling confirmed that resuspension of plutonium was not a problem.

The monitoring program used nasal swabs as a "screening" or rough indicator of any airborne hazard. Nearly 10,000 nasal swabs performed on all personnel who crossed the "zero line", generally revealed no detectable alpha contamination. Tritium exposures were evaluated by on-site liquid scintillation counting with equipment that confirmed insignificant quantities of tritium were detected in urine samples taken on location.

Of the 9,837 nasal swabs performed, in-house analysis resulted in 335 samples with detectable gross alpha activity. The mean value of the gross alpha activity detected was 14 pCi, ranging from 0 to 208 pCi. One hundred ninety nine (199) of the samples that were analyzed on-scene showed detectable activity with a mean value of 51 pCi. These values were all below the acceptable level (action level) of 300 pCi on a nasal swab that was established for response force personnel.

Using experience from the Palomares accident that showed the high likelihood of contamination of samples collected on station, a urinalysis program to sample personnel for plutonium after return to base of assignment was implemented.

Of 756 urine samples analyzed for ²³⁹Pu, none showed detectable activity. Of the 345 urine samples analyzed for tritium, 29 samples resulted in measurable concentrations ranging from 0.008 to 1.29 microcuries per liter (μCi/L). This urine concentration is not considered to be

significant because its corresponding tritium body burden (0.054 mCi) is approximately 5% of the MPBB (1,000 μ Ci).

Exposure and Dose Updates

The current approach to limiting radiation exposure in the United States uses the concept of Committed Effective Dose Equivalent (CEDE) - a cumulative dose, weighted for the contributions of individual organs, and summed over a 50-year period. Operational quantities derived from the CEDE such as the Annual Limit on Intake (ALI) and the Derived Air Concentration (DAC) provide guidelines for limiting exposures to workers so that the overall dose limits will not be exceeded. The ALI is the activity of a radionuclide that would irradiate a person to the limit set by the ICRP for each year of occupational exposure. The DAC is found by dividing the ALI by the volume of air inhaled (2,400 m³) in a working year (2,000 hours).

Two computer models - Code for Internal Dosimetry (CINDY), and Lung Dose Evaluation Program (LUDEP ver 2.06) - evaluated in a previous effort for AFMOA were used in estimating intakes and doses from tritium and plutonium.

Available Data

The USAF RHL used analytical procedures and kept records that were identical or very similar to those used in their support of the Palomares Accident of 1966. However, those records have not been located to date, and may have been misplaced or discarded. AFMOA and AFIERA provided records in the form of:

- A text file containing 80-character data records of results identified as Thule, or Crested Ice, samples characteristic of the content and formatting that USAF RHL used for computer punched card recording in the 1960s and early 1970s.
- Copies of reports of the accident response, follow-up documents generated by USAF and the Department of Energy in responding to inquiries from veterans and the Government of Denmark, and selected publications from journals and conference proceedings.

Review of the data indicated that the exposure date or dates were not available, sample date information was limited, and results were not completely recorded for all cases. Social Security Account Numbers for United States personnel and unique identifiers assigned to Danish citizens at Thule were recorded and available. Fortunately, the results support the conclusions that significant exposures were not experienced at Thule.

Results

Tritium results for only 29 of 251 urine samples were greater than the minimum detectable and ranged from 0.008 μ Ci/L to 1.29 μ Ci/L. From those data and appropriate assumptions estimates of body content and committed effective dose equivalent were calculated. The case with the highest urinary concentration produced a maximum body content at exposure of 404 μ Ci, which is about 5 percent of the Annual Limit on Intake from inhalation of tritium (80,000 μ Ci), representing a CEDE of 0.026 rem.

Of 526 urine results for plutonium, none reported detectable amounts of plutonium above the minimum detectable activity (MDA) of 0.5 picocurie per 24 hours. Attempts to estimate upper bound intakes and doses from the urine results produced unrealistically high values. Results for

169 air samples collected during the operation provide a reasonable basis for developing alternate estimates of plutonium intake and dose. Estimates developed for three scenarios indicate that intakes were significant only for the most extreme scenario, which produced an estimated CEDE of 11.57 rem – about twice the annual occupational limit.

Conclusions

The available data have been evaluated and processed into a usable data set for identifying the bioassay data available for most participants in Operation Crested Ice. The urine analyses for plutonium content were not sufficiently sensitive to provide a realistic estimate of intake and dose. Other available data, such as air samples, allowed alternate estimates for plutonium intake and dose. Those estimates support conclusions that Operation Crested Ice was conducted safely without significant exposures to plutonium.

The urine analyses for tritium were sufficiently sensitive to support a realistic evaluation. All but 29 samples showed no detectable tritium radioactivity. The highest values for tritium were well below the annual limit of intake and produced CEDEs of much less than 1 rem. Thus, Operation Crested Ice was also characterized by the safe handling of tritium contamination.

Recommendations

The available data provide a basis for supporting Air Force response to inquiries from participants about their participation in the operation and the results. However, individual-specific evaluations are not possible with the existing data. The following recommendations provide additional efforts that could resolve some of the difficulties.

- Continue efforts to identify individual sample results, including cooperation with the Department of Energy in searching its records and information.
- Continue searches for other sources of paper records of sample analyses that may provide missing information about sample collection or exposure.
- Complete the database development and upload Thule sample data available.

1 INTRODUCTION

The Air Force Medical Operations Agency (AFMOA) requires assistance in evaluating and updating the radiation exposure records of personnel who responded to nuclear weapons accidents and incidents. AFMOA's needs include efforts:

- To identify, locate and review the records of the incident, radiation exposure assessments, and other information pertinent to the study.
- To evaluate current methods and models for estimating radiation doses and risks from the intake of radioactive materials contained in nuclear weapons.
- To recommend a methodology for conducting the re-evaluation of the available radiation exposure information.
- To evaluate any and all radiation exposure information, such as urine bioassays, nasal swabs, air sampling information, etc. for scientific soundness and possible use in updating the radiation records of the response personnel.
- To develop an information system for their use that provides comprehensive, user-friendly retrievals of the radiation exposure information for responding to inquiries from participants, the Department of Veterans Affairs, other agencies, and Congress.
- To update and prepare records for input to the Air Force Master Radiation Exposure Registry.

In a recently completed effort (LABAT, 2001), radiation monitoring data for the nuclear weapons accident of January 17, 1966 at Palomares, Spain were reviewed and evaluated, and committed effective dose equivalent estimated for participants. This report continues AFMOA's effort to review and evaluate radiation exposures by addressing the nuclear weapons accident that occurred at Thule Airbase, Greenland on January 21, 1968.

An onboard fire and crash of a United States Air Force B-52G bomber (HOB0 28) on the sea ice west of Thule AB, Greenland caused the explosion of the conventional explosive components of the four thermonuclear weapons, release of radioactive materials, and a nine-month, two-phased response and disposal effort. During the effort, personnel were potentially exposed to aircraft debris, weapons residue, ice and snow contaminated with tritium and plutonium.

A comprehensive radiation-monitoring program, designed with the benefit of lessons learned from the Palomares accident response, concluded that no personnel were exposed to significant amounts of plutonium or tritium. Nevertheless, AFMOA required a review of the records and updating of radiation doses using currently accepted methods to support inquiries generated by heightened interest in radiation exposure of the participants.

This report reviews the accident details and radiation assessment efforts and results in Section 2; summarizes current methods and models previously evaluated for the Palomares accident and their application to this accident in Section 3; and reviews the radiation assessment data from 1968, its accuracy and usefulness for updating radiation doses in Section 4. Section 5 discusses preliminary intake and dose estimates based on the available data. Section 6 concludes with a summary of the data evaluation effort and recommendations for proceeding with a dose-evaluation update effort

2 BACKGROUND

On January 21, 1968, while flying a 24-hour airborne alert mission, B-52G HOB0 28 mysteriously caught fire. All attempts to extinguish the fire failed, and the “bail out” command was given while the aircraft was flying towards Thule Airbase in Greenland for an emergency landing. All seven crewmembers ejected and the aircraft crashed into the sea ice of Wholstenholme Fjord approximately 8 miles west of Thule Airbase (Sundstrom 1970) at 4:39 p.m. Atlantic Standard Time. The crash caused the conventional explosives in the four unarmed nuclear weapons to detonate, dispersing the plutonium and tritium through the momentum of the debris and the smoke from the ensuing fire. The response to the incident to find, safeguard, recover, and return weapons contents to the United States, and to assess and mitigate effects on the local populace and ecosystem required over 700 personnel for a period of nine months.

Responding personnel encountered contaminated debris, ice and snow, along with unique and hostile weather conditions. The crash site was secured, and emergency protection measures were followed. Monitoring of personnel, local villagers and the local ecology was performed.

This section provides additional details about the accident itself, discusses the nature of the response, reviews, the methods, procedures and operations of the health and safety assessment program, and reviews the results and limitations of the assessment.

2.1 Accident Summary

The aircraft was abandoned while flying towards Thule Air Base to attempt an emergency landing with four nuclear weapons on board. The aircraft struck the ice at a shallow nose-down angle at a speed of over 500 knots, spreading debris and partially burned fuel over an area approximately 500 feet wide and 2,100 feet long (Hunziker 1970). Six of the seven crewmembers survived.

