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THE THULE ACCIDENT

Assessment of Radiation Doses from Terrestrial Radioactive Contamination

2011

The Thule Accident: Assessment of Radiation Doses from Terrestrial Radioactive Contamination
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Foreword

In January 1968, an American B-52 bomber carrying four nuclear weapons crashed onto the ice in the vicinity of the Thule Air Base in Greenland, resulting in the dispersal of plutonium and other materials into the surrounding environment. Following the crash, the USA agreed with the Danish authorities to undertake a thorough cleanup of the ice. Subsequently, in the summer of 1968 and later, Danish experts carried out measurements and collected environmental samples from the area, which were then measured in Denmark.

In 1986, various sources suggested that the Danish workers who had participated in the cleanup operations following the accident had been exposed to radiation that would have been injurious to their health. The National Board of Health collected the available Danish and American information regarding this issue and initiated on this basis a series of registry, laboratory, and health surveys from 1986 to 1991, in part in collaboration with the Danish Cancer Society, the National Institute of Public Health, and the occupational medicine clinics. These surveys covered both previous Thule workers and Greenlandic trappers. On the basis of these studies, the National Board of Health could not confirm the suggestion of increased illness and mortality among these individuals as a result of the plane crash.

As part of Risø DTU's research into environmental plutonium at Thule, soil samples were collected in the coastal area to the southwest of the Thule Air Base in 2003. These showed varying plutonium contents as a result of the 1968 plane crash. The findings led to the creation of a collaboration committee between the Greenlandic and Danish health authorities, and it was decided to carry out both a health study of the population and further measurements as well as to conduct research on the occurrence of radioactivity in the area in order to assess the risk for people staying in the area.

This comprehensive health study of the population of Avanersuaq (the Thule area) was carried out by the National Institute of Public Health and the Department for Health in Nuuk in 2010 and 2011. The study has not shown increased illness or mortality that can be associated with the 1968 plane crash.

The new research on radioactivity in the Thule area has been carried out and independently reported by the Radiation Research Division at Risø DTU. The associated assessment of radiation dosesfor people as a result of terrestrial contamination and consequently the risk for people staying in the area was carried out by the National Institute of Radiation Protection at the National Board of Health. The applied dose models, the associated selection of parameters, and the results of the dose calculations are considered in detail in this report.

The National Board of Health hopes that the report will contribute to improving knowledge and understanding of plutonium contamination in the Thule area as well as how such a contamination could lead to radiation exposure for individuals and how this quantity of radiation exposure compares with other anthropogenic and natural sources of radiation.

Else Smith
Managing Director, National Board of Health

Summary

The Thule Accident: Assessment of Radiation Doses from Terrestrial Radioactive Contamination

Terrestrial radioactive contamination near Thule following the 1968 crash of an American B-52 bomber has been studied and characterised by Risø DTU. On the basis of the studies carried out in Greenland, the National Institute of Radiation Protection has assessed doses and consequently the risk of staying in and using the contaminated areas. The assessment shows that the dose for individuals is lower than the recommended reference level for the Thule accident.

Background

Risø DTU has carried out research on terrestrial contamination in the Thule area after the radioactive contents of four nuclear weapons were dispersed following the crash of an American B-52 strategic bomber in 1968. The results of Risø DTU's research are described in the report *Thule-2007 – Investigation of radioactive pollution on land*, which covers all terrestrial measurements that were carried out in Thule in the years 2003, 2006, 2007 and 2008.

The present report uses Risø DTU's report as a basis for assessing doses and consequently the risk for individuals as a result of terrestrial radioactive contamination in the Thule area.

Principles and Criteria of Radiation Protection

Principles and criteria of radiation protection in Danish and international rules and legislation are based on the recommendations of the International Commission on Radiation Protection (ICRP). These recommendations also contribute to the foundations of this report. The National Institute of Radiation Protection finds that contamination in the Thule area is what the ICRP characterises as an existing exposure situation, where no previous position has been taken regarding possible radiation exposure and how this could be optimised.

For assessments concerning the need for special control or protection measures in the Thule area (and the optimisation of such measures if necessary), it would be appropriate to select a reference level for the Thule accident lying at the low end of the ICRP's recommended range of 1–20 mSv/year, in which "mSv" (millisievert) is the unit of an radiation dose. Such a reference value cannot be regarded as an actual threshold value. The National Institute of Radiation Protection selected a Thule reference level of 1 mSv/year for the analyses and assessments in this report.

As a comparison with the Thule reference level, it can be noted that Greenlanders and Danes receive approximately 1 mSv/year as a result of naturally occurring radiation sources such as cosmic rays from space and naturally occurring radioactive materials in soil, construction material, and foodstuffs (natural background radiation). Furthermore, the Danish dose limit for members of the public as a result of planned expoure from all sources of radiation is also 1 mSv/year. A radiation dose of 1 mSv/year has no significance to health.

Exposure Pathways and Assessment of Doses

The 1968 accident resulted in the dispersal of various radioactive materials from the four nuclear weapons carried by the American B-52 bomber. The radioactive material at Thule does not emit significant penetrating radiation. Stays in the area thus do not result in external irradiation, for instance of the sort resulting from an x-ray examination. Irradiation can therefore only occur if the radioactive material enters a person's body so that radiation exposure occurs internally. The most significant radioactive materials in this context are plutonium-239 and americium-241. The presence of these radioactive materials is thus decisive for an assessment of radiation doses and associated risks in Thule and is covered by this report's dose assessments.

Internal irradiation from radioactive material is comparable with the injurious health effects of chemicals that are absorbed by the body and damage it from within. Absorption of radioactive material can occur in three different ways, with associated exposure pathways:

- Inhalation of air contaminated with radioactive material stirred up from contaminated soil
- Consumption of animals that have stayed in contaminated areas
- Through wounds or cuts in association with contamination of the skin.

All three exposure pathways are covered in the report, and the subsequent doses have been assessed on the basis of the results of Risø DTU's research and a number of assumptions concerning stays in the area, *etc.*

Radiation Dose from Inhalation

The dose from inhalation of radioactive material due to stays in the area is calculated on the basis of the measured concentrations of plutonium in the air for one person, who is assumed to spend 14 days/year in the area. The result is an equivalent dose of 0.000,000,1 mSv/year. This is an extremely small dose.

Radiation Dose from Ingestion of Musk Ox Meat

Meat from musk oxen is the most significant source of terrestrial mammal meat from the Thule area in the diets of the local population. No measurements of plutonium-239 and americium-241 in musk ox meat have been undertaken in the Thule area or elsewhere in Greenland. Generally speaking, however, plutonium is very poorly transferred by the digestive systems of both humans and animals, including ruminants such as musk oxen. The possibility of contamination of musk ox meat is therefore assessed on the basis of general considerations and knowledge of meat contamination from other ruminants present in areas contaminated with plutonium elsewhere in the world, though grazing conditions may have differed elsewhere. If such a provisional assessment is based on studies of cattle in the USA and sheep in the United Kingdom, and if it is assumed that an individual consumes 15 kg of musk ox meat/year, the resultant dose from meat ingestion is 0.000,1 mSv/year. Although this dose is greater than the inhalation dose, it is still to be regarded as being extremely small.

A superior assessment of radiation dose from meat ingestion could be obtained by collecting and measuring samples of musk ox meat taken in the Thule area. The National Institute of Radiation Protection does not anticipate that such measurements would show plutonium concentrations in the meat that deviate significantly (for instance, by a factor of 100–1000) from the plutonium content in the meat estimated by the provisional dose calculation. The dose assessment for meat ingestion can therefore be regard-

ed as robust over a wide range of conditions in relation to the reference level of 1 mSv/year.

Radiation Dose from Wound Contamination

Wounds and cuts on individuals present in contaminated areas can be contaminated by dust, soil, or particles. Soil and other foreign materials will normally be thoroughly washed and cleaned from wounds and cuts. If soil or particles remain in the skin after cleaning, these can be absorbed by the body. If the soil or a particle is contaminated with radioactive material, this could result in internal irradiation of the body. The probability of a wound contaminant containing radioactive material from the Thule accident is very small, and the probability of a person being exposed to such wound contamination more than once in his or her life is therefore exceptionally small.

If nevertheless a wound should, however improbably, be contaminated with radioactive material, a dose can be calculated on the basis of the measured plutonium concentrations in the soil and particles. The calculation assumes that 0.1 g of soil or a particle of a size yielding the biggest radiation dose enters a wound. The result in this case is a radiation dose of 0.001 mSv/year for soil in the wound or 0.1 mSv/year for a particle in the wound. These doses are very small.

Conclusions and Recommendations

Calculations and dose assessments have been undertaken on the basis of very conservative assumptions, which likely overestimate actual doses. Calculations and assessments are, however, subject to uncertainty and qualifications. By the same token, the results are presented as order of magnitude estimates of dose, and the results are valid for all individuals (from "tourists" to Greenlandic trappers) and for all ages (from children to adults) who might stay in the studied areas.

If the results of the three means of radiation exposure (ingestion, inhalation, and wound contamination) are combined, it is assessed that, even under extreme conditions and assumptions, the total dose for individuals in the Thule area resulting from the 1968 Thule accident is smaller than the applied reference level of 1 mSv/year and therefore has no significance to health.

On the basis of Risø DTU's research as well as the calculations and dose assessments undertaken, the National Institute of Radiation Protection can, from the perspective of radiation protection and public health, make the following recommendations regarding the need for follow up on the measurements and assessments, including assessments on the need for future measurements:

- From a radiation protection assessment perspective, based on the current patterns of use of the contaminated area in Thule, there is no need for restrictions to stays, *etc.* or for decontamination measures in the area.

- As noted in the assessment of the dose resulting from ingestion of foodstuffs, no direct measurements of plutonium in musk oxen from the Thule area or other parts of Greenland are currently available. As a result, the assessment has relied on models based on experiences from contaminated locations elsewhere in the world, which differ from the conditions in the Thule area in terms of climate, *etc.* The dose calculations from meat ingestion could thus be better qualified via a small survey program that samples musk oxen and other terrestrial mammals from the Thule area. The collected samples should then also be analysed for the presence of the naturally

occurring radioactive material polonium-210, which is estimated to cause significantly higher doses than the plutonium contamination does.

- The assessment of doses resulting from plutonium contamination for people in the Thule area is based on Risø DTU's research up to and including 2008, applied to the current use of the area. To ensure that the assumptions for this assessment remain valid, a small, tailored survey should be carried out every 5 to 10 years.

- The assessed radiation doses for people in the Thule area are significantly lower than the recommended Thule reference level. There is thus no need, from a dose monitoring perspective, to analyse for the presence of plutonium in individuals living in the area in survey programs such as the search for plutonium in the urine of previous Narsaarsuk residents carried out in 1989.

- If plans arise for changed use of the area, for instance involving the construction of buildings or other installations, including long-term stays or residence in the area, the need for restrictions concerning stays, *etc.* in the area or for decontamination measures should be reconsidered in detail prior to the plan's commencement.

