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Predicted Radiation Exposure from Mining at Kvanefjeld

Introduction to Radiation, Review of Baseline Information, and Predicted Radiation Exposures from Kvanefjeld Mining, Mineral Processing and Refining

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S. Nielsen, P. Roos and K. Andersson

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from Kvanefjeld Mining, Mineral Processing and Refining

Preface

This report has been prepared by agreement in July 2014 between Greenland Minerals and Energy Ltd and DTU Nutech to address the impact of mining at Kvanefjeld on radiation exposure to workers and the Greenland environment.

Roskilde, October 2015

Sven Poul Nielsen
Head of Division

Content

Executive Summary

Baseline surveys of gamma radiation and environmental radioactivity have been carried out by Greenland Minerals and Energy Ltd (GMEL) to show existing levels in the town of Narsaq and in the Kvanefjeld project area. Radiation levels in Narsaq are low but elevated in the project area due the presence of large uranium and thorium deposits in Kvanefjeld. These deposits are also the reason that radon in outdoor air show elevated concentrations in Narsaq and in the project area. It is recommended that future monitoring of external exposure and radon should be based on measurement techniques using integrating dosimeters.

The Technical University of Denmark (DTU) has reviewed the impact of Kvanefjeld operations on the future workforce to estimate radiation doses to individuals. Calculations were performed with conservative assumptions that reveal the annual radiation dose to workers to be between 1 and 5 millisieverts (mSv). This range of annual doses is below the internationally accepted limits for occupational exposure of 20 mSv averaged over five consecutive years and 50 mSv in any single year. The radiation dose estimates calculated by DTU are consistent with actual measured radiation doses from uranium mines in other developed countries such as Australia and Canada. From a radiation dose perspective Kvanefjeld operations are not expected to be any worse than current uranium mining operations elsewhere as the uranium content is significantly lower.

DTU was engaged by GMEL as an independent reviewer of baseline surveys carried out and data obtained. DTU (former Risø National Laboratory) has five-decades of experience in dealing with naturally-occurring and man-made radioactivity and radiation in the environment covering research and development as well as consultancy.

1 Introduction to Radiation and Radioisotopes

1.1 Atoms, isotopes and radioactive decay

All matter is made of atoms. Atoms are made up of protons and neutrons constituting a nucleus, and electrons orbiting around the nucleus. In a normal (un-ionised) atom the number of protons equals the number of electrons, and this number determines the chemical nature of that element (see Figure 1.1). Atoms of the same chemical type can have different numbers of neutrons in their nuclei. These are called isotopes of the element.
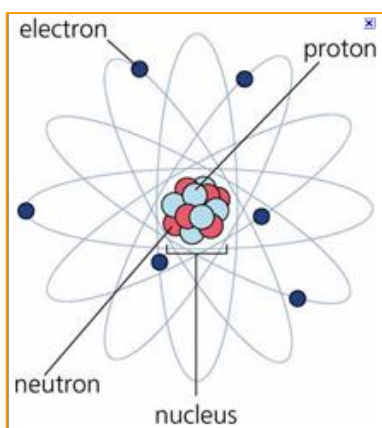
Figure 1.1. Atomic model. In the uranium atom there are for instance 92 protons and as many electrons. The number of neutrons in ^{235}U and ^{238}U is respectively 143 and 146.

Some isotopes are unstable, and will spontaneously emit radiation in the form of subatomic particles or electromagnetic energy, and form a lighter nucleus. This process is called radioactivity, and the atoms that undergo it are called radioactive. There are radioactive forms (called radioisotopes or radionuclides) of all elements. For example, lead has 27 different isotopes, 23 of which are radioactive and four are stable (that is non-radioactive). Most radioisotopes are produced artificially, usually in nuclear reactors, but there are also many naturally occurring radioisotopes. All isotopes of elements heavier than bismuth (^{209}Bi) are radioactive.