At the time of the crash, there were over 2,000 personnel stationed at Thule Airbase. Only 60 or so Greenlanders frequented the North Star Bay region, although that number could possibly grow to 200 during the hunting season. The main food sources for the local Greenlanders include seals, walrus, small mammals and birds. While fish are not normally used as food, certain fish that do migrate through the area are commercially caught elsewhere (Taschner 1995).

All four weapons were located at the crash site. However, the aircraft struck the ice with such speed that it broke up to such a level that, with the exception of the engines, all of the debris consisted of small components. The force of the crash caused the conventional explosives in all four nuclear weapons to detonate, resulting in the release of plutonium and tritium into the surrounding air, snow and ice. The heat from the fire and the violence of the explosions strew aircraft and weapons debris in an oval pattern from the impact point. Subsequent surveys confirmed that most of the plutonium and tritium was confined in a blackened area of ice, and snow corresponding to the debris patterned mentioned above. This significantly reduced the potential for plutonium and tritium residues to become airborne and inhaled by response personnel.

2.2 Response Summary

The first response to the crash was preliminary monitoring of the area by dogsled, which confirmed widespread alpha contamination, but no significant beta/gamma contamination. (McRaney 1970) Helicopter reconnaissance provided the first real view of the crash site, and the local Danish population was alerted. Shortly after word of the crash was received at the USAF Command Post on January 22, 1968, the Headquarters USAF Broken Arrow Control Group was mobilized.

Operation Crested Ice was initiated as the Department of State and Department of Defense established communications with the Danish government (Sundstrom 1970). Ultimately, over 700 personnel from over 70 agencies would be directly or indirectly involved in the recovery and cleanup operation. The peak involvement occurred on February 14, with 565 people (Hunziker 1970). The Commander in Chief, Strategic Air Command and the On-Scene Commander (Major General Robert O. Hunziker) were put in charge of the cleanup operation, and would work with the Danish government.

Upon arrival at the scene, General Hunziker assessed the situation, and began to request the personnel and material that would be required for the operation. These included items such as amphibious vehicles, arctic specialists and buildings for the base camp, and atomic specialists and equipment. The Military Airlift Command successfully transported much of the needed material. Thule Air Base also supplied material, including POL tanks that had been found in storage.

In February, American and Danish representatives held meetings to plan the recovery and cleanup efforts. Another meeting was held in Washington to further discuss and refine the cleanup operation. Towards the end of the search and recovery operation, the Vice Chief of Staff became the director of operations.

One of the early concerns faced was the inevitable comparison to the 1966 crash at Palomares, Spain. The Palomares crash also resulted in significant plutonium release, and produced measurable plutonium levels in responders; 26 of whom were monitored for almost two years (LABAT 2001). To help alleviate this problem, the Assistant Secretary of Defense for Public Affairs (ASDPA) made three press releases within the first two days. Despite the conditions and inherent difficulties of reaching and working in the crash site, many members of the media made the journey. The press was kept well informed of the recovery and cleanup progress.

Within days, the response team established a zero line using alpha scintillation (PAC-1S) instruments. Later surveys using the Lawrence Radiation Laboratory's Field Instrument for the Detection of Low-Energy Radiation (FIDLER) provided more reliable quantitative information about the contamination levels. These confirmed the majority of the contamination was confined to the blackened area mentioned above. Of the approximately 6 kg of plutonium (Taschner 1995) contained in the four thermonuclear weapons, scientists estimated that 3.15 kg were confined to the blackened area, 0.35 kg were confined in the ice, and the remainder was associated with aircraft debris. A total of 1,350 Curies (Ci) \pm 20% of tritium was also confined to the blackened area.

The aircraft debris was removed by airmen who walked shoulder to shoulder in order to pick up individual pieces. All of the debris was cleared from the area by March 15 (Sundstrom 1970) and

placed in 217 containers for shipment to the United States. An additional sixty-seven 25,000 gallon containers were filled with contaminated snow and ice, along with four more that were filled with contaminated clothing, tools, etc. The work was completed on March 30, 1968, officially ending the evaluation and recovery phase of Operation Crested Ice (Hunziker 1970). Activities involving final storage, sealing and decontamination continued until April 10. Preparation of contaminated debris, ice and snow for shipping and disposal was completed on September 13, 1968 (Dresser 1970).

The cleanup operation involved a series of sampling of personnel, equipment, debris, ice, water and air. It was ultimately determined that the contamination would prove no significant threat to the ecosystem and the inhabitants of Greenland.

2.3 Summary of Health Assessment Activities

This accident released tritium and plutonium from nuclear weapons onto the sea ice off the coast of Greenland. Although generally confined to accident debris and a well-defined area of blackened snow and ice, the contamination posed potential exposure hazards to response and recovery personnel, especially under the extreme Arctic weather and ice operating conditions. Consequently, a comprehensive radiation monitoring and control program was established to assess exposures to personnel.

2.3.1 Monitoring and Sampling

2.3.1.1 Monitoring

Stringent monitoring of personnel who worked onsite within the control area as well as those involved with debris decontamination and packaging of recovered weapons components were strictly enforced. Alpha monitors (PAC-1S) provided real-time assessments of contamination, which was prevalent on shoes and other articles of clothing. Action limits for alpha contamination, as measured by the PAC-1S, of 450 counts per minute for U.S. personnel and "none detectable" for foreign nationals were established. Air sampling with high volume air samples confirmed that resuspension of plutonium was not a problem (McRaney 1970).

2.3.1.2 Sampling

The monitoring program used nasal swabs as a "screening" or rough indicator of any airborne hazard. Problems with the nasal swab testing included running noses due to the extreme cold and the fact that many personnel simply did not like the testing method. Nearly 10,000 nasal swabs performed on all personnel who crossed the "zero line", generally revealed no detectable alpha contamination. The USAF Radiological Health Laboratory provided onsite counting for nasal swabs, air and swipe samples, thereby allowing prompt identification of serious contamination situations (McRaney 1970).

In addition to the alpha monitoring, tritium exposures were evaluated by on-site liquid scintillation counting with equipment provided by the Sandia Corporation at Livermore, California. This equipment confirmed that the tritium present in ice cores and other samples was

not a hazard to personnel since insignificant quantities of tritium were detected in urine samples taken on location (McRaney 1970).

Using experience from the Palomares accident that showed the high likelihood of contamination of samples collected on station, a urinalysis program to sample personnel for plutonium after return to base of assignment was implemented. The USAF RHL developed rosters of personnel who participated, as well as notification letters informing departing personnel of the requirement to submit a 24-hour urine specimen upon returning to their base of assignment. USAF RHL served as the clearinghouse to ensure that the collection of these important samples was completed (Odland 1970). The laboratory analyzed approximately 800 urine samples collected during this program.

2.3.2 Interpretation of Urine Results

At the time of the Thule accident, internal exposures to radioactive materials were evaluated in terms of a maximum permissible body burden (MPBB). The MPBB was developed as an operational tool for limiting dose to a critical organ (the organ judged most susceptible to radiation effects) during a period, such as a calendar quarter or year. For materials that the body eliminated relatively quickly, such as tritium, the radiation dose was delivered over a relatively short time; i.e. less than a year. In those cases, MPBBs were developed to limit dose to the critical organ during a calendar quarter. Radioactive materials that the body eliminates relatively slowly, such as insoluble plutonium oxide, delivered the dose over periods of years or more. In that case, the MPBB was calculated to provide adequate protection over a working lifetime. The dosimetry model used assumed uniform deposition of the radionuclide in the organ, energy emitted equals energy absorbed, and the characteristics of the model could be represented by "Standard Man" data.

2.3.2.1 Tritium

Tritium, an isotope of hydrogen (^3H), was present in the snow, ice, and aircraft debris following the crash of HOBO 28. Initially released in gaseous form, tritium burned in the explosion and fire following the crash. Consequently, some of the gas was dispersed downwind in the fire and smoke plume, and some was converted to tritium oxide (tritiated water) and dispersed in the plume. The remainder was deposited on aircraft debris or incorporated into the snow and ice. The gaseous and water form of airborne tritium can be inhaled or ingested and the tritium from contaminated surfaces could be resuspended and inhaled or ingested through hand to mouth transfer. Once tritium enters the body, the water form distributes throughout the body's water and tissues within hours and irradiates body tissues. The body eliminates tritium, primarily through the urine, at a rate that is similar to the rate of water elimination. Studies of tritium's behavior indicate that tritium is excreted with a biological half life of about 10 days, or at a constant rate of about 7% per day under normal conditions. Increasing the intake of water and exercise can increase the tritium elimination rate.

In 1968, results of urinalysis for tritium were evaluated in terms of the maximum permissible body burden of ^3H as recommended by the National Bureau of Standards (NBS) in Handbook 69 (NBS 1959). The NBS recommendations were based in part on Publication 2 of the International Commission on Radiation Protection, *Recommendations of the International Commission on*

Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, published in 1959 (ICRP 1960). The MPBB for ^3H considered body tissues as the “critical organ” and had a value of 1,000 μCi .