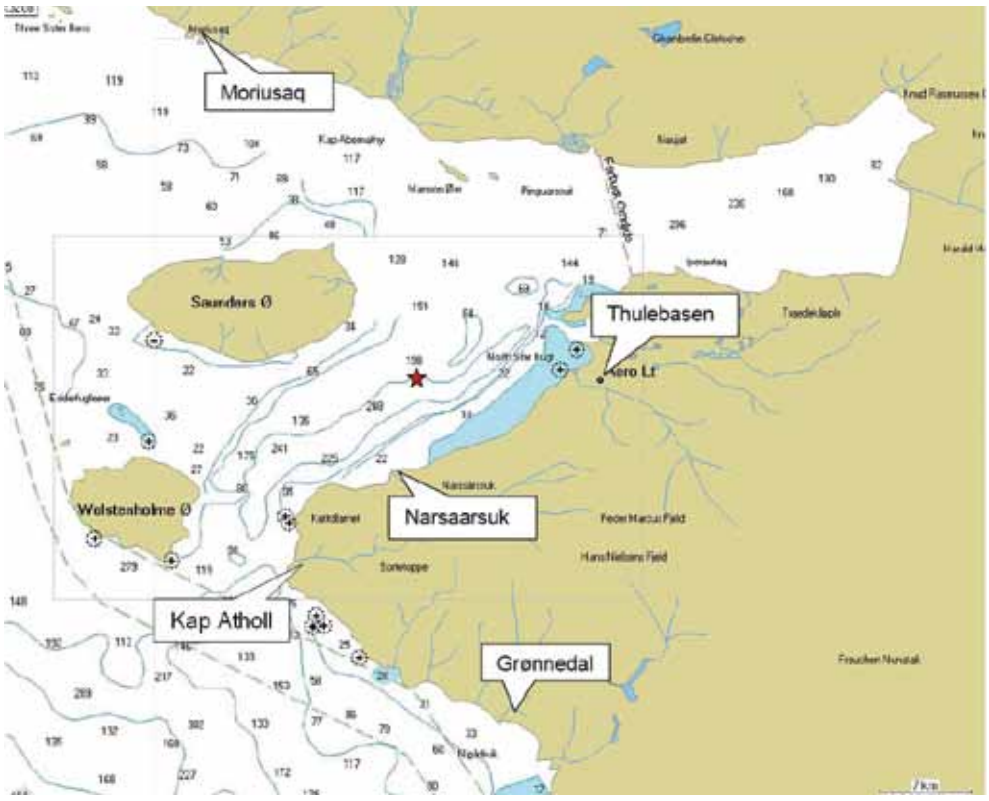
- Protection measures such as signposting or fencing off selected areas for reasons not related to radiation protection would not influence the National Institute of Radiation Protection's assessment of the total radiation dose for people in the Thule area, including radiation dose assessments for people tasked with placing or maintaining signs or fencing.

- Decontamination measures could cause the disturbance and stirring up of plutonium during decontamination, potentially raising the radiation exposure of not only the people undertaking the operations but also of the local population. Decontamination operations should thus not be decided upon or commenced prior to the completion of a comprehensive radiation protection safety assessment for such a project.

1 Background

On 21 January 1968, an American B-52 bomber carrying nuclear weapons crashed onto the sea ice approximately 15 km west of the Thule Air Base in northwest Greenland [Figure 1]. The plane caught fire, and the high explosive components of the nuclear weapons exploded, causing radioactive material to be released and blown into the burning jet fuel. Flames from the fire reached around 850 m in height, and the smoke column rose even higher. Eyewitness reports, meteorological observations, and radar observations from the Thule Air Base strongly suggested that smoke from the fire was driven to the south and southeast. At the time of the accident, the atmosphere was, due to inversion, stable up to an altitude of 830 m, and thermal stratification remained stable even up to 2200 m. The wind blew from the north at an altitude of 1000 m and from the west at an altitude of 3500 m. Wind speed was around 3 m per second at all altitudes. It was later estimated that smaller particles could have travelled great distances on the wind and been deposited in the soil in low concentrations, presumably below the detection limit. One could expect measurable contamination in the direction of the then-active settlement of Narsaarsuk, around 8 km south of the crash site. One could also expect that some radioactivity would have spread from the highly contaminated crash site during the storms of 24 and 29 January, with contaminants being transported west toward Saunders Island [1].

Figure 1



Overview map of the Thule area, showing the crash site (star) and the hunting area around Kap Atholl, Grønnedal, Narsaarsuk, Saunders Island, Wolstenholme Island, the Thule Air Base, and the Moriusaq settlement.

Land contamination may have spread further to some degree over the intervening years due to influence of wind and precipitation. The most significant redistribution of contaminants may be expected to be local in character and related to meteorological con-

ditions as well as the melting of snow and the subsequent washing away and transportation of particles.

Plutonium dispersal in the surrounding areas was studied in the weeks after the accident by means of collecting and analysing snow samples. Contamination was found in two zones, one to the south and one to the west of the crash site, resulting in part from direct deposition from the smoke plume and in part from resuspension from the most-contaminated area surrounding the crash site. Plutonium contamination along the south coast of Bylot Sund showed maximum levels in the vicinity of Narsaarsuk, where levels of up to 9 kBq/m^2 were found [1]. Subsequently, in the summer of 1968 and later, Danish experts carried out measurements and collected environmental samples from the area, which were then measured in Denmark. Moss samples showing the highest recorded plutonium levels (1.6 kBq/kg) were collected at Narsaarsuk [2] in the summer of 1968.

The marine survey that constituted Risø DTU's Projekt Thule-2003, which studied plutonium in the Thule environment [3], was supplemented with soil samples from eight locations in the Narsaarsuk coastal area. The top soil at all locations showed varying amounts of plutonium from the 1968 plane crash. Plutonium distribution was extremely variable and was associated with small particles. Projekt Thule-2003 demonstrated the need for further measurements and surveys in the area before a risk assessment of terrestrial radioactive contamination could be carried out.

In 2007, following a preliminary study of the area in the summer of 2006, the Radiation Research Division at Risø DTU and the National Institute of Radiation Protection at the National Board of Health proposed a project [4] aimed at further measurements and investigations in the area. The project sought to create the foundations for a risk assessment regarding the inhalation of radioactive particles and the dangers of staying in the studied areas. In line with the desires of the collaboration committee composed of the Department of Family and Health in Greenland and the Danish Ministry of Health, an international assessment by the International Atomic Energy Agency (IAEA) of the technical contents of the project proposal was carried out in 2008. The international group of experts concluded that the project was well planned and could be successfully executed, achieving its stated goals [5].

Projekt Thule-2007 incorporated field work carried out in the Thule area in the summers of 2007 and 2008. Risø DTU has reported on the project's numerous measurements in the report *Thule-2007 – Investigation of radioactive pollution on land* [6], with associated geostatistical analyses [7]. The present report uses these measurements and studies as a basis for a risk assessment regarding the inhalation of radioactive particles and the dangers of staying in the studied areas. The two reports should be read in parallel and comprise the combined reporting of Projekt Thule-2007.

2 Principles and Criteria of Radiation Protection

2.1 ICRP Recommendations

It has long been recognised and documented that radiation from radioactive material can be injurious to health, depending on the size of received dose and the conditions under which a person has been exposed. Differentiation is made between acute injuries and chronic injuries. Acute injuries occur if the dose is received over a short period of time and exceeds so-called threshold doses for the specific type of acute injury (for example, radiation burns or radiation sickness). It is assumed for radiation protection purposes, on the basis of the International Commission on Radiation Protection (ICRP), that no threshold value exists for chronic injuries (for example, cancer later in life, or genetic injuries among descendents) and that their probability increases proportionally with the dose.

The ICRP was established in 1928 and has developed recommendations over the years concerning principles, criteria, dose limits, *etc.* for radiation protection. As a result, the ICRP's recommendations have been the starting point for developing radiation protection legislation in most countries worldwide. In Europe, the ICRP's recommendations are the basis for the EU's directives on radiation protection and consequently also for national legislation in the European states. Denmark's fundamental radiation protection principles, based on ICRP's recommendations, are found in the National Board of Health's Order No. 823 of 31 October 1997 on Dose Limits of Ionising Radiation.

The latest fundamental recommendations from the ICRP are provided in ICRP Publication 103 from 2007 [8]. This prompted a review, which has not yet been completed, of the EU's Directive on Ionising Radiation. ICRP Publication 103 contains no significant changes to recommendations relative to previous fundamental recommendations in ICRP Publication 60 from 1990. This applies, for example, to the assessment of health impacts of ionising radiation as well as recommended dose limits. The ICRP's newest recommendations propose, however, an updated division into various exposure situations. This division of exposure situations and the associated ICRP recommendations are described in detail below and form the basis of the National Institute of Radiation Protection's assessments of terrestrial radioactive contamination in the Thule area as well as the associated recommendations contained in this report.

The ICRP recommends a radiation protection system consisting of three types of exposure situations in order to cover the broad spectrum of situations in which people are or can be exposed to radiation:

- *Planned Exposure:* Implementation of a societal activity involving the use of radioactive material or ionising radiation.
- *Emergency Exposure:* Unplanned situations, which can occur during the operations of planned situations or which can be malicious actions, that require acute assessment and potential implementation of protection measures.
- *Existing Exposure:* Situations that already exist at the time of assessment and potential decisions concerning implementation of control measures.

Planned exposure was previously called *practices* and includes, for instance, medical, industrial, and scientific use of radiation sources (radioactive material, x-ray apparatuses, nuclear facilities, *etc.*). Emergency exposure includes occurrences (emergencies and

accidents) related to the use of radiation sources as well as malicious actions (crime and terrorism) involving radiation sources. Existing exposure includes exposure to raised natural radiation (radon in houses, radioactive material in building materials, *etc.*), stays in areas that are contaminated as a result of prior uncontrolled use of radiation sources, as well as stays in areas following an accident once the acute phase (emergency exposure) has passed. Emergency exposure and existing exposure were previously both called *intervention*.

As before, ICRP recommends three basic principles of radiation protection. The principles of *justification* and *optimisation* apply to all three exposure situations. The principle of *limitation* applies only to planned exposure. These three principles are:

- *Principle of Justification:* Any decision that alters the radiation exposure situation should do more good than harm.
- *Principle of Optimisation:* The probability of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.
- *Principle of Limitation:* The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the ICRP. The dose limits must ensure that no individual is exposed to a risk that would be regarded as unacceptable under normal conditions.

The dose limits recommended by the ICRP, which are equivalent to the dose limits in the EU's current Directive on Ionising Radiation and the National Board of Health's Order, are shown in simplified form in Table 1.

In contrast with a planned situation, emergency and existing situations present a type of exposure the origins of which were not originally open to control or influence. This has an impact when the need for protection measures is considered. Dose limits cannot always be used in these situations, and one must instead use so-called reference levels to delimit the optimisation process. Reference levels are set for the total dose, from all exposure pathways, for a representative individual. This is done on the basis of the level that the relevant authority, in collaboration with other relevant parties, decides should not be exceeded in light of the conditions surrounding the exposure situation in question. Optimisation will normally be a gradual, forward-looking process in which one studies and potentially carries our protection measures with the aim of reducing the total equivalent dose to an optimised level below the reference level.

Table 1. Ionising radiation dose limits for planned radiation

Person Category	Effective Dose Limit[1] mSv/year
Occupational Workers (over 18 years)	20
Members of the public	1

The ICRP has provided a range within which it is recommended that national reference levels are set for particular situations. The ICRP's recommended reference level range, which is shown in Table 2, is provided both as a general recommendation in part for all existing situations and in part specifically for radon in housing, which is a significant radiation protection problem in many countries. The ICRP also recommends that, in the event of lengthy residence and the leading of a normal life in a contaminated area, the reference level should, from a long-term perspective, be selected at the low end of the recommended range of 1–20 mSv/year.

1 The effective dose is a measure of total risk from exposure to ionising radiation and is the unit used for radiation protection purposes to estimate risk and permit comparisons with exposure from various sources of radiation, equivalent to a homogenous irradiation of the entire body. The calculation of effective dose is described in the National Board of Health's Appendix 3 to its Order No. 823 of 31 October 1997 on Dose Limits of Ionising Radiation. In the remainder of this report, the words "radiation dose" and "dose" will be used with the significance of "effective dose".