Isotopes are written with their chemical symbol and the total number of protons plus neutrons in their nucleus (the mass number). Thus the most common isotope of uranium, with 92 protons and 146 neutrons, can be written as ^{238}U or uranium-238.

Different radioactive isotopes emit radiation at different rates. The breakdown (or decay) of radioactive atoms reduces the number remaining, so that the amount of radiation emitted continually decreases (see Figure 1.2).
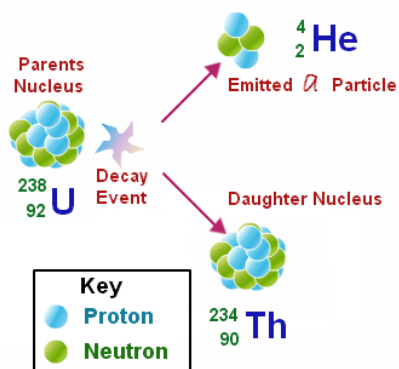
Figure 1.2. Decay of a uranium-238 nucleus through emission of an alpha particle (helium nucleus).

It is convenient to describe the rate of reduction by the 'half-life'. This is the time taken for one half of the radioactive atoms to decay away, and thus also the time for the rate of radiation emission to decrease to one half of its original value. Each radioactive atom has its own half-life, which is fixed, and cannot be changed. Half-lives of naturally occurring radioisotopes range from fractions of a second to billions of years. The half-life of ^{238}U is 4.5 billion years, one of the longest known.

The decay of a radioisotope with a half-life of 20 days is illustrated in Figure 1.3. An initial 1,000 atoms has been reduced to 500 atoms after 20 days, to 250 atoms after 40 days, and to 125 atoms after 60 days.
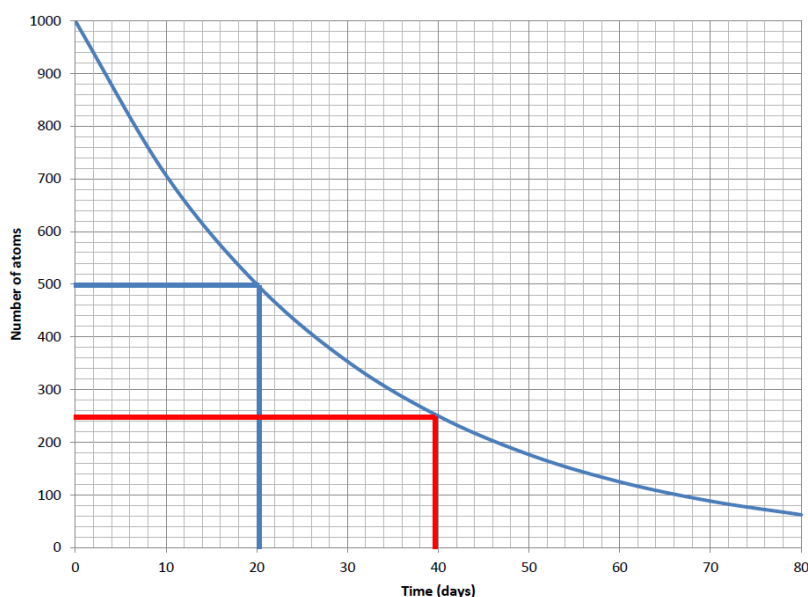
Figure 1.3. Decay of a radioactive isotope with a half-life of 20 days (number of atoms halved each 20 d).

When a radioactive atom decays, the new atom formed may itself be radioactive, which might in turn decay to another radioactive atom. For example, in Figure 1.2 above, the ^{234}Th formed from the decay of ^{238}U is also radioactive, and subsequently decays. Such chains of radioactive decay are called 'decay series' or 'decay chains', (see Figure 1.4).

1.2   Uranium

Uranium is a naturally occurring heavy metal. It is widespread in the earth's crust, and present in all normal soils with an average concentration of about three parts per million (ppm). The best known property of uranium is its radioactivity.