2.3.2.2 Plutonium

The urine analysis results were evaluated in terms of the maximum permissible body burden (MPBB, see Appendix A) of ^{239}Pu as recommended by the National Bureau of Standards (NBS) in Handbook 69 (NBS 1959). The NBS recommendations were based in part on Publication 2 of the International Commission on Radiation Protection, *Recommendations of the International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation*, published in 1959 (ICRP 1960). The MPBB for ^{239}Pu considers the bone as the “critical organ” or the organ that is most susceptible to radiation from plutonium and is the basis for developing protection limits. The body burden is defined as that portion of ^{239}Pu distributed by systemic circulation. It does not include that amount fixed in the lungs. The MPBB was 0.044 microcurie (μCi) of ^{239}Pu .

An individual’s body burden was estimated from the measured urinary gross alpha for initial samples. The following equation was used, taken from Langham (Langham 1956):

$$D_r = 435 U t^{0.76}$$

where:

- D_r = retained systemic body burden; meaning the amount retained in the body “t” days after exposure
- U = ^{239}Pu activity in a 24-hour sample
- t = time in days from exposure to sampling

Analysis of systemic body burden from urinary results required assumptions about the type of exposure (acute or continuous), and about whether samples represented true 24-hour urine outputs. This calculation applies to a single acute exposure. These calculations apply when ^{239}Pu is detected in urine samples. Apparently if none was detected above the detection level, then no further evaluation was attempted.

2.4 Summary of Results

Of the 9,837 nasal swabs performed, in-house analysis resulted in 335 samples with detectable gross alpha activity. The mean value of the gross alpha activity detected was 14 pCi, ranging from 0 to 208 pCi. One hundred ninety nine (199) of the samples that were analyzed on-scene showed detectable activity with a mean value of 51 pCi. These values were all below the action level of 300 pCi (Odland 1970).

The USAF RHL analyzed 756 urine samples for ^{239}Pu using alpha spectrometry procedures similar to those employed for the Palomares accident (Odland 1968a). None of the samples showed detectable activity. A quality control spike of ^{236}Pu was added to each of the specimens with an average recovery of 81 +/- 9.5 %. The laboratory estimated a detectable level of 0.5 pCi per 24-hour specimen considering a 50-minute counting period and the efficiency of the alpha spectrometry detectors. Ten samples were also analyzed for gross alpha activity. Activities of

about 0.5 pCi per 24-hour sample were found. This was not considered unusual, since the background radiation level of thorium at Thule was above average (USAF RHL, undated).

Of the 345 urine samples analyzed for tritium, 29 samples resulted in measurable concentrations ranging from 0.008 to 1.29 microcuries per liter ($\mu\text{Ci/L}$). This urine concentration is not considered to be significant because its corresponding tritium body burden (0.054 mCi) is approximately 5% of the MPBB (1,000 μCi) (Odland 1970).

3 SELECTION OF DOSE METHODOLOGY

Responders to the Thule accident encountered sources of possible exposure from plutonium and tritium-contaminated aircraft debris, and contaminated snow and ice. Evaluation of the potential radiation effects requires estimates of the exposure and associated radiation dose, and comparison with knowledge about the effects of radiation on human health. Furthermore, these evaluations must take into account current knowledge and apply accepted methods for estimating the radiation exposure and dose. The approach to accomplishing these estimates is guided by recommendations of both international and national scientific bodies concerned with radiological protection. These bodies, primarily the International Commission on Radiological Protection (ICRP) have published recommendations on the relevant guidelines for limiting radiation effects and exposure, and estimating doses from radioactive materials that may enter the body, as plutonium and tritium do.

This section reviews the current understanding of those guidelines and approaches, describes the mathematical models and methods available to estimate the doses, describes the evaluation and selection of models and methods for this project, and summarizes the interpretation of radiation effects on human health.

3.1 Review Internal Dosimetry Methods

The current approach to limiting radiation exposure in the United States is derived from recommendations in ICRP Publications 26 and 30. The ICRP approach uses the concept of Committed Effective Dose Equivalent (CEDE) - a cumulative dose, weighted for the contributions of individual organs, and summed over a 50-year period. Operational quantities derived from the CEDE such as the Annual Limit on Intake (ALI) and the Derived Air Concentration (DAC) provide guidelines for limiting exposures to workers so that the overall dose limits will not be exceeded. The ALI is the activity of a radionuclide that would irradiate a person to the limit set by the ICRP for each year of occupational exposure. The DAC is found by dividing the ALI by the volume of air inhaled ($2,400 \text{ m}^3$) in a working year (2,000 hours) (ICRP 1979).

For internal exposures, determining the dose requires knowledge of the following questions:

- How does the material get into the body?
- Once in the body, how quickly does the material move to other organs?
- Does the material in the initial organ leave the organ or does some remain?
- Once in an organ, how does the material irradiate the organ and other organs?

- Once in an organ, how does the material move to other organs?
- Finally, how is the material eliminated from the body if at all?

Answers to these provide the basis for developing an approach to calculate the dose to organs, the effective dose equivalent to the body, and interpreting the effects of the dose.

3.1.1 Internal Dosimetry Methods

The methods for estimating organ dose from internal radionuclides have evolved since radioactive materials were discovered and used. Until 1979, ICRP Publication 2 provided the guidelines and methodology. In 1979, ICRP Publications 26 and 30 changed the basic approach to limiting radiation, and for internal radionuclides in particular. That approach currently remains the accepted approach in the United States for purposes of regulation. However, progress in all areas of radiation effects and the behavior of radionuclides in the body have produced more recent recommendations on a number of key elements in the process as presented in ICRP Publications 54, 60 and 66.

3.1.1.1 ICRP-30 Models and Methods

The ICRP changed its basic recommendations and revised the system of dose limitation in ICRP Publication 26 based on the availability of sufficient information about the effects of radiation to estimate risk for fatal cancer from a unit dose equivalent in exposed people and in the risk of serious disease to offspring of exposed people. The basic recommendations addressed both stochastic effects and non-stochastic effects. For stochastic effects, such as cancer and hereditary effects, risks are assumed to be directly related to dose equivalent with no threshold meaning that the probability of the effect occurring, rather than the severity, is related to the dose equivalent. The severity of non-stochastic effects, such as cataracts and erythema, varies with dose, usually above a threshold or minimum dose.

The revised dosimetry model of ICRP Publication 30 assumes that organ retention is represented by one or more exponential expressions, that the critical organ concept no longer applies, that dose in an organ must consider radiation emitted by other organs in the body, and that the physical characteristics are represented by "Reference Man" data in ICRP Publication 23 (ICRP 1975). The model assumes that deposition in an organ is uniform, and that the total dose is averaged over the organ.

Under the revised system, dose equivalent limits are intended to prevent non-stochastic effects and to limit stochastic effects to acceptable levels. To meet this end, an annual occupational limit of 50 rem (0.5 Sv) to an internal organ was established (ICRP 1979). For stochastic effects, the limit on risk is equal whether the whole body is irradiated or non-uniform irradiation of organs occurs. This is accomplished by assigning organ weighting factors, w_T , that represent the ratio of the risk for the effect in an organ to the risk for whole body irradiation. The limit on risk to the whole body is then determined by summing the contributions for each irradiated organ and is given by:

$$\sum_T w_T H_{50, T} \leq 5 \text{ rem (0.05 Sv)}$$

where $w_i H_{50,T}$ is called the weighted committed dose equivalent or the committed effective dose equivalent, and $H_{50,T}$, called the committed dose equivalent (CDE), is the total dose equivalent averaged over tissue (T) in the 50 years following intake and is limited to 50 rem (0.5 Sv).

3.1.1.2 System Deposition and Retention Models for Tritium from ICRP-30

Tritium at Thule existed in either elemental form (HT or T₂) or as water vapor (HTO). Generally, inhalation of elemental tritium considers direct exposure in the lung and conversion to the water form (HTO) in the intestinal tract. The ICRP also notes that the dose and dose limit for elemental tritium differ from those for tritium as water by a factor of more than 10,000 (ICRP 1979). Consequently, treatment of exposures from tritium in water form provide more than adequate protection from elemental tritium under most exposure conditions.

Models that describe the behavior of tritium in elemental and water form have been developed and published in ICRP-30. Figure 1 illustrates those models.

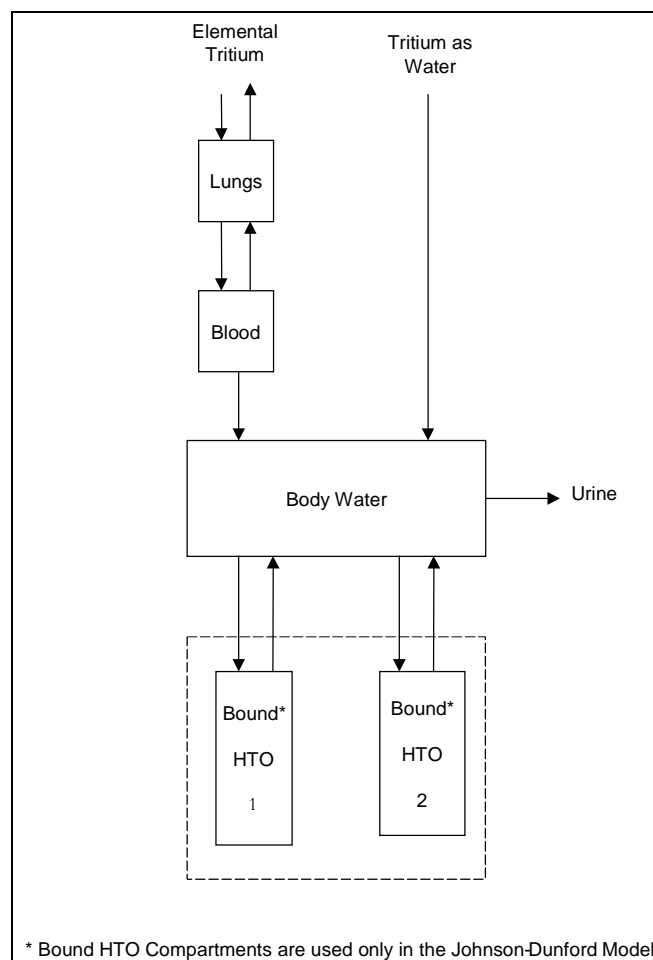


Figure 1. Tritium metabolic model.