Table 2. The ICRP's recommended range for the setting of national reference levels for existing exposure situations

Existing Situation	Reference Level mSv/year
General	1 - 20
Radon in Houses and Workplaces	≤ 10

2.2 Reference Level for the Thule Accident

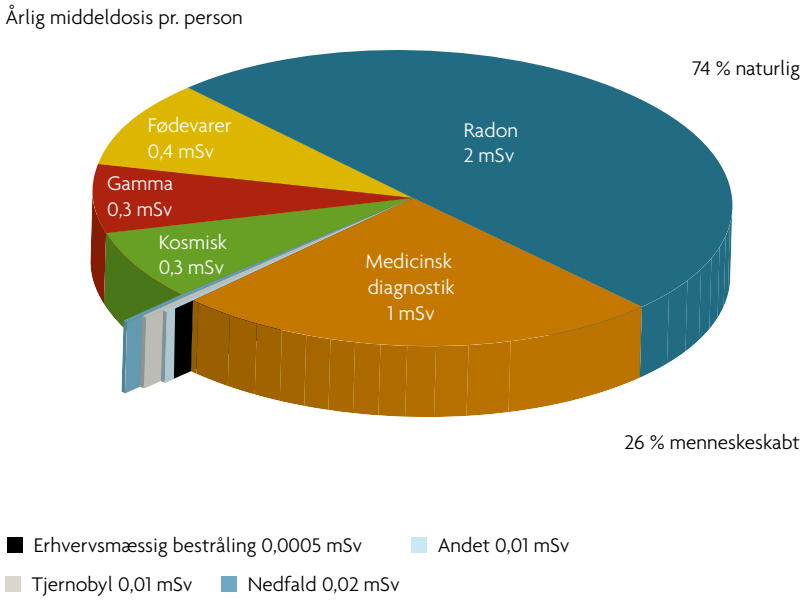
There are multiple types of existing exposure situations that can lead to such high exposure for individuals as to justify considering and/or implementing radiation protection measures. Existing exposure situations can be complex inasmuch as they can involve multiple exposure pathways, and they often occasion a wide range of annual doses for affected individuals, depending, for example, on their individual habits. An example of this is elevated radon levels in houses. It may also become necessary to decide on carrying out radiation protection measures for anthropogenic exposure situations, for instance in the event of environmental contamination resulting from earlier uncontrolled use of radiation sources or from an accident or event involving radioactive material.In addition, some existing exposure situations may not justify measures aimed at reducing radiation doses.

Decisions on which existing exposure situations should be subject to an active control and protective system require that the relevant authorities carry out an assessment and take a position on the issue which will be dependent both on the controllability of the exposure (contamination and exposure pathways) and the reigning economic, societal, and cultural conditions. In most existing exposure situations, the affected individuals and the authorities will wish to reduce exposure to a level that is at or close to the level present in situations that are regarded as "normal".

The National Institute of Radiation Protection regards the contamination in the Thule area following the 1968 Thule accident as an existing exposure situation and has determined that the ICRP's aforementioned recommendations can form the basis for assessing and possibly following up on the measurements of radioactive contamination that have been carried out in the Thule area. The National Institute of Radiation Protection have therefore used a Thule reference level of 1 mSv/year for analyses and assessments. A dose of 1 mSv/year has no significance for an individual's health.

In order to place the reference level of 1 mSv/year in perspective, this can be compared with the dose of 4 mSv/year that the average Dane receives from all sources of radiation [Figure 2]. A fourth of this comes from anthropogenic radiation sources, the vast majority of which are the result of medical use of radiation to diagnose patients. Three-fourths comes from naturally occurring radiation sources such as cosmic rays from space. Radioactive materials in soil, building materials, and foodstuffs as well as radon in houses account for half of the average dose. It must be emphasised that the dose from radon and diagnostic medicine exhibits significant variance, depending on the individual's housing conditions and state of health. The other components of the total dose are very uniform for the entire population. Finally, it should be noted that although this overview was developed for the Danish population, radon measurements in Greenlandic houses [9] strongly suggest that similar conditions prevail in Greenland as well.

Figure 2



Annual average dose per Dane from natural and anthropogenic radiation sources.

The Thule reference level may also be compared with other reference levels that are in use for existing situations in Denmark. The National Institute of Radiation Protection has, on various occasions, worked with the other Nordic radiation protection authorities to recommend reference levels for radon in housing, most recently in 2009 [10]. Radon recommendations have primarily been directed at the authorities responsible for construction (in Denmark, the Danish Enterprise and Construction Authority), but the recommendations have also influenced communication with the general population concerning the radon issue. Table 3 shows the radon reference levels, converted from radon concentration to radiation doses, alongside the recommended Thule reference level.

Table 3. The National Institute of Radiation Protection's recommended reference levels for existing exposure situations

Existing Situation	Reference Level mSv/year
Contamination Resulting from the Thule Accident	1
Radon in Houses	3 – 6

3 Radioactive Materials, Exposure Pathways, and Dose Calculation Methods

3.1 Radioactive Materials Involved in the Thule Accident

The American B-52 bomber that crashed near Thule in 1968 carried four nuclear weapons, the radioactive contents of which were dispersed as a result of the crash. Without going into detail about the function and quantities of these materials in the nuclear weapons, the most significant of the radioactive materials, are shown in Table 4.

The radioactive materials that were vital for the functioning of the nuclear weapon included plutonium-239, uranium-235, uranium-238, and tritium (H-3). Uranium-234, plutonium-240, and plutonium-241 are, in principle, undesired radioactive materials that follow or result from the production of weapons grade uranium or plutonium. Plutonium-240 cannot be differentiated from plutonium-239 with the analytical methods used by Risø DTU and is therefore always reported and assessed as part of plutonium-239. Plutonium-241 decays to americium-241 and is thus the reason for the build up of americium-241. This makes it possible to screen plutonium radioactive contamination by measuring the relatively low-energy gamma radiation emitted by americium-241, per DTU Risø [6].

Table 4. Radioactive materials from the Thule Accident

Radioactive Material	Short Name	Half Life	Type of Radiation		
			Alfa	Beta	Gamma
Tritium	H-3	12 Years		✔	
Uranium-234	U-234	0.25 Million Years	✔		
Uranium-235	U-235	0.70 Billion Years	✔		
Uranium-238	U-238	4.5 Billion Years	✔		
Plutonium-239	Pu-339	24,000 Years	✔		
Plutonium-240	Pu-240	6600 Years	✔		
Plutonium-241	Pu-241	14 Years		✔	
Americium-241	Am-241	430 Years	✔		✔

3.2 Exposure pathways

Radioactive material emits ionising radiation, and the assessment of exposure is to the first level divided into the following two types of exposure:

- *External Radiation,* in which the radioactive material is present outside the body or as a contaminant on the skin and therefore irradiates the body from the exterior.
- *Internal radiation,* in which the radioactive material has entered the body and irradiates it from within.

External radiation is characterised in accordance with the type and quantity of the emitted radiation. Alpha radiation is characterized by a very short range (~ cm in the air, ~ µm in tissue) and cannot, for example, penetrate the skin's outer layer of dead

skin cells. Alpha particles thus are not significant to health as far as external radiation is concerned. Beta radiation have a somewhat longer range (~ m in the air, ~ cm in tissue) and may result in irradiation of the skin in particular as well as of the outermost layers of tissue. Gamma rays can, depending on their energy, be extremely penetrating, radiating all of the body's organs and tissue from an external source. This potential for external influence over multiple meters or farther is a unique attribute of radioactive materials and is not present among other kinds of hazardous materials. It is not, however, an issue in the case of Thule. It nevertheless provides a broad spectrum of possibilities for directly measuring and characterising a specific case of exposure.

Table 4 shows the type of radiation emitted by the radioactive materials that are relevant in the case of Thule. With the exception of americium-241, plutonium-241, and tritium, all of the radioactive materials emit only alpha particles. As noted above, americium-241 also emits low-energy gamma rays, and tritium emits low-energy beta radiation. All three of these radioactive materials are such that their external radiation is insufficient to cause significant exposure, with the result that, in the case of the Thule contamination, external radiation can be completely disregarded. This is also illustrated by the fact that during the cleanup operations on the ice in 1968, radiation protection measures were undertaken solely for assessing the risk of internal radiation and not for external radiation [1].

Internal radiation from radioactive material is comparable with the injurious health effects of chemicals that are absorbed by the body and damage it from within. Absorption of radioactive material can occur in three different ways, with associated exposure pathways:

- I*nhalation* of contaminated air
- *Ingestion* of contaminated foodstuffs as well as transfer of loose contaminants from the fingers into the mouth
- *Through wounds* via contamination of the skin.

In contrast to the situation with external radiation, alpha particles play a significant role when it comes to internal radiation in which the radioactive material has entered the tissue and organs, allowing the short-range energetic alpha particles to hit the closest living cells. It should also be noted that alpha particle-emitting radioactive materials often remain in the body for a long period and can thus continue to radiate tissue and organs for many years following their initial ingestion.

The radioactive materials included in Table 4 can all cause internal irradiation if they enter the body through one or more of the aforementioned exposure pathways. In the case of Thule, however, it is plutonium-239, plutonium-240, and americium-241 that have the decisive effect on the assessment of radiation doses and their associated risks, and it is thus these radioactive materials alone that are covered by the assessments, *etc.* in the present report. On account of their extremely long half-lives, uranium-235 and uranium-238 show very little activity per unit of mass (specific activity). This means that the activity content of uranium in the contaminating Thule material is insignificant in relation to the activity content of the plutonium isotopes. It is also insignificant in relation to the naturally occurring uranium in the Thule area. Tritium is an isotope of hydrogen, and following the 1968 crash and its subsequent fire, it would have occurred in the form of water or ice, which would have been extensively diluted into the environment after the summer of 1968. Tritium was already present in nature, created both by cosmic radiation in the atmosphere and by earlier atmospheric testing of nuclear weapons.

3.3 Dose Calculation Methods

1.1.1 Inhalation

Assessing the radiation dose from inhalation of radioactive material (radioactive particles) that has been stirred up (resuspended) in the air in the contaminated areas in Thule requires knowledge of a variety of properties and conditions characterising the area's contamination and its patterns of use. These properties and conditions can be determined or assessed on the basis of measurements by using recognised models or by combining these models with knowledge of local conditions.

The following conditions will be discussed in detail below:

- Resuspension
- Radioactive particles and incorporation into the body
- Thule particles
- Stays in the area
- Dose calculations.

3.3.1 Resuspension

When a cloud (a volume of air) containing radioactive particles passes over the ground surface, a deposition of radioactive particles onto the surface may occur, dependent on the meteorological situation, the course and surface properties of the terrain, and the properties of the radioactive particles themselves, especially their size distribution. After the cloud has passed, and radioactive particles are no longer present in the air, new contamination of the air can occur as a result of the resuspension of particles from the contaminated ground surface. The possibility and extent of this kind of resuspension is dependent on the climate, the meteorological situation, the structure and surface properties of the terrain, and the properties of the radioactive particles as well as their distribution on the surface. The result is a complex interplay that is always heavily dependent on local conditions, including the use of the contaminated area. Resuspension from a contaminated area is generally largest in the period directly following deposition, with a subsequent appreciable decrease over the course of the next few years, as the contaminants bind to and penetrate the surface soil, thereby becoming less susceptible to being stirred up. Once 10 years have passed, resuspension of the deposited material will have dropped by multiple orders of magnitude.