Like all elements, there are different isotopes of uranium that have different numbers of neutrons in their nucleus. The most common is uranium-238 (^{238}U) with 92 protons and 146 neutrons, and it makes up more than 99% of natural uranium (by weight). ^{235}U, with 92 protons and 143 neutrons, is the next most abundant, with 0.72% by weight.
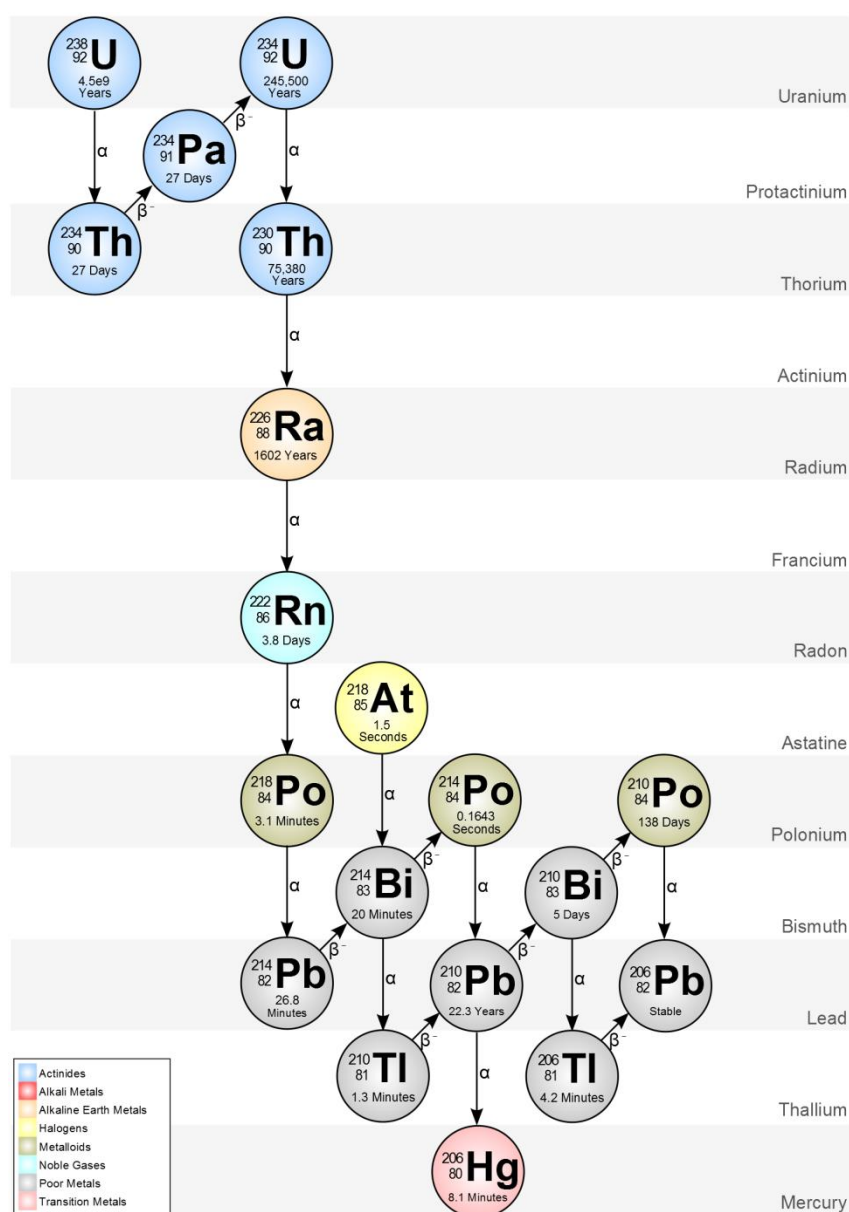
Figure 1.4. Decay series of uranium-238, with half-life of each radioisotope produced. Also indicated are classifications of each of the elements according to physicochemical properties.

The relatively rare ^{235}U isotope is essential for the operation of nuclear reactors, and before uranium can be used for that purpose the concentration of ^{235}U must usually be increased from 0.7% to about 3%, by the process of enrichment.