Water Vapor

The ICRP-30 model (ICRP 1979) for inhaled or ingested tritium as water assumes the tritium is instantaneously absorbed and mixed with body water. Retention in the body water is represented by a single exponential with a half-life of 10 days. The rate of change of the tritium activity in body water is given by the following expression:

$$\frac{dY}{dt} = I(t) - KY + D$$

where: Y = activity of tritium in body water, pCi

I(t) = intake rate of tritium into the body, pCi/d

K = removal rate constant for tritium from body water, d⁻¹

D = net radioactive decay rate of tritium, pCi/d

Following this, the fraction of tritium taken into the body, which is retained at time *t* days later, R(t), is given by:

$$R(t) = \exp(-0.693 * t / 10)$$

An alternate model for tritium metabolism, proposed by Johnson and Dunford, considers two additional compartments that account for conversion and elimination of bound tritium. However, these will not be considered further here because studies have noted that these additional pools contribute less than 10% of the committed dose equivalent to the whole body from inhaled and ingested tritiated water and were not considered further by the ICRP (ICRP 1979).

Elemental Tritium

The ICRP model for elemental tritium only considers exposure from tritium in the lungs as a gas during breathing. Since some of the elemental tritium can be converted to tritiated water, some models include additional components that treat the tritium as water (HTO). Equations are developed that describe the amount of tritium in the lungs and blood during the exposure (ICRP 1979).

3.1.1.3 Excretion Functions

The tritium in body water is excreted with a half life of 10 days (ICRP 1988). The concentration of tritium in urine can be evaluated for dilution in the total volume of body water, which is taken as 42,000 grams from Reference Man (ICRP 1975). The concentration of tritium in urine is represented by the following equation:

$$C_u(t) = 1/42,000 \exp(-0.693 t / 10)$$

where $C_u(t)$ is the tritium concentration in urine at time *t* following an acute intake, in pCi/ml, and 10 days is the excretion half-time for tritium. The total activity of tritium in the body water can be determined from the actual metabolic model chosen and the excretion rate at any time. Factors are included for the loss of tritium through the skin and by exhalation.

3.1.2 Description of Computer Models

Many computer programs have been developed and are available for performing the calculations of the models discussed above. Currently more programs automate the ICRP-30 system than the ICRP-66 model. This comes as no surprise since the ICRP-30 system remains the current system for regulation of the doses from radioactive materials in the United States. As part of a previous effort for AFMOA (LABAT 2001) three computer models were evaluated for use in estimating intakes and doses from plutonium - the Radiological Bioassay and Dosimetry Program (RBD) as modified for the Air Force, Code for Internal Dosimetry (CINDY), and Lung Dose Evaluation Program (LUDEP ver 2.06). CINDY and LUDEP were selected. Those two models will also be used for performing intake and dose assessments for Thule personnel when adequate data are available.

3.2 Interpretation of Radiation Dose

This study of exposure to plutonium at Palomares and calculation of possible doses to internal organs raises questions about the possible health effects that may be associated with them. This section provides a brief summary of our understanding of the possible health effects from ionizing radiation and plutonium in particular, some of the guidelines for limiting exposure to it, and some basic information about the possibility that a certain dose could cause some kind of effect on health.

3.2.1 General Radiation Effects

In discussing health effects relating to ionizing radiation, the term “dose” is used. “Dose” comes from the early medical use of x-rays, much as a dose of medicine is measured in grains or ounces. It refers to the amount of radiation energy absorbed by an organ, tissue, or cells, measured in rem (or Sv). Today, the average American receives a dose of 0.3 rem (0.003 Sv) every year from natural sources—radioactive materials in rocks and soil, cosmic radiation, radon, and radioactivity in our bodies. Over a 70-year lifetime, the cumulative background dose averages 21 rem (0.21 Sv). In some areas of the world, people receive much higher doses from background radiation. For example, in areas of India and Brazil the ground is covered with monazite sand, a radioactive ore. Radiation exposure rates there are many times the average background levels elsewhere. People who live in these areas receive doses of up to about 0.7 rem (0.007 Sv) each year from the gamma radiation alone (NAS 1990). These levels combined with the other sources of background radiation (cosmic rays, radon, etc.), cause average doses that are about three times more than the U.S. average. Yet these people show no unusual rates of cancer or other diseases linked to radiation.

The effects of ionizing radiation can be categorized as either prompt or delayed, based on the time frame in which the effects are observed. Prompt effects, like rapid death, occur when high doses are received in a short period of hours to weeks. Delayed effects, such as cancer, can occur when the combination of dose and dose rate is too small to cause prompt effects. Both animal experiments and human exposures to high levels of radiation show that ionizing radiation can cause some cancers (NAS 1990). All of the observed effects of ionizing radiation in humans occur at relatively high doses. At the low doses that are of interest to radiation workers and the

general public (that is, below a few rem), studies to date are inconclusive (NAS 1990). Although adverse health effects have not been observed at low doses, the carcinogenic nature of ionizing radiation makes it wise to limit the dose.

For low-doses, there are no conclusive data that relate dose to health effects or showing a threshold, or minimum, level for cancer. Because of this, experts who study radiation effects have decided that the results from high-dose, high-dose-rate studies must be used to control the low-dose, low-dose-rates experienced by workers and the public. A convenient way to do this is to assume that no effects occur at zero dose. In addition, since the rate at which effects occur is extrapolated from higher doses, it is also assumed that the effect increases linearly with dose. These two assumptions are known as the “linear-dose-response, non-threshold” (LNT) hypothesis. This implies that the same number of additional cancers would occur from exposing 100 persons to 100 rem (1 Sv), or 10 thousand persons to 1 rem (0.01 Sv), or 10 million persons to 0.001 rem (0.00001 Sv). No prompt effects have ever been reliably observed in humans below about 10 rem (0.1 Sv). Reports from the Japanese atomic bomb survivor studies conclude that the location and reality of such a threshold, if one does exist, are difficult to assess. Nevertheless, the Health Physics Society (HPS 1996) has stated that “Below 10 rem (which includes occupational and environmental exposures), risk of health effects are either too small to be observed or are non-existent.”

Within the first 30 years after the discovery of x-rays, standards were developed for the measurement of radiation. At about the same time, acceptable levels of dose were set. The first level, known as the ‘tolerance dose’, or that amount of radiation that could be tolerated, was set at one-tenth of a unit (about 0.1 rem (0.001 Sv) in today’s units) per day for 300 days a year, which amounts to 30 rem (0.3 Sv) in a year.

From World War II to the early 1980s, radiation dose limits were adjusted downward in response to increased concern about radiation effects, the increased uses of radiation, and because improved radiation protection technologies appeared. The National Council on Radiation Protection and Measurements (NCRP, established in the 1930s) developed the recommended changes for the United States. During that time, the dose limit was reduced from three-tenths of a rem in a six-day period in 1946 to 5 rem (0.05 Sv) per year in the mid-1950s. In addition, a limit for the public was set at one-tenth of the worker limit to provide an additional margin of safety.

Research does not show a clear threshold dose for cancers from radiation, so the small risk per person at low doses had to be considered in relation to the large number of workers who were receiving those doses (NCRP 1993b).

The NCRP adopted three radiation protection principles: (a) no practice shall be carried out unless it produces a positive net benefit (sometimes called justification); (b) all exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account (called optimization); and (c) the dose equivalent to individuals shall not exceed the recommended limits (called limitation). These principles work together to protect against both prompt and delayed effects in large groups of workers and the public.

In 1993, the NCRP released a new set of national recommendations based on International Commission on Radiation Protection’s 1990 recommendations. Those limits for non-threshold effects differ slightly from the earlier recommendations: 50 rem (0.5 Sv) per year to any tissue or

organ and 15 rem (0.15 Sv) to the lens of the eye to avoid cataract formation. The recommended occupational limits on whole-body doses (total effective dose equivalent), first set at 5 rem (0.05 Sv) per year in 1958, are now set at no more than 5 rem (0.05 Sv) in any one year and a lifetime average of no more than 1 rem (0.01 Sv) per year (NCRP 1993a).

Occupational radiation exposure limits for federal agencies are currently established in "Radiation Protection Guidance to Federal Agencies for Occupational Exposure," 52FR 1717, signed by President Reagan on January 20, 1987. The Nuclear Regulatory Commission implemented that guidance in its regulations on radiation protection (Title 10, Code of Federal Regulations, Part 20). These limits apply to all licensed uses of radioactive material under NRC's jurisdiction. Similarly, other Federal agencies as a matter of policy and directive, including the DoD in DODI 6055.8, Occupational Radiation Protection Program, also observe this guidance.