Quantitatively speaking, resuspension is described either by using a resuspension factor or the so-called dust load method [11]. For the former method, the resuspension factor, *RF*, is defined as the ratio between the concentration of radioactive particles in the air, C_L, measured in Bq/m^3, and on the ground surface, C_O, measured in Bq/m^2. This means that the concentration of particles in the air can be estimated using the following formula, assuming that the surface concentration and the resuspension factor are known:

$$C_L = RF \cdot C_O$$

The unit of *RF* is m^{-1}. Numerous time dependent formulas for the resuspension factor have been published, relating associated measurements of the activity of the air and ground surface following the original incident of contamination, for instance following the Palomares accident (see Section 5.1) and following the nuclear weapon detonations and the Chernobyl accident. The resuspension factor immediately subsequent to deposition is usually in the range of 10^{-5}–10^{-6} m^{-1}; once 10 years or more have passed since

the contamination, the range is 10^{-9}–10^{-10} m^{-1} or less. If, for example, a resuspension factor of 10^{-9} m^{-1} were used, a surface concentration of 1000 Bq/m^2 would be expected to result in an average air concentration of 10^{-6} Bq/m^3 (1 µBq/m^3).

The dust load method assumes that the contaminating radioactive particles are closely bound to the soil's constituent parts and will accompany them when they are stirred up by the wind under normal conditions, resulting in a dust load (dust concentration) in the air. It is known that radioactive particles can become concentrated in airborne dust relative to their concentration in the soil in general. This concentration can be described as a concentration factor. If the general dust load, *DL,* of an area is known and is expressed in µg/m^3, and if the C_J concentration of radioactive material in the uppermost soil layer is measured in Bq/kg, the air concentration can be estimated using the following formula:

$$C_L = kf \cdot SB \cdot C_J \cdot 10^{-9}$$

in which *kf* is the dimensionless concentration factor. In rural districts, dust concentrations often lie in the 5–50 µg/m^3 range. In arctic areas, where the air is very clean, the concentration factor can be even smaller. If, for example, a dust load of 10 µg/m^3 and a concentration factor of 5 are adopted, a 20 Bq/kg contamination in the uppermost soil layer would be expected to result in an average air concentration of 10^{-6} Bq/m^3 (1 µBq/m^3).

As noted above, resuspension depends on many different parameters, which are highly influenced by local conditions and can also vary greatly over time. Generic resuspension models for estimating air concentration must thus be used with caution and with the awareness of their inherent uncertainty. Reversely, use of the models may be warranted for initial assessments of the order of magnitude of expected air concentration and for comparing the situation with results from other contamination sites.

Radioactive Particles and incorporation into the Body

Knowledge of the activity concentration in the air alone is insufficient for assessing a radiation dose from inhalation by an individual staying in a contaminated area. Alongside physiological conditions, the physical and chemical properties of airborne radioactive particles play a large role in the particles' absorption by and distribution within the body as well as their subsequent excretion and thereby the resulting radiation dose.

For example, particle size distribution and the individual's breathing habit and rate affects where in the respiratory system and in what quantities the particles are deposited upon inhalation. The particle-size distribution is usually described in terms of a characteristic diameter and a spread[2]around this value. This diameter is often simply called *particle size*, and this nomenclature will be adopted here.

The chemical properties are also significant for how quickly and in what quantities activity enters the blood via absorption by the lungs and how it is distributed throughout the body's other organs and tissues and subsequently excreted from the body. The ICRP has developed a detailed model of the respiratory system for use in dose calculations [12] as well as models for the decomposition of various substances in the body (biokinetic models). The ICRP also suggests standard values for the considerable

2 The geometric mean diameter of the particles, the sizes of which can be assumed to be log-normally distributed. In technical terminology, this is known as AMAD (activity mean aerodynamic diameter).

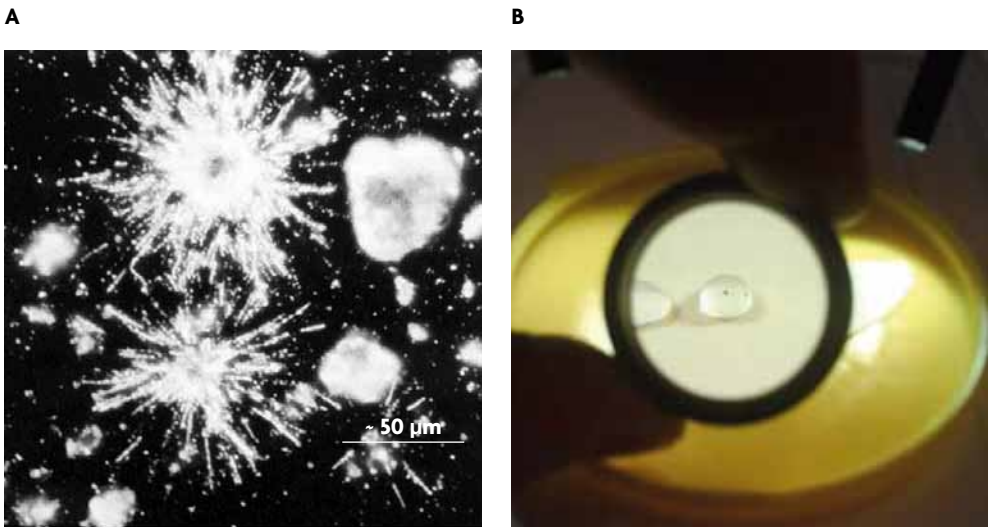
number of parameters included in the models and for the resulting dose coefficients (in the unit of Sv/Bq) for inhalation. The dose coefficients express the accumulated dose over the 50 years (70 years for children) following intake of 1 Bq of a radioactive material (mSv/Bq). Since dose coefficients are largely dependent on absorption of activity by the lungs, the ICRP has calculated standard dose coefficients for each radioactive material for three types of standard materials (chemical compounds), called Type F (fast), Type M (medium), and Type S (slow) respectively. The ICRP points out, however, that these standard dose coefficients prefereably should be replaced by coefficients specific to the situation in question once the necessary knowledge has been obtained concerning the physical and chemical properties of the radioactive material considered.

Thule Particles

The chemical and physical properties of the radioactive particles that were created and dispersed by the 1968 Thule crash are associated with the high temperatures resulting from the detonation of conventional explosives in the four nuclear weapons as well as the extensive burning of the plane's engine fuel. As expected, studies after the crash showed the occurrence of plutonium as oxide particles of variable sizes. Particle sizes of 5.6 µm and 2 µm respectively were found in the snow and the ice of the crash site [Figure 3]. It was not possible to determine the particle size in snow samples from Narsaarsuk (too few particles in the samples), but on the basis of meteorological considerations, it was estimated to be around 20 µm [1].

The Thule particles are quite complex in their chemical structure, and the properties may vary between particles. Particles in the environment are exposed to changing weather conditions and may break down and change properties as the years pass. This includes, to an extent, the disassociation of plutonium and americium. A 2010 Nordic study of a number of Thule particles thus showed that, even though the particles are difficult to break down completely, they release material in, for instance, aqueous solutions, though to a lesser extent in solutions resembling respiratory fluid [13].

Figure 3



A: Photomicrograph with alpha traces from plutonium particles, present in a sample of crushed ice from the crash site. Photo from [1].

B: Two isolated Thule particles in a drop of water. Photo from [12].

Plutonium particles created in Thule-like circumstances are known, for example, from the 1966 Palomares accident (see Section 5.1), and numerous studies suggest that the chemical and physical properties of Thule particles and Palomares particles are very similar [14]. Knowledge concerning the Palomares particles and previous studies of their chemical and physical properties as well as assessments of absorption following inhalation and associated dose coefficients represent a preferable alternative to the ICRP standard values as a starting point for the Thule assessment. It is important to recall, however, that the particles may have been affected differently by the arctic and temperate climates respectively.

The National Radiological Protection Board (NRPB, now HPA Radiation Protection Division) in the United Kingdom and the Research Center for Energy, Environment and Technology in Spain (CIEMAT) have, for their parts, carried out animals studies in order to determine plutonium absorption by the lungs into the blood from Palomares particles. When the results are applied to the ICRP's biokinetic models, specific dose coefficients for plutonium-239 and americium-241 are available for use in assessing the radiation dose from inhalation of contaminated Palomares dust [15, 16]. The specific Palomares dose coefficients are shown in Table 5 alongside the ICRP's suggested standard dose coefficients.

Table 5. Dose coefficients for inhalation of plutonium-239 and americium-241

Radioactive Material	**Person Category**	**Palomares Dust** mSv/Bq	**ICRP Type M** mSv/Bq	**ICRP Type S** mSv/Bq
Pu-239	Adult	0.024	0.050	0.016
	10 Years	0.025	0.048	0.019
	1 Year	0.046	0.077	0.039
Am-241	Adult	0.031	0.042	0.016
	10 Years	0.030	0.040	0.019
	1-årige	0.057	0.069	0.040

The Palomares dose coefficients are based on a particle size of 2.8 µm while the ICRP coefficients are based on a particle size of 1 µm. For the setting of Palomares dose coefficients, it is furthermore assumed that adults carry out physical labour (agricultural work) 10% of the time. The table shows that the specific dose coefficients for plutonium-239 most closely resemble ICRP Type S whereas those for americium-241 most closely resemble ICRP Type M. This difference between plutonium-239 and americium-241 is documented in animal studies showing a faster and larger absorption by the lungs into the blood for americium-241 than for plutonium-239.

As noted in Section 3, the relative quantities of plutonium-239 and americium-241 in a soil sample depend in part on the quantity of plutonium-241 in the originally used weapons grade plutonium and the time that passed since its production. It also depends on whether the radioactive material originates from the global deposition resulting from atmospheric nuclear weapons testing or from the Thule accident itself. In soil samples from 2007 and 2008 [6], Risø DTU found that the ratio between plutonium-239 and americium-241 increases with measured surface concentrations of americium-241. Furthermore, a current ratio of Pu-239/Am-241 of 6:1 for surface concentrations greater than 1 kBq/m^2, was found where deposition from the Thule accident is predominat. If these conditions are used for all calculations of inhalation

doses, a specific dose coefficient for Thule plutonium can be calculated, accounting also for the presence of americium-241, assuming that the Thule particles possess the same physical and chemical properties as the Palomares particles. Table 6 shows the specific Thule dose coefficients for the three person categories.

Table 6. Dose coefficients for inhalation of Thule plutonium

Radioactive Material	Person Category	Thule Dose Coefficient mSv/Bq
Thule Plutonium	Adult	0.029
	10 Years	0.030
	1 Year	0.056

Stays in the Area

The total amount of time a person spends in a contaminated area plays, of course, a role in the quantity of contaminated air that he or she inhales, thereby affecting the radiation dose. For the Thule contamination, the time of year may also be important since the potential for resuspension of radioactive material can be assumed to be smaller in the winter, when the area is frozen over and partially covered by snow.

For calculations of radiation doses in the context of radiation protection for the general population, including application to the recommended Thule reference level, the ICRP suggests the use of a so-called *representative person*. This means a person (usually hypothetical) who receives a dose and who is representative of the most exposed individuals among the affected population. The ICRP also recommends in this context that the population be divided into three age categories, Adults (16–70 years), Children (6–15 years), and Infants (0–5 years) respectively and that lifestyles, dose coefficients, *etc.* for these three categories equate to adults, 10-year-olds, and 1-year-olds respectively.