The isotopes of the elements formed by the decay of ^{238}U are themselves radioactive, and so form a decay series, ending with the stable (non-radioactive) lead-206. The decay products in the ^{238}U series are shown in Figure 1.4. Uranium ore contains all of these radioisotopes and they all have different properties. The radiation emitted by all of these needs to be included when considering the radiation exposures that may occur in uranium mining and processing. Uranium-235 and its decay products are also present in the ore, but its relative abundance is so low that they make only a very small contribution to the overall radiation levels.

Uranium is extracted from ore by physical and chemical processes. The processes aim to remove only the uranium isotopes, leaving all other radioisotopes in the waste (tailings). As some of these radioisotopes have very long half-lives (the ^{230}Th half-life is 77,000 years), the tailings will remain radioactive for hundreds of thousands of years, decreasing over time.
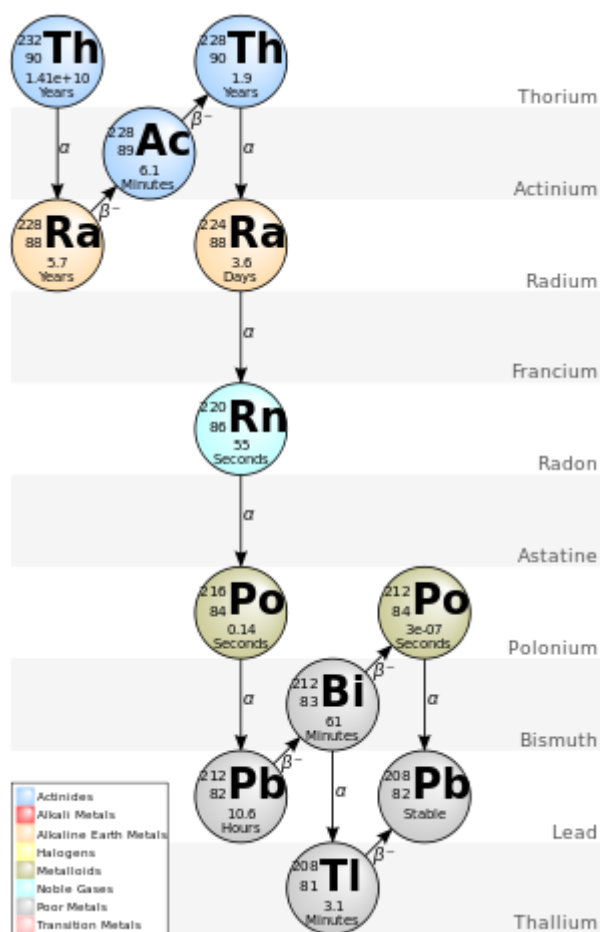
Figure 1.5. Decay series of thorium-232, with half-life of each radioisotope produced. Also indicated are classifications of each of the elements according to physicochemical properties.

1.3   Thorium

Thorium is a chemical element with symbol Th and atomic number 90. A thorium atom thus has 90 protons and 90 electrons. All its known isotopes are radioactive, with the six naturally occurring ones (thorium-227, -228, -230, -231, -232, and -234) having half-lives between 26 hours and 14 billion years. Thorium-232, which has 142 neutrons, is the isotope of thorium with the longest half-life and accounts for nearly all natural thorium, with the other five natural isotopes occurring only in traces: it decays very slowly through alpha decay to radium-228, starting a decay chain named the thorium series that ends at lead-208. Thorium is estimated to be about three to four times more abundant than uranium in the Earth's crust, and is chiefly recovered as a by-product of extracting rare earth metals.

It remains popular as a material in high-end optics and scientific instrumentation; thorium and uranium are the only radioactive elements with major commercial applications that do not rely on their radioactivity. Thorium is predicted to be able to replace uranium as nuclear fuel in nuclear reactors, but no thorium reactors have yet been completed.