The current established protection standards are (NRC 1999):

- 5 rem in a year for workers (to protect against cancer).
- 50 rem in a year for workers to any organ (to protect against threshold effects, such as radiation burns, etc.).
- 50 rem in a year to the skin or to any extremity.
- 15 rem in a year to the lens of the eye (to protect against cataracts).
- 0.1 rem in a year (70-year lifetime) for members of the public.

These limits are in addition to the radiation doses a person normally receives from natural background, medical testing and treatment, and other sources.

The protection standards mentioned above provide regulatory guidelines to be used primarily for designing radiation protection programs and facilities. Their intent is to limit dose to a worker so that risk is limited to levels that are similar to so-called "safe industries." Limits for the public perform the same purpose but generally include additional margins of safety to account for a wider range of ages (childhood to aged), more diverse health condition, and individual sensitivities. Their primary purpose is to prevent exposures that are associated with risks exceeding the established guides.

These guidelines also offer usable comparisons for evaluating the possible effects of exposures. For example, the occupational limit of 5 rem (0.05 Sv) in a year provides one such value. Since 5 rem (0.05 Sv) represents an acceptable risk, any exposure below 5 rem (0.05 Sv) should be considered acceptable. NCRP recommends that the average dose equivalent per year for workers should not be more than 1 rem (0.01 Sv) a year over 50 years or work. That is the same as 50 rem (0.5 Sv) in 50 years. Therefore, 50 rem (0.5 Sv) provides a reasonable guide for an exposure from radioactive materials in the body, such as plutonium. Since these guides are set with margins of safety, receiving a higher dose does not mean that one will be harmed. However, it would mean that further evaluation might be needed to determine whether the exposure was a one-time incident or one that could recur.

An alternate approach to evaluating the possible effects of an exposure considers the possibility that an exposure will lead to health effects, such as cancer or hereditary effects. The NCRP has provided risk factors for the probability that a certain dose equivalent from radiation will cause

an effect. Those factors for workers are 0.0004 per rem (0.04 per Sv) for fatal cancer, 0.00008 per rem (0.008 per Sv) for non-fatal cancer, and 0.00008 per rem (0.008 per Sv) for hereditary disorders for a total of 0.00056 per rem (0.056 per Sv) (NCRP 1993a). For members of the entire population, these factors are 0.0005 per rem (0.05 per Sv) for fatal cancer, 0.0001 per rem (0.01 per Sv) for non-fatal cancer and 0.00013 per rem (0.013 per Sv) for hereditary disorders, for a total of 0.00073 per rem (0.073 per Sv).

3.2.2 Health Effects of Tritium

As discussed above, tritium that enters the body distributes very quickly throughout the water in the body. The tritium subsequently enters organs along with the water. Once inside the organs, tritium's low energy beta-particle emissions irradiate internal cells. In effect, tritium distributes throughout the body and irradiates the organs uniformly. Therefore, tritium exposures are treated as whole body exposures. Consequently, the possible effects on health from tritium exposure are the same effects as those resulting from irradiation of the body with radiation from sources outside the body. These effects and their limits are discussed in the previous section.

3.2.3 Health Effects of Plutonium

Plutonium, discovered in 1941, is radioactive and can be dangerous when it gets into the human body. Some have even referred to plutonium as "the most toxic substance known to man. Early concerns about the health risks of plutonium arose from knowledge of the effects of radium, discovered by Marie Curie in 1899. With its half-life of 1620 years, radium-226 presents an intense and constant radiation source for hundreds of years. Early uses of radium exposed workers to significant doses with acute cases ending in rapid death, and lower exposures leading to infections of the jawbones, pathological bone fractures, or cancers of the bone.

The National Bureau of Standards addressed radium's dangers by developing an occupational standard for radium, adopted in May 1941, about two months before the discovery of plutonium. Scientists on the Manhattan Project then recognized the potential hazards of plutonium, which is similar to radium. They estimated that plutonium would be roughly as dangerous as radium when comparing equal masses.

Plutonium gives off alpha particles that produce heavy ionization and give up their energy more quickly than the lighter beta particles, or x-rays and gamma rays. In air, alphas travel only 3 to 5 centimeters and in living tissue only about 30 micrometers. That distance is less than the thinnest part of the dead layer of external skin cells (called the epidermis), or the thickness of a piece of paper (about 100 micrometers). Because of this low penetrating power, materials that give off alpha particles present no hazard when kept outside the body.

Unfortunately, when they get inside the body, alpha emitters come into very close contact with the body tissues and irradiate cells. Plutonium can be inhaled, ingested, or passed into the blood stream through a wound. When that happens, about 90 percent eventually goes to the lung, liver, or bones.

The half-life of plutonium-239 is 24,065 years. This half-life is short enough that 1 microgram of material will undergo more than 2000 decay events per second, but it is long enough to allow that microgram to decay at an approximately constant rate for thousands of years.

No one has ever died from an acute plutonium uptake. But, researchers have estimated lethal doses from studies on dogs, rats, and mice, which indicate that a few milligrams of plutonium per kilogram of tissue is a lethal dose. Extrapolated to humans, an intravenous injection of about 22 milligrams into an average human (70 kilograms; about 154 pounds) would be lethal within about 30 days to half the people exposed. Inhalation would require about four times more or 88 milligrams.

Recognizing the similarity of plutonium to radium, scientists worked to develop exposure standards that would limit the risks to workers, especially on the important war-time effort of developing a plutonium-implosion bomb. Beginning in 1945, those efforts have evolved into a set of radiation protection recommendations that have received international acceptance. In 1977, the ICRP published major revisions in those recommendations that based radiation protection for plutonium on dose rather than deposition in the body. Those recommendations, known as ICRP 30, have been largely adopted in the United States. In 1991, the ICRP published new recommendations (ICRP 60), which reduced the recommended annual occupational limit to 2 rem (20 millisieverts) per year. Thus far, these recommendations have not been adopted in the United States, however, they are considered in most radiation protection assessments.

Plutonium absorption in the body depends mainly on the plutonium compound and how it enters the body. The body generally absorbs the soluble forms (nitrates, citrates, and certain oxides) more readily than insoluble forms. Plutonium absorption through intact skin is usually quite low, but deposits in tissues through puncture wounds, cuts, and somewhat less through skin burns. Soluble plutonium begins movement throughout the body within minutes or hours of the uptake and may move to the lymph nodes near the wound; remaining for years. Some insoluble plutonium gets into the blood circulation quickly, but most remain at the site and are slowly redistributed over weeks and months. About 90 percent of the systemic burden deposits in the liver and bones. The kidneys excrete plutonium in urine that represents the concentration of the plutonium in the blood making plutonium measurements in urine a convenient indicator of plutonium in the body.

Ingesting plutonium is perhaps the least likely means for plutonium to enter the body. But even if plutonium is ingested, the gastrointestinal tract provides a natural barrier, and in adults only about 0.05 percent of the soluble plutonium compounds and a mere 0.001 percent of the insoluble ones enter the blood stream. The rest of the plutonium simply moves out of the body in feces.

Inhalation of plutonium dust provides the most likely entry route for plutonium. Particle size affects plutonium absorption. Smaller particles are more likely to be retained. Particles over 10 micrometers in diameter (considered large) are filtered out in the nose and upper respiratory region, swallowed, and eventually passed out through the gastrointestinal tract. Particles less than 10 micrometers in diameter (called respirable particles), deposit on the mucus layer of the bronchial tubes. Through a process, known as lung clearance, hair-like structures of the lining (called cilia) transport the mucus layer and dust particles up to the throat, removing much of the foreign material deposited in the bronchial tubes.

Smaller particles, especially those under 1 micrometer in diameter, are carried down into the tiniest airways of the lung and into alveoli (also known as air sacs). These structures have no

effective lung-clearance mechanisms, but scavenger cells called phagocytes, engulf the inhaled plutonium particles, and transport them into lymph nodes or into lung tissues.

Autopsy studies reveal that, initially, plutonium is mostly deposited on the bone surfaces. Less than 5 percent of the plutonium is typically found within the bone marrow. Based on this pattern of deposition, the primary carcinogenic risk from plutonium in the skeleton is bone cancer. There is no conclusive evidence that plutonium increases the risk for leukemia, which is the unchecked proliferation of certain blood cells produced in the bone marrow.

Plutonium in the bone remains there for a very long time, gradually being redistributed throughout the bone. Current models (based on observation of exposed persons and autopsy data) estimate a half time of about 50 years for plutonium retention.

The plutonium deposited in the liver is eventually transformed from relatively soluble forms in hepatic cells into insoluble forms (hemosiderin deposits), which are sequestered in the cells that form the linings of liver ducts (reticuloendothelial cells). The retention half time for the plutonium deposited in the liver is approximately 20 years.

To date, there have been only few epidemiological studies of workers exposed to plutonium. Studies of workers at Los Alamos National Laboratory (Wiggs 1994) and Rocky Flats (Wilkinson 1987) are the only ones in the United States to have used quantitative measurements of plutonium exposures, but they involved few workers: 303 at Los Alamos and 1450 at Rocky Flats. These two studies showed no evidence of statistically increased rates of lung, liver, and bone cancers, which are shown in animal experiments to be the highest-risk cancers due to plutonium exposure. Another study (Reyes 1984) indicates that an increased brain-cancer rate in Rocky Flats workers was not caused by plutonium exposure or external radiation.