The National Institute of Radiation Protection has not had the opportunity to collect detailed information on the extent to when Greenlandic trappers use the areas around Narsaarsuk and Grønnedal and is therefore unable to define the characteristics of a representative person in association with the contamination of the land area. As part of the Health Survey in Avanersuaq [17], participates were asked about their activities in various parts of the Thule area, including the Narsaarsuk area. The National Institute of Radiation Protection has had the opportunity to discuss the collected data with the health survey's project leader [18]. The National Institute of Radiation Protection has deemed this data to be appropriate for use in the dose calculations in this report, conservatively assuming that the Greenlandic trappers stay in the area for around two weeks a year.

During sampling in the Thule area in the summers of 2007 and 2008, it also became clear that the area around Grønnedal and Kap Atholl has been used on multiple occasions as a recreational excursion destination by Thule Air Base employees and possibly by cruise ship passengers. The National Institute of Radiation Protection also conservatively/cautiously assumes that other individuals may stay in the area for up to 48 hours each year. Table 7 shows the assumed periods of stay in the Thule area for use in the dose calculations.

Table 7. Assumed periods of stay in the contaminated areas in the light months, for use in dose calculations

Representative Person	Period of Stay Days/Year (Hours/Year)
Greenlandic Trappers	14 (336)
Others	2 (48)

Dose Calculation

The annual dose (E, given in the unit of Sv/year) resulting from inhalation of radioactive material during stays in a contaminated area can be calculated using the following formula:

$$E = e_i \cdot B \cdot f \cdot C_L$$

where C_L is activity concentration in air, given in Bq/m^3,
f is the period of stay in the area, given in hours/year,
B is the inhalation speed, given in m^3/h (m^3/hour),
e_i is the dose coefficient for inhalation, given in mSv/Bq.

Period of stay values, f, and dose coefficients, e_i, are discussed above. Activity concentration in C_L, as used in the formula, can be based on active and passive measurements that have been carried out around Narsaasuk or estimated on the basis of previously described resuspension models combined with measuremed concentrations of radioactive material in the uppermost soil layer.

Table 8 shows the standard breathing rates for the person categories, as suggested by the ICRP, which are based on a standard distribution of daily activity levels (sleeping, sitting, light activity, high activity) along with associated breathing rates. The table also shows the adopted breathing rates for estimating Palomares-specific dose coefficients, where it is assumed that hard agricultural labour is being carried out 10% of the time [15, 16].

Table 8. Breathing rates for individuals in the population

Person Category	Breathing rate m^3/hour
ICRP, Adult	0.93
ICRP, 10-Year	0.64
ICRP, 1-Year	0.22
Palomares Worker	0.95

1.1.2 Ingestion

Assessing equivalent dose from ingestion of radioactive material in contaminated areas in Thule requires knowledge or an assessment of the contamination of foodstuffs originating in the contaminated areas, of the annual consumption of these contaminated foodstuffs, and of the physical and chemical properties of the radioactive material in question.

The following conditions will be discussed in detail below:

- Dose coefficients for ingestion
- Ruminants and plutonium contamination
- Consumption of locally procured musk ox meat
- Dose calculations.

Dose Coefficients for Ingestion

Physical and chemical properties affect the extent to which radioactive material is absorbed by the blood and its distribution, decomposition, and elimination by the body. As for inhalation, the ICRP recommends standard ingestion dose coefficients for use in dose calculations. These are based on animal studies and human studies. Table 9 shows the standard dose coefficients that the ICRP recommends for plutonium-239 and americium-241. The dose coefficients for ingestion are smaller than those for inhalation by a factor of around 100. This is because absorption of plutonium and americium by the digestive system into the blood is very low, resulting in ingestion causing a significantly smaller radiation dose per Bq than does inhalation. The ICRP's models thus calculate that just 0.5% of the quantity of plutonium or americium that is ingested with foodstuffs is absorbed by the blood.

Table 9. Dose coefficients for ingestion of plutonium-239 and americium-241

Radioactive Material	Person Category	ICRP Dose Coefficient mSv/Bq
Pu-239	Adult	0.000,25
	10-Years	0.000,27
	1-Year	0.000,42
Am-241	Adult	0.000,20
	10-Years	0.000,22
	1-Year	0.000,37

Ruminants and Plutonium Contamination

Foodstuffs originating in contaminated land areas around Thule consist primarily of musk oxen meat harvested around Kap Atholl. In 2010 and 2012, the Government of Greenland set a Kap Atholl hunting quota of 15 musk oxen [19]. Caribou hunting takes place mainly in Inglefield Land and Olrik Fjord to the northeast of the Thule Air Base rather than in the area contaminated by the 1968 plane crash [20]. Consumption of caribou meat is thus not included in the following assessments.

The absorption of plutonium and americium through the roots of grass and other vegetation is very limited and can, generally speaking, be ignored as a means of exposure [21]. Musk oxen can ingest plutonium and americium by consuming grass and vegetation growing directly on surfaces contaminated by resuspension and subsequent deposition of radioactive material. Musk oxen also ingest a considerable quantity of soil while grazing in the relatively barren areas. If the soil is contaminated, this too can be a source of plutonium and americium ingestion by musk oxen.

No measurements of plutonium-239 and americium-241 in musk ox meat have been made in the Thule area or elsewhere in Greenland. At present, the potential contamination of musk ox meat can therefore only be assessed on the basis of very general observations and knowledge of contamination in the area and on the absorption and

distribution of plutonium and americium in other ruminants, including musk oxen elsewhere.

The ICRP's models for plutonium and americium absorption by the human digestive system is, as noted above, in large part derived from animal testing and animal studies and shows in a general sense that only a small proportion of plutonium and americium is absorbed by animal digestive systems and that the absorbed material primarily resides in the liver and bones, which is also the case for humans. A handbook by the IAEA has, for example, suggested parameter values for predicting the transfer of radioactive material in terrestrial and freshwater environments, assuming a general plutonium and americium absorption factor of around 0.01% by the digestive systems of adult ruminants [22]. It can thus be assumed that if musk oxen ingest plutonium and americium while grazing in contaminated areas, only a very small quantity of the ingested material will be absorbed by the animals' blood, and only a portion of this will be distributed in their meat (muscles).

An American study from the 1970s measured the americium and plutonium content of cattle that had grazed for up to three years under natural conditions, with no supplemental feeding, in a closed-off desert area of Nevada that was contaminated with plutonium and americium as a result of a 1957 test detonation of the high explosive components of a nuclear weapon (without significant activation/fission of the bomb). The study showed an average plutonium-239 and americium-241 absorption factor by the digestive system into the meat of around 0.0001%. There was thus nothing to suggest a greater environmental accessibility of plutonium and americium for absorption by cattle 20 years after deposition [23].

The contaminated areas in the American study consisted of an inner zone (1 km^2) and an outer zone (3 km^2), with an average (geometric mean value) plutonium-239 concentration in the uppermost 2.5 cm of soil of 23 kBq/kg and 1.9 kBq/kg (dry weight) respectively. The measured plutonium-239 concentrations in the meat of studied cattle older than 1.5 years varied from 0.001 to 0.06 Bq/kg (wet weight), in part dependent on how many days the animals spent in the areas in question prior to slaughter (200–1000 days) [24]. If the model used to analyse the experimental data [24] is adopted, it can be assumed that the cattle that grazed in the two contaminated areas would have late-life plutonium concentrations in their muscle tissue in the order of 0.1 Bq/kg and 0.01 Bq/kg (wet weight) respectively.

A British study from the 1980s addressed whether sheep could be used as an indicator of plutonium deposition from earlier atmospheric nuclear weapons testing and release from the Sellafield reprocessing facility. The study showed that measurements of plutonium-bearing faeces from sheep that had grazed in the area represent a sensitive and reproducible indicator of plutonium deposition on the dietary vegetation and in the soil of a particular area [25]. The radioactive release from Sellafield could be detected in sheep faeces up to 60 km from the facility. In the British study, it was found that the plutonium-239 content in one gram of faeces (dry weight) was roughly equivalent to the deposition on the vegetation covering 1 m^2 ground and that 10%–40% of the plutonium in the faeces could stem from soil ingestion. The study also showed that a plutonium-239 content of 1000 Bq/kg (dry weight) in the faeces would equate to a plutonium concentration of around 0.01 Bq/kg in sheep meat and around 20 Bq/kg in sheep liver.

The conditions present in the American and British studies are not immediately transferrable to those of the musk oxen in the Thule area. This is in part because those studies concerned other species of ruminants but more significantly because grazing conditions in Greenland are different. The studies may, however, be used to provide a preliminary estimate of the applicable orders of magnitude for the plutonium content of musk oxen in the Thule area. In August 2006, Risø DTU by chance found and collected two samples of musk ox faeces in Narsaarsuk and Grønnedal respectively. The plutonium-239 content was determined in the samples, which are not necessarily representative, and both showed a content of around 10 Bq/kg (dry weight) [26]. Table 10 shows the order of magnitude for plutonium-239 concentration in musk ox meat obtained by directly transferring the results of the American and British to Greenland studies with no corrections and using the plutonium concentrations that Risø DTU found in musk ox faeces and in soil from Narsaarsuk.

Table 10. The order of magnitude for plutonium-239 concentration in musk ox meat, based on uncorrected American and British studies applied to measurements in the Thule area

Study	**Narsaarsuk Soil** Bq/kg	**Musk Ox Faeces** Bq/kg	**"Meat"** Bq/kg
Cattle in Nevada	1,800*	-	0.01
Sheep in Northern England	-	10	0.000,1

Numeric values marked with * are based on Risø DTU's report [6].

The intake of plutonium by musk oxen is predominantly the result of ingestion of contaminated soil over time. If ingested soil is assumed to compose 10% of the total consumption in terms of mass, a faeces content of 10 Bq/kg, as measured in the Greenlandic samples, would result in an estimated concentration of 100 Bq/kg in the ingested soil and therefore a lower concentration in the meat than in the "cattle model" in Table 10.

Consumption of Locally Procured Musk Ox Meat

Detailed information on musk ox meat consumption in Greenland is unavailable. Over the years, however, a number of dietary surveys have been undertaken, and these make it possible to assess annual consumption of musk ox meat among the local population in the Thule area. Dietary surveys in 2004 and 2006 in Uummannaq and Narsaq respectively show a daily consumption of around 20 g of meat from terrestrial animals (sheep, caribou, musk oxen, hare), amounting to around 7 kg/year [27]. A later dietary survey [28], which covered 12 towns and settlements, shows an average of 12 g per day (4 kg/year) of caribou and musk oxen across all of Greenland, with significant geographical variation, presumably based on the ability to hunt these two species in the surveyed towns and settlements. The average consumption in Avanersuaq is around 15 g per day. The National Institute of Radiation Protection uses on this background the values shown in Table 11 as a basis for estimating annual consumption of musk ox meat by a representative person in the Thule area. Musk ox liver is not part of the local diet [28].

Table 11. Assumed consumption of musk ox meat from contaminated areas in Thule, for use in dose calculations

Representative Person	**Musk Ox Meat Consumption** kg/year
"Normal Eater"	3
"Big Eater"	15

Dose Calculations

The annual equivalent dose (E, given in the unit of mSv/year) as a result of ingestion of a particular foodstuff contaminated with a particular radioactive material from a contaminated area can be calculated using the following formula:

$$E = e_s \cdot M \cdot C_F$$

where C_F is the activity concentration of the foodstuff, given in Bq/kg,
M is the ingestion of the foodstuff, given in kg/year,
e_s is the dose coefficient for ingestion of the radioactive material, given in mSv/Bq.