The isotopes of the elements formed by the decay of ^{232}Th form a decay series, ending with the stable (non-radioactive) lead-208 (see Figure 1.5).

1.4   Ionising radiation

The type of radiation emitted by radioactive material, including uranium and its decay products, is called ionising radiation because it is able to ionise material through which it passes. That is: it will produce charged particles called ions as it passes through matter. Ionising radiation is distinguished from non-ionising radiation, which does not have sufficient energy to produce such ions. Examples of non-ionising radiation include microwaves, ultra-violet radiation, infra-red radiation, lasers and radio waves, including those from mobile phones. Non-ionising radiation is different from ionising radiation, arises from different sources, and any health effects it may produce arise from entirely different mechanisms. This section is concerned only with ionising radiation, and wherever the term radiation is used, it means ionising radiation.

Types of radiation
There are three major types of ionising radiation emitted by naturally occurring radioisotopes: alpha, beta and gamma radiation (see Figure 1.6).

Alpha
Alpha radiation consists of alpha particles, which consist of two protons and two neutrons bound together. Alpha particles are relatively heavy and slow moving. Their range in air is only a few centimetres and they are not able to penetrate matter to any significant extent. For example, they cannot penetrate a sheet of paper or, importantly, the outer layer of the skin. Inside their range they ionise very heavily, (i.e. they produce a dense trail of ionisation) when they pass through matter. To be a health hazard, alpha emitters need to be inside the human body to irradiate sensitive cells.

Beta
Beta radiation consists of electrons. They have moderate penetration, typically (for ^{238}U decay products) about one metre in air and a few millimetres in water or tissue. Because of their

relatively short range, most of the ionisation from external beta radiation occurs in the skin cells. However, irradiation of internal cells can occur if the beta emitters are within the body.

Gamma

Gamma radiation is not particles but electromagnetic waves similar to light and x-rays but of much higher energy. Gamma rays associated with uranium mining are generally able to penetrate up to several centimetres of metal or 10 cm of concrete, and can pass through the human body. Gamma radiation has a much lower ionizing ability when compared to that of an alpha particle.
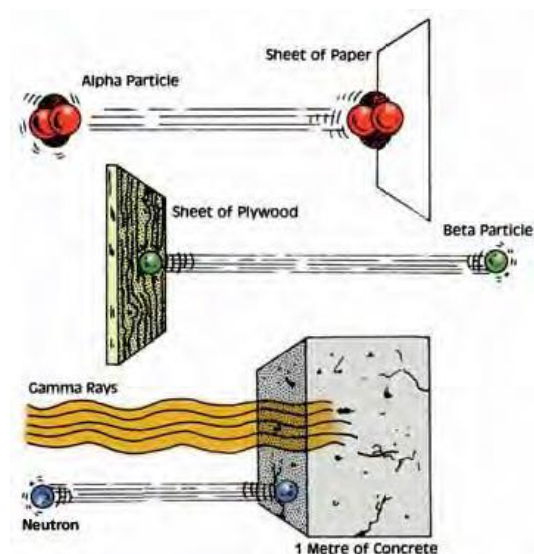
Figure 1.6. The penetrating power of alpha, beta and gamma radiation. Neutron radiation is also included here, although not relevant in the specific case.

Radiation exposure pathways

Radiation exposure can only occur when there is a pathway or exposure route between the radioactive material and the person exposed. There are two general types of exposure, external and internal.

External radiation

External exposure occurs when the source of radiation is outside the body. Examples include exposure received during a medical X-ray examination, or gamma radiation received by standing near radioactive ore. In uranium mining and processing, gamma radiation is the dominant form of external radiation. Because alpha radiation cannot penetrate the skin, it is not a source of external radiation.

Internal radiation

Internal exposure arises from radioactive material inside the body. The most common ways that radioactive material enters the body are by inhalation or ingestion (swallowing), with less common ways of entry through wounds and skin absorption. Once inside the body (e.g. the lung or the gut), the radioactive material may be absorbed into the bloodstream and transported around the body. Some radionuclides are quickly excreted, but others may be absorbed by various organs and retained for long periods, so that internal radiation exposure can continue

long after the initial intake. In contrast, external exposure ceases as soon as the source is removed.