A study (Voelz 1983) involving 224 males exposed to plutonium between 1944 and 1974 who had plutonium deposition greater than 0.16 microgram (0.01 microcurie) found no cases of bone or liver cancer. By 1980, the final year of the study, only one person had died of lung cancer indicating risks were much lower than predicted by some nuclear-industry critics. Another study looked at 26 chemists, metallurgists, and technicians at Los Alamos, who were accidentally exposed to plutonium between 1944 and 1946. Their plutonium body burdens ranged from 50 Bq to 3,180 Bq when estimated by analysis of their urine (Voelz 1997). Interestingly, the mortality rate of these men has been lower than that of the population in general, and in 1996, 19 of them were still living.

Of those who are no longer alive, one died of lung cancer in 1989, at the age of 66, and two died of prostate cancer and congestive heart failure, respectively, but both had lung cancer at the time of death. All three men were very heavy smokers. Significantly, three cases of lung cancer are consistent with the national cancer incidence rate, over the same period, in U.S. white males of the same age. Another subject, who had an estimated plutonium deposition of 0.245 microgram, developed a rare bone cancer 43 years after exposure and died in 1990. This finding is statistically significant for the small group of 26, but in the Los Alamos study (Wiggs 1994) of 303 workers, this same individual remained the only one to have developed bone cancer. That one death from bone cancer in this larger group could well be due to chance and is not statistically significant. Finally, three more died of causes unrelated to cancer.

Overall, data from the several studies of persons exposed to low levels of plutonium radiation in the United States do not show a relationship between dose and effect. They merely indicate that such a relationship does not exist or cannot be confirmed. If plutonium is harmful at these low levels, its health risks are so small that, given the small number of workers involved, epidemiological methods cannot differentiate between effects triggered by plutonium radiation and variations in a group of people unexposed to such radiation.

Although studies on plutonium workers in the United States did not demonstrate the risk from plutonium radiation, there are data from much higher doses to which Russian plutonium workers have been exposed. Russian scientists have recently published two studies (Tokarskaya et al.1997, Koshurnikova et al.1998) of workers who had been exposed to plutonium at the Mayak Plant. The authors demonstrate that an increased risk for lung cancer is associated with higher exposures. Although both studies investigate this risk on many of the same workers, their conclusions about the relationship between dose and risk are different.

In one study, (Koshurnikova 1999) analyzed data from a cohort of 1479 workers who had been exposed to high doses of various types of radiation, including plutonium radiation, between 1948 and 1993. The control group was composed of 3333 other workers at Mayak who had also been exposed to radiation but within occupational limits. The study found a linear relationship between lung doses from 0.5 to 30 sieverts (or 50 to 3000 rem) and standardized mortality ratios. While this result found no threshold for effects, the trend of increasing rates with increasing dose is impressive.

The second study (Tokarskaya 1997) found a nonlinear threshold relationship between dose and lung cancer risk in a case-control study devoted to 162 plutonium workers who developed lung cancer between 1966 and 1991 and a control group of 338 Mayak workers who, during the same period, did not. The authors found no lung cancer risk up to a threshold dose of 16 sieverts, corresponding to about 1.6 micrograms of plutonium deposited. Above this threshold value, however, the risk rises rapidly. The two Russian studies are very different in the dose response relationships reported. However, the data demonstrate that lung cancer risk does indeed increase with higher doses.

It has been almost six decades since plutonium was first made. No doubt, the dangers of plutonium are real. However, plutonium has been handled in different chemical forms, fabricated as a metal, machined, and used successfully primarily because standards and procedures were established early. Because of this, there has been no instance of acute death from taking plutonium into the body.

4 DATA REVIEW, ASSESSMENT, AND PREPARATION

The response effort discussed in Section 2 included a health evaluation program that generated records of the possible doses to those who responded to the accident. The USAF RHL performed preliminary analyses of nasal swabs and urine samples on site, as well as final analyses at the laboratory located at Wright-Patterson AFB, Ohio. Locating analytical records involved contacts with the Air Force Medical Operations Agency (AFMOA) at Bolling AFB, DC and the Air Force Institute for Environmental, Safety and Occupational Health Risk Analysis (AFIERA), which succeeded the USAF RHL, at Brooks AFB, TX. We believe that the USAF RHL used analytical

procedures and standard forms that were identical or very similar to those used in their support of the Palomares Accident of 1966 as recently described (LABAT 2001). However, those records have not been located to date, and are believed to have been misplaced or discarded. Discussions with the last Operation Crested Ice health physicist revealed that the records of on-site analyses were incorporated with those of the SAC response team. Further searches of SAC records archives may be useful.

AFIERA provided copies of computerized records containing some of the laboratory analytical data generated during USAF RHL's support for Operation Crested Ice. The relevance of those data for conducting credible estimates of intake and dose are discussed in this section.

4.1 Description of Air Force Data

AFMOA and AFIERA provided records in the form of:

- A text file containing 80-character data records of results identified as Thule, or Crested Ice, samples. These records represent information characteristic of the content and formatting that USAF RHL used for computer punched card recording of analytical sample results in the 1960s and early 1970s.
- Copies of reports of the accident response, follow-up documents generated by USAF and the Department of Energy in responding to inquiries from veterans and the Government of Denmark, and selected publications from journals and conference proceedings.

Appendix A contains a detailed discussion of the information contained in the electronic data file and its interpretation in terms of data for use in dose reconstruction efforts.

4.1.1 Data Set

AFIERA representatives provided a copy of a computer text file containing the result records for samples from the Thule accident processed by USAF RHL, stored on computer tape and subsequently converted to disk files by AFIERA and its predecessor organizations.

4.1.2 Reports

Several other documents provided essential information about the details of the accident, the response effort, and the approach to evaluating health and safety issues during the response. These documents provided a narrative overview of the approach to assessing possible exposure to plutonium and tritium at Thule.

4.2 Evaluation of Air Force Data

4.2.1 Condition of the Data

The data were evaluated to assess the availability of the elements required by the internal dosimetry models, including: the type of intake (inhalation, ingestion, skin contact), the date or dates the exposure occurred, the date of collection of nasal swab or urine samples, the duration of the urine sample collection, and the results of the sample analysis. Review indicated that the exposure date or dates were not available, sample date information was limited, and results were

not completely recorded for all cases. Social Security Account Numbers for United States personnel and unique identifiers assigned to Danish citizens at Thule were recorded and available. At best these data records can be used to identify and store records for specific individuals and to verify exposures during Operation Crested Ice. However, the data seem very limited in their relevance to calculations using currently accepted models. Fortunately, the results support the conclusions that significant exposures were not experienced at Thule.

4.2.2 Sample Collection and Handling

Urine sampling was begun within three days of the accident. Nasal swabs were collected and screened on site. Although these were subject to various uncertainties such as continuously runny noses and sample collection issues, they generally indicated little if any exposure.

4.2.3 Sample Analysis Procedures for Plutonium

The USAF Radiological Health Laboratory analyzed urine and nasal swab samples during the recovery and disposal phases. Urine samples for recovery personnel were collected after they returned to their permanent base of assignment. This procedure was instituted to avoid sample contamination problems experienced during the Palomares effort.

4.2.3.1 Gross Alpha Counting

Samples were processed for gross alpha counting by: digesting a portion of the urine sample with nitric acid and hydrogen peroxide to a white residue; dissolving the residue and coprecipitation of plutonium with bismuth salts; dissolving the salts with hydrochloric acid, addition of lanthanum carrier, and coprecipitation of plutonium on lanthanum fluoride; and direct mounting of the precipitate onto 2" stainless steel planchets for gross alpha counting (Odland 1966). Only a limited number of urine samples (10) were processed using this procedure.

A small amount of ^{239}Pu tracer was added to pooled urine and processed in the same batch as Palomares samples. The added tracer served as an indicator of the effectiveness of plutonium recovery (Odland 1966).

The samples were counted in internal proportional counters optimized for detecting alpha particles. Daily checks monitored instrument response, and daily background counts were done. According to reports (Odland 1966), samples were counted for 120 minutes, and background was counted for 960 minutes. Review of the initial data indicated that samples were often counted for 55 minutes. Background was reported to range from 0.02 to 0.06 count per minute and counting chambers were decontaminated whenever the background counts exceeded 0.1 count per minute.

Gross alpha results were reported in pCi/sample, where:

$$\text{pCi/sample} = \frac{(\text{gross counts/gross ctg time}) - (\text{background counts/bkgrd ctg time})}{(\text{counting efficiency})(2.22)(\text{procedural yield})}$$

Analysis of selected samples from the initial phase indicated that the results and estimated errors were calculated, recorded, and reported. The estimated errors were determined from counting data only and were reported at the 95% confidence level.

Procedural yield was determined from the results of the traced urine sample for each batch of urine processed.

4.2.3.2 Alpha Spectrometry

The laboratory derived its procedures from those used for monitoring workers at other facilities handling significant quantities of plutonium. The process involved nitric acid digestion, coprecipitation of alkaline earth and plutonium phosphates, precipitation with cerium, ion exchange to remove interfering ions, and electrodeposition onto stainless steel planchets for radioactivity counting. A small quantity of ^{236}Pu was added to each sample before chemical processing to evaluate radiochemical recovery.