If multiple radioactive materials in one or more foodstuffs are under consideration, all contributions from each foodstuff and each radioactive substance must be combined in order to obtain the total annual radiation dose from ingestion. Values of ingested musk ox meat, M, and dose coefficients, e_s, are discussed above. The activity concentration in musk ox meat, C_F, must currently be based on assumptions in order to assess potential orders of magnitude for the associated radiation dose.

1.1.3 Wounds

During stays in contaminated areas, open or closed wounds and cuts in the skin can be contaminated by dust, soil, or larger particles. Wounds include punctures in the skin, scrapes, cuts, and burns. Contaminated material can affix itself to the surface of the wound or become embedded deeper inside the wound. The contaminated material may later quickly be exfoliated or expelled, be encapsulated in the wound area, or be partially absorbed by the body, for example via blood or lymphtic fluid.

In order to assess the radiation dose from wound contamination, one should ideally know the surface area of the body which is typically exposed to wounds, the probability of wounds occurring, and the quantity of contaminating material that enters and remains in the wounds. In addition, contamination in the Thule area is not evenly distributed throughout the soil, meaning that a certain probability exists of soil contamination in a wound containing a certain amount of plutonium. Compared with inhalation and ingestion through diet, wound exposure is thus far more closely linked with the probability of a dose actually being received. Calculations are thus limited to providing potential doses for situations involving wound contamination by an assumed quantity of soil with an assumed plutonium content.

For example, in the assessment of the potential for radiation doses from wound contamination in Maralinga (see Section 5.2) it was assumed that the total wound contamination over one year was 1 g soil. Calculations were then made as to the probability of and associated doses for 1 g soil containing particles with various activities, based on the characterisation of contamination in Maralinga [29]. It should be noted that a total wound contamination of 1 g soil/year is very large and must be viewed in light of the Aborigines way of life in the Australian desert.

Following a given wound contamination by a radioactive substance, the absorption of this material by the body and thereby the resultant dose depends, as with the two other exposure pathways, on the physical and chemical properties of the material in question. The National Council of Radiation Protection and Measurement in the USA

(NCRP) has worked with the ICRP to develop a model for retention and excretion of radioactive material from wounds, based on animal studies and experiences with human wound contamination [30]. Alongside the ICRP's models for the metabolism of radioactive materials in and their excretion by the body, the model allows for calculation of radiation dose following wound contamination. The NCRP model differentiates between small and large particles (called particles and fragments respectively) among relatively insoluble materials such as plutonium and americium, where the distinction between particles and fragments is set at approximately 20 µm.

Dose coefficients for plutonium-239 and americium-241intake via wounds is estimated using the IMBA Professional Plus calculation program [31], which covers both the ICRP's models and the NCRP's wound model. The dose coefficients for intake via wounds expresses the accumulated dose over the 50 years (70 years for children) following intake of 1 Bq of a radioactive material. (mSv/Bq). Table 12 shows the results for plutonium-239, americium-241, and Thule plutonium for materials smaller and larger than 20 µm.

Table 12. Dose coefficients for plutonium-239, americium-241, and Thule plutonium intake via wounds

Radioactive Material	**Person Category**	**Particles** (≤ 20 µm) mSv/Bq	**Fragments** (> 20 µm) mSv/Bq
Pu-239	Adult	0.39	0.017
Am-241	Adult	0.33	0.014
Thule-plutonium	Adult	0.45	0.019

The dose coefficient for fragments is considerably smaller than for particles since the NCRP model for fragments assumes that a greater amount of the radioactive material in the fragment remains in the wound and thus is not transferred to the blood or the lymph nodes in contrast to the case for particles (~ 95% compared to ~ 1% after 2 years).

4 Assessment of Radiation Doses in Thule

1.1 Contamination Levels

Surface concentration values and plutonium-239 and americium-241 soil concentrations are included in the models for calculating radiation dose by all three exposure pathways. Table 13 shows the concentrations for the Thule contamination from Risø DTU's studies, which are used for the calculations and assessments in this report.

Table 13. Concentrations of plutonium-239 and americium-241 for the Thule contamination used in this report

Radioactive Material	Surface Concentration kBq/m^2	Soil Concentration kBq/kg
Pu-239	50	1.8
Am-241	9	0.3

The surface concentrations in Table 13 are based on the geostatistical analysis [7] of the Narsaarsuk area, which estimates a total deposition of 270 GBq plutonium-239 and 45 GBq americium-241 respectively over an area of 4.8 km^2. The values in the table may be compared with the arithmetic mean value of Risø DTU's primary measurement results of 39 kBq/m^2 for plutonioum-239 and 6.6 kBq/m^2 for americium-241.

On the basis of Risø DTU's measurements [7], it has been assumed for the soil concentrations in Table 13 that the above estimated total deposited activity for plutonium and americium respectively is evenly distributed in the upper 2 cm of soil with a density of 1.5 g/cm^3. The soil concentration for plutonium is significantly higher than the maximum concentration of 0.08 kBq/kg reported by Risø DTU in 2006 [2].

It is the National Institute of Radiation Protection's assessment that use of the present concentrations provides a conservative assessment of the calculated doses for all three exposure pathways.

1.2 Inhalation

The method for assessing inhalation doses is covered in Section 3.3.1, and the applicable parameter values for assessing periods of stay, breathing rates, and dose coefficients in relation to the Thule accident are provided. The concentration of plutonium in the air as a result of terrestrial contamination is currently the decisive factor for assessing inhalation doses. Air concentration in Narsaarsuk was measured by Risø DTU in the summers of 2007 and 2008 [6] and can also be estimated on the basis of the measurements carried out on plutonium surface concentrations in the area. Table 14 juxtaposes the measured and estimated air concentrations used for dose calculations. The table also shows the parameter values used in the models, per Sections 3.3.1 and 4.1.

Table 14. Measured and estimated air concentrations of plutonium-239

Method	Parameter values					
	Surface Concentration kBq/m^2	**Resuspension Factor** m-1	**Soil Concentration** kBq/kg	**Dust Load** µg/m^3	**Concentration Factor**	**Air Concentration** µBq/m^3
Measured with Filter	-	-	-	-	-	0.0044[1)]
Measured with Sticky Foil	-	-	-	-	-	0.001[1)]
Estimated Resuspension Factor	50[2)]	10-10	-	-	-	5
Estimated Dust Load	-	-	1.8[2)]	1	5	9

1) Based on Risø DTU's report [6, 7].

2) Based on Table 13.

The air concentrations shown above are all very small. The measured concentrations are comparable to background levels that are measured today in, for example, Germany and the Czech Republic. They are also around three orders of magnitude smaller than the plutonium concentrations measured at the Thule Air Base in the period of 1966-1976, in both cases as a result of earlier atmospheric nuclear weapons testing, per Risø DTU [6].

The estimated air concentrations based on generic resuspension models result in significantly higher air concentrations reflecting that these models clearly overestimate actual resuspension in the area around Narsaarsuk, per Risø DTU [6].

Risø DTU has measured the americium-241 content in 56 samples collected at Narsaarsuk by vacuuming surface soil over a 1 m^2 area [6]. The geometric mean value of these measurements is 0.2 Bq/m^2, which when using a Pu-239/Am-241 relation of 6:1, equates to a plutonium-239 surface concentration of 1.2 Bq/m^2. If it is assumed, for example, that this surface activity measurement provides the actual surface activity available for resuspension, and if air concentration is calculated on this basis, the result is an air concentration of 0.0001 µBq/m^3. This matches much more closely the air concentrations actually measured by Risø DTU.

Table 15 shows dose calculations based on the measured and estimated air concentrations given in Table 14. Since the air concentrations are very small, the calculated doses are also very small.

The calculation of doses includes a number of requirements, assumptions, and measurements, all of which possess considerable uncertainty. The provided inhalation doses are therefore associated with considerable uncertainty, which should be kept in mind when the results are compared and the risk of staying in the Narsaarsuk area is assessed. This uncertainty also allows for the potential for locally raised resuspension levels as a result of individuals staying in the area. Although there are significant differences (many orders of magnitude) between the direct and indirect assessments of inhalation dose, they provide, when considered together, a robust understanding that the potential doses resulting from resuspension and subsequent inhalation of plutonium by indi-

viduals staying in the area are trivial and do not represent a significant exposure pathway.

Table 15. Inhalation doses for representative persons, based on measured and estimated air concentrations of plutonium-239

Representative Person	Method of Air Concentration	Radiation Dose, mSv/year
Greenlandic Trappers	Measured with Filter	0.000,000,04
	Measured with Foil	0.000,000,009
	Estimated Resuspension Factor	0.000,05
	Estimated Dust Load	0.000,08
"Tourists"	Measured with Filter	0.000,000,006
	Measured with foil	0.000,000,001
	Estimated Resuspension Factor	0.000,003
	Estimated Dust Load	0.000,006

The direct measurements of plutonium content in air filters should be considered most significant and will offer the best basis for a quantitative assessment of the order or magnitude for inhalation doses. The following value is used as an indicator of inhalation doses for all individuals (both Greenlandic trappers and tourists) who might be staying in the area:

- Indicator of Inhalation Doses: 0.000,000,1 mSv/year.

A radiation dose of this size is extremely small.

4.1 Ingestion

The method for assessing inhalation doses is covered in Section 3.3.2, and the applicable parameter values for assessing the order of magnitude for plutonium in musk ox meat, the annual consumption of this meat, and dose coefficients in relation to the Thule accident are provided. It is also highlighted that the plutonium concentration in musk ox meat is currently based on preliminary estimates. Table 16 shows the assumed orders of magnitude for doses from the assumed ingestion of musk ox meat by "big eaters". The table refers only to "big eaters" because although the dose for "normal eaters" will be five times smaller than that for "big eaters", it will be expressed by the same order of magnitude.

Table 16. Approximate magnitude of radiation dose for representative persons, based on indirectly estimated plutonium-239 concentrations in musk ox meat

Representative Person	Method for Estimate	Radiation Dose, mSv/year
"Big Eaters"	Cattle in Nevada Soil Measurements [1.8 kBq/kg]	0.000,1
	Sheep in England Faeces Measurements	0.000,000,1

The estimated radiation doses in Table 16 do not include americium-241 in musk ox meat. Americium behaves similarly to plutonium in the soil-ruminant meat-human exposure chain, though with a tendency toward slightly greater absorption by animals

and humans. Since the relationship between plutonium and americium in Thule is around 6:1, the contribution of americium will not have a decisive influence on the estimated orders of magnitude for doses shown in Table 16. The values can therefore be regarded as a collective estimate of dose by ingestion of terrestrial animals from areas contaminated with plutonium following the Thule accident.

If the preliminary order of magnitude estimates of dose are accepted, the following value can be used as an indicator of radiation dose from ingestion of musk ox meat from the Thule area:

- Indicator of Radiation Dose from Ingestion: 0.000,1 mSv/year.

Although this equivalent dose is greater than the indicator of inhalation dose, it must still be regarded as being extremely small.

As noted above, the plutonium concentrations in musk ox meat, which are used for the calculations in Table 16, are to be regarded as preliminary orders of magnitude estimates that could potentially be applicable to plutonium contents in musk oxen in the Thule area. Similarly, the calculated orders of magnitude for radiation doses must be regarded as preliminary estimates based on studies of other ruminants in contaminated terrestrial areas differing from arctic Thule. A better estimate for radiation dose could only be achieved by collecting and measuring meat samples from musk oxen taken in the Thule area. The National Institute of Radiation Protection does not anticipate that such measurements would show plutonium concentrations in musk ox meat that diverge significantly (by 2–3 orders of magnitude) from the concentrations in Table 10. Radiation doses that are 2–3 orders of magnitude (100–1000 times) greater than the indicator dose for ingestion would also be regarded as extremely small and of no significance to health. The National Institute of Radiation Protection therefore regards the adopted indicator of radiation dose for ingestion as being widely applicable in relation to a reference level of 1 mSv/year.