Radioactivity counting was conducted using alpha particle spectrometry with solid-state surface-barrier detectors in a vacuum. Count data were collected with a multichannel pulse-height analyzer. Detector efficiency and background were monitored daily. Background was counted for 800 minutes duration and samples reportedly for 50 minutes.

Data were accumulated in 255 storage positions. Total events in a 236-Pu band and in a 239-Pu band were determined. The activity in the counting sample was determined from the following equation:

$$\text{pCi/sample} = \frac{(\text{net cpm in 239 - Pu band}) \times (\text{dpm 236 - Pu added})}{(\text{net cpm in 236 - Pu band}) \times 2.22}$$

$$\text{where net cpm in 239 - Pu band} = \left[\begin{array}{c} \frac{\text{gross cts in 239 - Pu band}}{\text{gross ctg time}} - \\ \frac{\text{bkg cts in 239 - Pu band}}{\text{bkg ctg time}} \end{array} \right]$$

$$\text{and net cpm in 236 - Pu band} = \left[\begin{array}{c} \frac{\text{gross cts in 236 - Pu band}}{\text{gross ctg time}} - \\ \frac{\text{bkg cts in 236 - Pu band}}{\text{bkg ctg time}} \end{array} \right]$$

dpm 236-Pu = activity of 236-Pu spike added to sample corrected for decay to date of count.

Corrections for sample volume to convert the result into the amount excreted in a day (24 hours) were also applied before calculating the body burden. Errors were estimated based on counting statistics and minimum detectable activity levels established and applied. Odland reported that the minimum detectable activity (MDA) as used in the program was defined as the sample activity associated with a counting error at the 95% confidence level equal to 0.95 times the sample activity (Odland 1968a). That means that any sample whose estimated error exceeded

95% of the sample activity was reported as no detectable activity (NDA). The MDA for the Thule effort was reported as 0.5 picocurie per 24-hour specimen.

4.2.4 Sample Analysis Procedures for Tritium

Although not specifically documented in the available reports, the USAF RHL most likely used the liquid scintillation technique for analyzing tritium in both nasal swabs and urine. The urine procedure most likely consisted of distilling the urine sample to obtain water (containing any tritium) that was purified of the normal constituents in urine that could interfere with the liquid scintillation process. Nasal swabs were likely processed by merely placing the cotton portion of the swab into the liquid scintillator solution.

4.3 Data Content

4.3.1 Relevant Parameters

Estimates of intake and dose require information including the exposure date, sample collection date, sample duration, and urinary excretion rate and its estimated error. The data (Appendix A) contain some but not all of these parameters.

4.3.1.1 Exposure Date

Exposure dates were not recorded in the electronic data set provided. That information was most likely recorded in log books on site and on AFLC Forms 1165 upon receipt of the sample at USAF RHL. Unfortunately, those data were not present in the result records provided.

However, information from the various reports provide a reasonable view of activities on site. Also, most of the nasal swab records contain sample collection dates. It appears these samples were routinely collected and processed. Correlation of the nasal swab collection dates with SSAN could provide indications of the time specific individuals were on site. For those, reasonable estimates of exposure dates may be possible. These correlations were performed and used in the range estimates calculated in this project.

4.3.1.2 Sample Date

Sample Date entries were found for only 10 urine samples - those processed by gross alpha counting. Sampling dates were recorded for the majority of nasal swab samples. Also, counting dates were recorded for most samples. Reasonable estimates of the transit time to RHL and laboratory processing time may allow estimates of the sampling date when otherwise not available.

4.3.1.3 Urinary Excretion Rate

When recorded, urinary results appear to be expressed in terms of appropriate units. That is in picocuries per 24-hour specimen for ^{239}Pu , and in nanocuries per liter for tritium.

4.3.1.4 Identification of Participant Results

As discussed in Appendix A, the data set contained only SSN information for samples from Operation Crested Ice participants. Names were not included, presumably because they recorded on other electronic records that had become separated from the result records.

The data records provided by AFIERA were processed into tables of participating SSNs. Also, a list of participants' names and organizations was prepared from the numerous Operation Crested Ice reports. The Locator Service at the Air Force Personnel Center, Randolph AFB, Texas searched its records for matches with the individuals listed and prepared revised listings with the information located. The listings were processed further and combined with the result records to associate names with the SSNs and result records. The process successfully identified names for 754 of 978 cases. Further evaluation of the names and organizations extracted from written reports suggested that the unidentified cases were generally associated with individuals who were assigned to other agencies or services, or were members of the local population who were assigned operation-unique identifiers.

4.3.1.5 Other Inconsistencies

Other inconsistencies in the data set were also identified and corrected where possible. Although these did not affect the actual intake and dose assessments, they do affect identifying information. These reviews discovered inconsistencies in names, SSNs caused by typographical errors or keyboarding errors, errors in analysis type, inconsistent base names, and others.

5 DOSE CALCULATION

5.1 Exposure Scenario

The type of exposure (acute or chronic; inhalation, ingestion, direct) must be known or assumed to perform a meaningful estimate of an intake of radioactive material and its associated dose equivalent. One or more of the common routes of entry (inhalation, ingestion, or direct) generally apply. Examinations of the activities that may have caused the exposure provide the clues to determining the type and route of the exposure.

As discussed above, the response to the Thule nuclear accident involved over 700 personnel working toward the common purpose of recovering vital materials, protecting themselves, and restoration of the accident scene to useable and safe conditions. The accident itself released plutonium and tritium during explosions and fires that followed the impact of the aircraft and its four nuclear weapons with the sea ice. Fortunately most of the plutonium was found to be trapped in a dark, thin layer of ice and fuel, lubricants, and fire debris or on aircraft debris. Most of the tritium was released during the explosion and subsequent fire. Some tritium was also found on aircraft debris and in the darkened sea ice. Consequently airborne contamination was a minor problem.

Handling of contaminated aircraft and cargo debris posed the major radiation control problem. Tritium and plutonium could be resuspended from the debris when warmed in buildings on Thule Air Base in preparation for packaging and disposal. Also melted snow and ice could leak

from containers for possible contamination of hands with transfer to the mouth. This is a potential major route for tritium exposure.

5.2 Preliminary Estimates of Intake and Dose

The available data allow preliminary estimates of intake and dose for plutonium and tritium. These estimates support the general conclusions about the extent of exposures developed during Operation Crested Ice. However, they do not currently support estimates of intake and dose for individuals because of the missing data and high limits of detection for plutonium.

5.2.1 Estimates for Tritium

The data set contained tritium results for 251 urine samples. Of those, 29 were greater than the minimum detectable and ranged from 0.008 $\mu\text{Ci/L}$ to 1.29 $\mu\text{Ci/L}$. More than one result was available for several individuals. From those data and appropriate assumptions about exposure date, sample collection date, and elimination half-time, estimates of body content and committed effective dose equivalent were calculated.

The case with the highest urinary concentration produced a maximum body content at exposure of 404 μCi , which is about 5 percent of the Annual Limit on Intake from inhalation of tritium (80,000 μCi) according to the NRC (NRC 1999). That body content translated into a CEDE of 0.026 rem. Specific details of the case are shown in Table 1. The case assumes an exposure date of January 22, 1968 – one day after the incident. Also, urine collection dates were estimated at 14 days before the sample counting date in the laboratory. Finally, the tritium elimination half-time was assumed at 10 days as recommended by the ICRP (see above), body content was calculated for a total body water content of 42 kilograms, and dose was estimated using a conversion factor of 1.7×10^{-11} Sv/Bq (USEPA, 1988). Three other cases with more than one urine result produced body contents of about 3 to 150 μCi and CEDEs of about 0.0005 to 0.1 rem – well below (0.1 percent) recommended limits.

Table 1. Data for highest tritium urine result.

Sample	Exposed Date		Count Date	Result	Unit	Intake (μCi)	Intake (Bq)	Sv	Rem
	Collect Date	Days from Exposure							
1	2/20/68	29	3/6/68	1.29	uCi/L	404.4	0.506%	1.50E+07	0.00026
		0		9.63					
2	3/2/68	40	3/13/68	0.375	uCi/L	252.0	0.315%	9.32E+06	0.00016
		0		6.0					

Air sample data for tritium were not available. Consequently, intake and dose estimates from those data could not be performed.

5.2.2 Dose Estimates for Plutonium

5.2.2.1 Estimates from Urine Results

The data set contained plutonium results for 526 urine samples. That number is 230 less than reported by the USAF RHL, however, the data set only contained 526 results. Resolution of this

apparent discrepancy was not successful. None of the results reported detectable amounts of plutonium. The reported (Section 4.2.3.2) minimum detectable activity (MDA) for the Thule effort was 0.5 picocurie per 24 hours. Collection dates for the urine samples and exposure dates for the participants were not available in the data set, however, Operation Crested Ice procedures provided for collection of urine samples after return to the main base. Estimates of a typical exposure case were developed with the following assumptions:

- Sample collection occurred 90 days after exposure.
- Plutonium was represented by 1 μm activity median aerodynamic diameter (AMAD) particles of ICRP 66 Type S (slow).
- Weighting Factors from ICRP 60 were used to convert committed dose equivalent in organs to committed dose equivalent.