No actual collection of musk ox meat samples have been taken in the Thule area in order to measure plutonium content. However, provisionally indicative measurements of a relatively small subsample, collected during a Nordic project on the radioactive elements polonium-210 and lead-210, are available [32]. Analysis of this small sample shows plutonium content of less than 0.05 Bq/kg [33], which was the detection limit for plutonium in the particular measurement. This value corresponds to the order of magnitude of the plutonium concentrations in Table 10, which are used for the dose calculations in this section.

For comparison with the indicative radiation dose for ingestion of plutonium, it can be noted that the analyses in the aforementioned Nordic project yielded a polonium-210 content of 90 Bq/kg (dry weight) in the sample of musk ox meat from the Thule area, which equates to around 20 Bq/kg (wet weight) [32]. Polonium-210 is a naturally occurring radioactive material that follows radon-222 in the uranium-238 decay chain. After its creation in the airborne stage, it is deposited on the ground surface when radon-222 decays. Like plutonium-239, polonium-210 emits alpha radiation. If the method described in Section 3.3.2 and the associated parameter values are used to assess radiation doses from ingestion combined with the ICRP's recommended dose coefficient for polonium-210, the polonium in musk ox meat would give an radiation dose of 0.07 mSv/year for "normal eaters" (3 kg/year) and 0.2 mSv/year for "big eaters" (10 kg/year), both of which equate to an order of magnitude of 0.1 mSv/year.

The adopted indicator of equivalent dose for ingestion does not include foodstuffs from the marine environment. Since the 1968 accident, many analyses of the seabed beneath the crash site have been carried out, and marine animals have been sampled to measure contamination levels. Throughout this period, the conclusion has been that there is a measurable contamination of the marine environment but this does not represent a risk for humans, even in the event of consumption of shellfish with the highest measured contamination [34, 35]. In 1998, the total intake of plutonium from marine foodstuffs over the period of 1968–1995 was assessed. Under the assumption that all marine foodstuffs came from Bylot Sund, the average annual radiation dose from this source was calculated as being 0.005 mSv/year [35]. Radiation doses from ingestion of marine animals are therefore not included in this report and will not be discussed further.

1.3 Wounds

The method for assessing radiation doses after wound contamination with soil and particles is covered in Section 3.3.3. As noted above, assessments concerning wounds as a exposure pathway are linked to their probability of occurrence, the quantity of radioactive material in the soil that enters a wound or cut, and as a result, the magnitude of the associated dose.

If it is assumed that 0.1 g soil/year enters the wounds of an individual staying around Narsaarsuk and Grønnedal, it is necessary to assess the probability of this quantity of soil containing a given quantity of plutonium. The probability of the contents of this quantity of soil exceeding the average activity concentration of Thule plutonium among all collected soil samples would be very small when one considers that the samples were collected in those places where the field instruments could measure raised americium-241 levels in the soil. Similarly, the probability would be very small of that particular soil containing a highly active particle. In both cases, the National Institute of Radiation Protection estimates that these probabilities are significantly smaller than 1% and thus, the probability of an individual being exposed in this manner via a wound more than once in his or her life is exceptionally small.

The size of the radiation dose for an individual whose wound has been contaminated by soil containing a given quantity of plutonium can be calculated using the dose coefficients for plutonium intake via wounds provided in Table 12. The dose coefficients express the accumulated dose over the 50 years (70 years for children) following intake of 1 Bq of a radioactive material (mSv/Bq). Table 17 shows the assessed accumulated doses for a wound contamination of 0.1 g soil, using the soil activity concentrations for the most active Thule particles found in the soil in the Thule area, as provided in Table 13. These accumulated doses can be regarded as being in the upper range of the possible doses via wound contamination. Since the probability of being thus exposed with more than one such wound over the course of one's life is extremely small, the average annual dose in Table 17 also equates to the accumulated doses. This is significant in that the accumulated dose from plutonium-239 and americium-241 would, in reality, be spread out evenly over the subsequent 50 years on account of the very long periods that these materials remain in the body.

Table 17. Radiation dose from wound contamination for individuals in the population

Soil/Particle	Activity Bq	Accumulated Radiation Dose mSv	Radiation Dose/year mSv
0.1 g Soil	0.18 (1.8 kBq/kg)	0.08	0.002
Particle (20 µm)	20	9	0.2
Fragment (~ 50 µm) Largest Found on Land	150	3	0.06

The following indicative doses for wound contamination of soil or a single particle are used below:

– Indicator of Radiation Dose for Wound Contamination (Soil): 0.001 mSv/year

– Indicator of Radiation Dose for Wound Contamination (Particle): 0.1 mSv/year

Since very large (conservative) values have been selected for both the activity of the entered particle and the plutonium concentration of the soil contaminating a wound, and since the probability of intake is less than 1%, the adopted doses lie in the very upper range of the doses that are at all possible from plutonium contamination via wounds for individuals staying in the Thule area.

1.4 Combined Assessment

The indicative doses for the three exposure pathways (inhalation, ingestion, and wound contamination) are described in detail in the preceding sections and have taken associated uncertainties, limitations, and probabilities into account. Table 18 shows an overview of the indicative radiation doses for the three exposure pathways.

Table 18. Indicative orders of magnitude for radiation dose as a result of terrestrial radioactive contamination in the Thule area

Exposure Pathway	Dose/year mSv	Notes
Inhalation	0.000,000,1	Based on measurements with filters
Ingestion	0.000,1	Based on models for cattle in the USA
Through Wounds 0.1 g Soil	0.001	Probability significantly lower than 1%
Through Wounds ~ 20 µm Particle	0.1	Probability significantly lower than 1%

If the doses shown in the table are combined with the recommended reference level of 1 mSv/year for contamination resulting from the Thule accident (see Section 2.2), the assessed doses for inhalation and ingestion as exposure pathways are many orders of magnitude below the reference level (10,000–10 million times smaller). The wound contamination exposure pathway is associated with a dose that is smaller than the reference level by a factor of 10–1000. It should also be recalled that the probability of this exposure pathway is assessed as being less than 1%.

With this in mind, it is the assessment of the National Institute of Radiation Protection that the total dose for representative persons in the Thule area for plutonium contamination resulting from the 1968 Thule accident is lower than the recommended reference level, even under extreme conditions and situations.

A series of tables in Section 3 shows the applicable parameter values for all three person categories. Although this section only provides provisional calculations and the results of the calculated doses for adults, the indicative orders of magnitude for doses cover the 10-year-old and 1-year-old person categories as well. Assessment of the total dose is thus applicable to all person categories.

The above assessment can also be supported by the following extreme example, which is unrealistic and could not occur in practice. Risø DTU measured the americium-241 content of 56 samples collected in Narsaarsuk by vacuuming surface soil over a 1 m^2 area [6]. The weight of the vacuum bags after incineration varied from 1 g to over 400 g. In two cases, the measurements showed an americium-241 content of 30 Bq, which is assumed to have originated from one or more Thule particles. This equates to a plutonium-239 content of around 200 Bq and is included in the above assessment of dose from wound contamination. In all other cases, the vacuum bags contained less than 3 Bq americium-241, equivalent to around 20 Bq plutonium-239. Assuming that the contents of a vacuum bag of this kind were to be either inhaled or ingested in its entirety, this would result in, on the basis of the previously specified dose coefficients, an inhalation dose of 0.6 mSv or an ingestion dose of 0.05 mSv.

1.5 Previous Measurements of Plutonium Excretion

In 1988, the National Institute of Radiation Protection and Risø DTU carried out studies of plutonium excretion by individuals who had, for various reasons, been associated with the 1968 Thule accident [36]. The analytical program covered, among other things, the collection and measurement of urine samples from Greenlandic trappers, *etc.* who had participated in the work at the crash site or had lived in the Narsaarsuk settlement.

The analytical technique applied in 1988 had a detection limit of, at best, 0.0002 Bq plutoium-239 per urine sample. According to the then-standard recommendations from the ICRP for absorption, distribution, and excretion of plutonium by the body, it should have been possible in 1988 to detect a 1968 intake of 300 Bq plutonium-239 from inhalation. None of the urine samples in 1988 showed plutonium, and it was thus concluded from the results that all of the studied individuals had a plutonium-239 intake of below 300 Bq in 1968. Such a plutonium intake was assessed in 1988, on the basis of the same ICRP recommendations, to yield a radiation dose of 20 mSv for an individual over the following 50 years (0.4 mSv/year).

Section 3.3.1 explains how the present report's inhalation doses are calculated on the basis of data specific to Palomares dust as well as the latest recommendations from the ICRP concerning distribution and excretion of plutonium by the body. This data and these recommendations today form the best foundations for assessing plutonium measurements in urine samples and can thus also be used to assess the 1988 urine measurements. Table 19 compares the 1988 assessment and a corresponding assessment today, calculated using the IMBA Professional Plus calculation program [31].

Table 19. Assessments in 1988 and 2011 concerning the quantity of plutonium-239 inhaled in 1968 and associated radiation dose, equivalent to a detection limit of 0.0002 Bq plutoium-239 in a 1988 urine sample

Year of Assessment	Material	Minimum Recognised Intake Bq	Minimum Recognised Radiation Dose mSv
1988	Type S	300	20
2011	Palomares Dust	600	15
	Type M	200	9
	Type S	1,000	20

Table 19 shows that the calculated intake of plutonium today and the resultant dose vary by a factor of 2–3 compared to the 1988 assessment, depending on the type of material used in the calculation. This is within the overall margin of error of the calculations and thus shows that the earlier assessment of the significance of the urine measurements carried out in 1988 remains valid.

Intake and associated radiation dose in Table 19 are calculated assuming a single intake 20 years prior to the urine measurement. If it is, on the other hand, assumed that the intake is evenly distributed over the 20 years prior to the sample collection, the calculation for Palomares dust provides a daily plutonium-239 intake of 0.05 Bq, equivalent to a total intake of 300 Bq and an associated total dose of 8 mSv over the 20 years.

5 Contamination from Other Accidents

Terrestrial contamination by weapons grade plutonium has occurred in connection with the production and testing of nuclear weapons multiple places around the world as well as in connection with accidents during flights carrying operational nuclear weapons. These contaminations have resulted in the risk of plutonium exposure among local populations, and monitoring programs have been carried out to assess the extent of these exposures. The programs have formed the basis for following cleanup programs. To assist in this, the relevant authorities have set reference levels and cleanup criteria or acceptability criteria related to the use of and residence in the contaminated areas. A brief overview of the situation in Palomares, Spain and Maralinga, Australia will be given in order to provide background information and a basis for comparison relating to contamination in the Thule area. Both of these areas are comparable to some degree with the Thule contamination.

5.1 Palomares, Spain

In 1966, an American B-52 bomber crashed in Palomares following a collision with a tanker plane during mid-air refuelling. The plane carried four nuclear weapons of the same type as were involved in the Thule accident. The high explosive components in two of the bombs detonated, contaminating a 2.25 km^2 area, including agricultural and urban areas.

Measurements immediately following the accident indicated plutonium-239 concentrations from 80 Bq/kg up to 8 kBq/kg in the soil [37]. Cleanup operations commenced immediately, and the topmost 10 cm of soil covering most of the contaminated area, where surface concentration exceeded 1.2 MBq/m^2, was removed and sent to the USA as radioactive waste. Following this, areas with surface concentrations exceeding 0.12 MBq/m^2 were deep ploughed and homogenised in order to lower contamination concentrations [38].