The computer program (LUDEP 2.06) was used to estimate the intake and dose for this case, producing an intake of 2.5 μCi and a CEDE of 140 rem. This is clearly a significant situation that highlights the potential difficulties in evaluating plutonium exposures using analytical methods with insufficient sensitivity.

5.2.2.2 Estimates from Air Sampling

Air sample results were available for 169 samples collected during February through April 1968. Those samples, analyzed for gross alpha radioactivity, provide a reasonable basis for developing alternate estimates of plutonium intake and dose. As discussed in Appendix A, those air sample results ranged from $8.89 \times 10^{-4} \text{ pCi/m}^3$ ($3.3 \times 10^{-5} \text{ Bq/m}^3$) to $2.38 \times 10^4 \text{ pCi/m}^3$ ($8.8 \times 10^2 \text{ Bq/m}^3$) with a median concentration of $2.05 \times 10^{-1} \text{ pCi/m}^3$ ($7.58 \times 10^{-3} \text{ Bq/m}^3$). Further analysis of those data provided the air concentrations for the fifth percentile ($2.0 \times 10^{-3} \text{ pCi/m}^3$; $7.4 \times 10^{-5} \text{ Bq/m}^3$) and the ninety-fifth percentile ($1.18 \times 10^2 \text{ pCi/m}^3$; 4.38 Bq/m^3) of the distribution. Those two values and the median concentration were used to represent the lower bound exposure, the median exposure and the upper bound exposure for several scenarios.

The three values for lower, median and upper bound exposures were used as reasonable values for air concentrations that response force personnel could have experienced. Those values were combined with dose conversion factors for Type S plutonium calculated using LUDEP. Since breathing rates affect the intake – the more air one breathes in the more plutonium that enters the lungs – the calculations were performed for standard workers (breathing rate of 1.2 m^3 per hour) and for heavy workers (1.688 m^3 per hour). Also, the calculations were performed for particle sizes of 1 micrometer and 5 micrometers AMAD.

The calculations were performed for three exposure scenarios. The first assumed that response force workers were on site for two weeks, worked 6 days per week for 12 hours a day. This would represent many of the responders who were rotated after two weeks on site. The second scenario involved 4 weeks on site under the same work conditions to represent those who stayed somewhat longer. Finally, the last scenario assumed that responders could have been exposed for 11 weeks, which represents essentially the entire period of activity; i.e. from just after the accident until March 31, 1966. Those estimates are shown in Table 2 and indicate that intakes and doses are insignificant except for the 95th percentile air concentration – a situation that existed

for only a very few samples. Further analysis of the 95th percentile air concentrations indicate the highest CEDE (11.57 rem) represents slightly more than twice the recommended annual limit for workers and would not be expected to result in significant effects on health.

Table 2. Intake and dose estimates from air concentrations.

		5th Percentile Air Concentration		Median Air Concentration		95th Percentile Air Concentration									
		7.40E-05 Bq/m ³		7.59E-03 Bq/m ³		4.38 Bq/m ³									
Scenario	Worker Type	Breathing Rate (m ³ /hr)	Particle Size (um)	Exposure Time (hours)	Dose Conversion Factor (Sv/Bq)		5th Percentile Air Concentration		Median Air Concentration		95th Percentile Air Concentration				
					ICRP-26	ICRP-60	Intake (Bq)	CEDE (Sv)/CEDE (rem)		Intake (Bq)	CEDE (Sv)/CEDE (rem)		Intake (Bq)	CEDE (Sv)/CEDE (rem)	
								ICRP-26	ICRP-60		ICRP-26	ICRP-60		ICRP-26	ICRP-60
2 weeks 6 days per week 12 hours per day	Standard	1.2	1	144	1.95E-05	1.53E-05	0.013	2.49E-07	1.96E-07	1.31	3.26E-07	2.57E-07	757	1.47E-02	1.16E-02
	Heavy	1.688	1	144	1.08E-05	8.65E-06	0.013	0.00002	0.00002	1.31	0.00003	0.00003	757	1.47	1.16
			5	144	1.98E-05	1.57E-05	0.018	1.39E-07	1.11E-07	1.84	1.82E-07	1.45E-07	1,065	8.21E-03	6.55E-03
4 weeks 6 days per week 12 hours per day	Standard	1.2	1	288	1.95E-05	1.53E-05	0.026	3.55E-07	2.83E-07	2.62	6.55E-07	5.21E-07	1,514	2.10E-02	1.67E-02
	Heavy	1.688	1	288	1.23E-05	1.01E-05	0.026	0.00004	0.00003	3.69	0.00007	0.00005	2,130	2.10	1.67
			5	288	1.98E-05	1.57E-05	0.036	2.21E-07	1.82E-07	1.84	4.07E-07	3.35E-07	1,065	1.31E-02	1.08E-02
Full Response 11 weeks 6 days per week 12 hours per day	Standard	1.2	1	792	1.95E-05	1.53E-05	0.070	0.00002	0.00002	7.21	0.00004	0.00003	4,164	1.31	1.08
	Heavy	1.688	1	792	1.08E-05	8.65E-06	0.070	4.98E-07	3.92E-07	7.21	0.00005	0.00004	1,514	2.95	2.32
			5	792	1.98E-05	1.57E-05	0.099	2.77E-07	2.21E-07	10.14	7.27E-07	5.80E-07	1,514	1.64E-02	1.31E-02
Full Response 11 weeks 6 days per week 12 hours per day	Standard	1.2	1	792	1.95E-05	1.53E-05	0.070	0.00003	0.00002	7.21	0.00007	0.00006	4,164	1.64	1.31
	Heavy	1.688	1	792	1.08E-05	8.65E-06	0.070	7.10E-07	5.65E-07	10.14	0.00007	0.00006	2,130	4.21	3.35
			5	792	1.98E-05	1.57E-05	0.099	4.41E-07	3.63E-07	10.14	1.63E-06	1.34E-06	2,130	2.613E-02	2.151E-02
Full Response 11 weeks 6 days per week 12 hours per day	Standard	1.2	1	792	1.95E-05	1.53E-05	0.070	0.00004	0.00004	7.21	0.00016	0.00013	4,164	2.61	2.15
	Heavy	1.688	1	792	1.08E-05	8.65E-06	0.070	1.37E-06	1.08E-06	7.21	9.87E-06	7.76E-06	4,164	8.10E-02	6.37E-02
			5	792	1.98E-05	1.57E-05	0.099	0.00014	0.00011	7.21	0.00099	0.00078	4,164	8.10	6.37
Full Response 11 weeks 6 days per week 12 hours per day	Standard	1.2	1	792	1.08E-05	8.65E-06	0.070	7.62E-07	6.08E-07	7.21	5.50E-06	4.38E-06	4,164	4.51E-02	3.60E-02
	Heavy	1.688	1	792	1.98E-05	1.57E-05	0.099	0.00008	0.00006	10.14	0.00055	0.00044	5,857	4.51	3.60
			5	792	1.98E-05	1.57E-05	0.099	1.95E-06	1.55E-06	10.14	1.98E-05	1.58E-05	5,857	1.16E-01	9.20E-02
Full Response 11 weeks 6 days per week 12 hours per day	Standard	1.2	1	792	1.08E-05	8.65E-06	0.070	1.95E-04	1.55E-04	10.14	0.00198	0.00158	5,857	11.57	9.20
	Heavy	1.688	1	792	1.23E-05	1.01E-05	0.099	1.21E-06	9.99E-07	10.14	1.23E-05	1.01E-05	5,857	7.186E-02	5.915E-02
			5	792	1.23E-05	1.01E-05	0.099	0.00012	0.00010	10.14	0.00123	0.00101	5,857	7.19	5.92

6 CONCLUSIONS AND RECOMMENDATIONS

The available data have been evaluated and processed into a usable data set for identifying the bioassay data available for most participants in Operation Crested Ice. Sample results are available that have SSN that have not, as yet, been associated with names. Furthermore, data are limited by a general lack of collection date information, exposure date information, and individual-specific scenarios. Also, the urine analyses for plutonium content were not sufficiently sensitive to provide a realistic estimate of intake and dose. Evaluation of other available data, such as air samples, allow alternate estimates for plutonium intake and dose. Those estimates support conclusions that Operation Crested Ice was conducted safely without significant exposures to plutonium.

The urine analyses for tritium were sufficiently sensitive to support a realistic evaluation. Most (all but 29 samples) showed no detectable tritium radioactivity. The remaining samples, combined with reasonable assumptions, allowed reasonable estimates of the body content of tritium and the associated radiation dose. The highest values for tritium were well below the annual limit of intake and produced CEDEs of much less than 1 rem. Thus, Operation Crested Ice was also characterized by the safe handling of tritium contamination.

The available data provide a basis for supporting Air Force response to inquiries from participants about their participation in the operation and the results. Also, generic information

can be provided about the range of possible plutonium and tritium exposures. However, individual-specific evaluations are not possible with the existing data. The following recommendations provide additional efforts that could resolve some of the difficulties.

- Continue efforts to identify individual sample results, including cooperation with the Department of Energy in searching its records and information.
- Continue searches for other sources of paper records of sample analyses that may provide missing information about sample collection or exposure.
- Complete the database development and upload Thule sample data available.

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