Subsequent studies in the environment around Palomares have included measurements of plutonium-239 concentration in the air at four locations, including the crash sites of the two weapons, another contaminated area, and the town of Palomares itself. From 1966–1995, the highest annual mean concentration was 440 $\mu Bq/m^3$, measured in 1967. The highest weekly mean concentration was measured in March 1967 and was 11,000 $\mu Bq/m^3$. The mean concentration over all 30 years was 39 $\mu Bq/m^3$ in the agricultural area and 4 $\mu Bq/m^3$ in the urban area. Radiation doses were calculated on the basis of plutonium-239 concentrations in air and the method described in Section 3.3.1 [39]. The largest dose of 0.054 mSv/year was calculated for agricultural workers in 1967. The total dose from intake over all 30 years was calculated at 0.21 mSv for agricultural workers and 0.037 mSv for town residents, equivalent to average annual doses of 0.007 mSv/year and 0.001 mSv/year respectively.

Analyses of air were carried out in areas where plutonium-239 surface concentrations varied from 0.12–1.2 MBq/m^2. It has thus been possible to estimate the resuspension factor for the Palomares accident on the basis of the association between measurements of surface concentration and those of air concentration. The studies indicated that the resuspension factor was initially around 10^{-7}, falling to 10^{-9} after a few months and around 10^{-10} after a couple of years.

Over the course of the 1990s, use of the Palomares area changed significantly, with more technologically sophisticated agriculture (greenhouses) and a significant development in the tourism industry, leading to many new buildings. This change of use, causing the relocation of large quantities of soil, could have increased the accessibility of the remaining plutonium contamination. In 2000, the Research Center for Energy, Environment and Technology in Spain (CIEMAT) assessed that the total quantity of plutonium in the upper 45 cm soil in the so-called Zone 2 equalled 2.9 TBq. In 2003, the Spanish authorities established criteria (reference levels) for the use of the upper 15 cm soil in Palomares. The criteria stated that unrestricted land use was permissible if it was assessed that the resultant dose would be less than 1 mSv/year; that partial land use was conditional upon further studies if the dose would exceed around 1 mSv/year; and that land use was banned if the dose would exceed 5 mSv/year. Table 20 shows the derived plutonium-239 soil concentrations set by the Spanish authorities on the basis of these reference levels [40].

Table 20. Criteria for use of terrestrial areas in Palomares associated with derived plutonium-239 soil concentrations

Use of Land Areas	**Radiation Dose per Year** mSv	**Pu-239 Soil Concentration** kBq/kg
Banned	› 5	› 25
Partial, with Further Studies	~1	1 – 25
Unrestricted	‹ 1	‹ 1

A research program was initiated with the aim of carrying out a detailed characterisation of the remaining contamination. Americium-241 contamination was measured over a large number of samples from a 6.6 km^2 area. These measurements showed, among other things, contamination in a 0.2 km^2 area lying outside the "contaminated area" boundary set in 1966. This area was closed off to the public, and additional contamination measurements were carried out. A rehabilitation plan was developed for the most-contaminated areas but was never decided upon or implemented since it remains unclear whether the contaminated soil can be removed to the USA [40].

5.2 Maralinga, Australia

Between 1955 and 1963, the United Kingdom carried out a nuclear weapons testing program in Maralinga, a relatively desolate area in southern Australia. The program covered, among other things, "small tests" involving the burning and explosive dispersion of plutonium and uranium, similar to the plutonium dispersion that occurred as a result of the plane crashes in Palomares and Thule. After the British testing was complete, the area was found to still be subject to significant contamination, which was assessed as possibly constituting a health risk to potential residents of the area, who had not had access to the area during the period of testing. Potential residents were expected to consist of groups of the Australia's original inhabitants, the Aborigines, who lived a nomadic existence without a fixed place of residence.

In 1993, the Australian authorities implemented a rehabilitation project for the area, which involved the setting of cleanup criteria and new measurements in the area. The cleanup criteria were set on the basis of a reference level of 5 mSv/year, assuming continual, year-round stay in the contaminated area by the local residents. All three exposure pathways (inhalation of stirred-up dust, ingestion of contaminated foodstuffs, and wound contamination) were considered [41]. The cleanup criteria therefore took into

account two primary requirements. The first of these was a requirement regarding the maximum plutonium concentration in the surface soil, which could be subject to resuspension and inhalation. This criterion was expressed in terms of the measurable americium-241 inasmuch as a Pu-239/Am-241 relationship of 8:1 and a concentration factor of 6 had been assumed. Secondly, a limit was placed on the quantity and activity of contaminated particles and fragments near the ground surface that could be unintentionally ingested or could contaminate a wound. Table 21 shows the cleanup criteria that were set.

Table 21. Cleanup criteria in Maralinga, with associated derived americium-241 surface concentrations, particle activity, and particle concentration

Cleanup/Land Use	**Surface Concentration** kBq/m^2	**Particle Activity** kBq	**Particle Concentration** (› 20 kBq)
Soil Removal[1)]	› 40 (over 10,000 m^2)	› 100	› 1 pr. 10 m^2
Release following Soil Removal[2)]	‹ 3 (over 10,000 m^2)	‹ 100	‹ 1 pr. 10 m^2
Unrestricted[2)]	‹ 3 (over 3 km^2)	‹ 100	‹ 1 pr. 10 m^2

1) Only one criterion must be fulfilled.

2) All three criteria must be fulfilled.

Considering the dose coefficients that were recommended for general use at the time and the specific factors concerning conditions in Maralinga, an americium-241 surface concentration of 3 kBq/m^2 would be expected result in an annual total dose of 5 mSv from the inhalation of plutonium and americium in contaminated dust, assuming continual, year-round stay in the area. Realistic scenarios for the other two exposure pathways would contribute less than 10% to the total equivalent dose.

5.3 Comparison with the Thule Contamination

Assessment of the need for special control and protection measures in a terrestrial area that has been contaminated by radioactive material depends primarily on the levels and extent of contamination. Just as significant, however, are the ways in which the area is used and stayed in as well as societal, climatic, and other relevant conditions. It is thus impossible to directly compare the adopted reference levels and set cleanup and usage criteria for contaminated areas in various countries. A purely numerical comparison between the adopted reference levels and criteria in Palomares and Maralinga on the one hand and the research in Thule on the other is provided below.

Palomares

The ban on the use of and stay in the most-contaminated areas of Palomares is based on a reference level of 5 mSv/year. In both Thule and Palomares, unrestricted use of a contaminated area is based on a dose below a reference level of 1 mSv/year.

The adopted derived criteria for plutonium-239 soil concentration in the contaminated areas are 25 kBq/kg for prohibitions against stays and 1 kBq/kg for unrestricted use. These can be compared with the conservative estimated level of 1.8 kBq/kg for the Narsaarsuk area (see Table 13).

Maralinga

The ban on the use of and stay in the most-contaminated areas of Maralinga is based on a reference level of 5 mSv/year. This same reference level is also used as the upper limit for unrestricted use of contaminated areas.

The adopted derived criteria for americium-241 surface concentration are 40 kBq/m^2 for soil removal and 3 kBq/m^2 (over 3 km^2) for unrestricted use. These can be compared with the Narsaarsuk area's conservative estimated level of 9 kBq/m^2 (see Table 13).

With reference to the Australian criteria for maximum particle activity and particle concentration (see Table 21), no measurement in either the terrestrial or marine sediments in Thule have found particles with activities exceeding the adopted upper limits for either individual particles or particle concentrations.

6 Conclusions and Recommendations

6.1 Conclusions

Risø DTU has carried out research on the terrestrial contamination in the Thule area after the radioactive contents of four nuclear weapons were dispersed following the crash of an American B-52 bomber in 1968. The results of Risø DTU's studies are described in the report *Thule-2007 – Investigation of radioactive pollution on land*, which covers all measurements that were carried out on land in Thule in the years 2003, 2006, 2007 and 2008.

The present report uses Risø DTU's report as a basis for assessing radiation doses and consequently the risk for individuals as a result of terrestrial radioactive contamination in the Thule area.

The assessment of radiation doses involves a number of conservative assumptions, estimates, and measurements, all of which are subject to considerable uncertainty. In some cases, models have been used based on experiences from other contaminated areas elsewhere in the world, which are subject to climatic and other conditions that diverge from those in the Thule area. The calculated doses are thus associated with considerable uncertainty, which must be taken into account when the results are used for comparison and when the risks of staying in the Thule area are assessed. It has therefore been chosen to provide the assessed radiation doses in the form of indicative orders of magnitude, which are applicable to everyone who might stay in the area, across various age groups.

If the estimated doses in this report are combined with the National Institute of Radiation Protection's recommended reference level for contamination as a result of the Thule Accident of 1 mSv/year, the assessed magnitudes of radiation doses for inhalation and ingestion as exposure pathways are many orders of magnitude below the reference level (10,000–10 million times smaller). The wound contamination exposure pathway has a magnitude of radiation dose that is smaller than the reference level by a factor of 10–1000, and it should be recalled that the probability of this exposure pathway is assessed as being less than 1%.

With this in mind, it is the assessment of the National Institute of Radiation Protection that the total radiation dose for representative persons in the Thule area for plutonium contamination resulting from the 1968 Thule accident is lower than the recommended reference level, even under extreme conditions and situations.

6.2 Recommendations

On the basis of Risø DTU's research as well as the calculations and radiation dose assessments, the National Institute of Radiation Protection can, in a radiation protection and public health perspective, make the following recommendations regarding the need for follow up on the measurements and assessments, including assessments of the need for future measurements:

- From a radiation protection assessment perspective, based on the current patterns of use of the contaminated area in Thule, there is no need for restrictions to stays, etc. or for decontamination measures in the area.

- As noted in the assessment of the radiation dose resulting from ingestion of foodstuffs, no direct measurements of plutonium in musk oxen from the Thule area or other parts of Greenland are currently available. As a result, the assessment has relied on models based on experiences from contaminated locations elsewhere in the world, which differ from the conditions in the Thule area in terms of climate, *etc.* The dose calculations from meat ingestion could thus be better qualified via a small survey program that samples musk oxen and other terrestrial mammals from the Thule area. The collected samples should then also be measured for the presence of the naturally occurring radioactive material polonium-210, which is estimated to cause significantly higher doses than the plutonium contamination does.

- The assessment of radiation doses resulting from plutonium contamination for people in the Thule area is based on Risø DTU's research up to and including 2008, applied to the current use of the area. To ensure that the assumptions for this assessment remain valid, a small, tailored survey should be carried out every 5 to 10 years.

- The assessed radiation doses for people in the Thule area are significantly lower than the recommended Thule reference level. There is thus no need, from a dose monitoring perspective, to analyse for the presence of plutonium in individuals living in the area in survey programs such as the search for plutonium in the urine of previous Narsaarsuk residents carried out in 1989.

- If plans arise for changed use of the area, for instance involving the construction of buildings or other installations, including long-term stays or residence in the area, the need for restrictions concerning stays, *etc.* in the area or for decontamination measures should be reconsidered in detail prior to the plan's commencement.

- Protection measures such as signposting or fencing off selected areas for reasons not related to radiation protection would not influence the National Institute of Radiation Protection's assessment of the total radiation dose for people in the Thule area, including radiation dose assessments for people tasked with placing or maintaining signs or fencing.

- Decontamination measures could cause stirring up of plutonium during decontamination, potentially raising the radiation exposure of not only the people undertaking the operations but also of the local population. Decontamination operations should thus not be decided upon or commenced prior to the completion of a comprehensive radiation protection safety assessment for such a project.

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