Some of the pathways between the source and the person exposed may be complex. For example, radioactive dust may be deposited on grasses or plants that are then eaten by cows, the radionuclides may be excreted in milk, which may subsequently be consumed by people.

1.5 Radiation measurements and units

Two types of radiation quantities are used widely in radiation protection. One refers to the amount of "radioactive material" in a sample, or activity. The other refers to the amount of "radiation" received at a point and is measured as a dose rate (dose per unit time). They are quite different and there is no simple relationship between them.

Activity

Activity is the measure of the amount of radioactive material. Its unit is the *becquerel* (Bq), which is defined as the quantity of radioactive material that produces one radioactive decay per second. It may be applied to either a single radionuclide, or to a mixture. The activity concentration is the amount of radioactivity in a unit mass or volume of material and is measured in becquerels per gram or becquerels per litre respectively (Bq/g or Bq/L). As an example, the total activity of all ^{238}U series radionuclides in 1 g of peak grade Kvanefjeld ore is about 70 Bq, of which 5 Bq is from ^{238}U. In comparison, the activity concentration of ^{238}U in Danish soil is about 0.02 Bq/g.

Dose

Dose refers to the amount of radiation received at a point or to a person. The two main measures of radiation dose are called absorbed dose and effective dose. Absorbed dose refers to the physical amount of ionisation produced in matter by the radiation, as might be directly measured by an instrument such as a Geiger counter. The unit of absorbed dose is the *gray* (Gy). Absorbed dose may refer to the dose to an object, a person, or parts of a person (organs or tissues). Effective dose includes factors that take account of the biological effects of radiation on a person. These factors include the type of radiation (alpha, beta or gamma) and the different sensitivities of organs or tissues to radiation. The unit of "effective dose" is the sievert (Sv). For "whole body" gamma radiation the absorbed dose (in Gy) is often taken to be equal to the effective dose (in Sv). The sievert is quite a large unit of measure, and doses are usually expressed in millisieverts (mSv - thousandths of a sievert). The effective dose (mSv) gives a measure of the effect (or "detriment") of radiation on the human body. One mSv has the same detriment no matter if it is for example 1 mSv of gamma radiation to the whole body, or 1 mSv to the lung only, or any combination. The limits on dose (to people), that are most relevant in uranium mining are expressed in terms of effective dose, and where the term "dose" is used alone, "effective dose" is usually meant. Dose can refer to either internal or external exposure, or a combination of both. As an example, typical natural background radiation in Denmark results in an annual (effective) dose of about three millisieverts (3 mSv).

1.6 Natural background radiation

Radiation is very common in nature and everyone is exposed to natural radiation throughout their life (see Figure 1.7). This radiation essentially comes from the rocks and soil of the earth,

the air we breathe, water and food we consume, and from space. Exposure to this radiation is from both external and internal sources.

External radiation pathways

The two main sources of external background radiation are cosmic rays and gamma radiation from soil.

Cosmic radiation is a form of ionising radiation that comes from outer space. The atmosphere provides shielding against cosmic rays, and consequently cosmic ray exposure is higher at higher altitudes. Aircrew who regularly fly at high altitudes can receive significant radiation doses from cosmic radiation. Almost all normal soils naturally contain uranium, thorium and potassium. The average uranium and thorium soil concentrations are approximately 3 ppm and 10 ppm respectively. Both of these have gamma-emitting radionuclides in their decay series, and so contribute to external radiation levels. In addition, one of the isotopes of potassium, K-40, is radioactive, emitting both gamma and beta radiation, and this also contributes to the external dose rate. In several parts of the world, soils naturally contain much higher concentrations of radionuclides. This is particularly so of thorium, and some parts of Brazil and southern India have quite high natural external dose rates for this reason (UNSCEAR 2000).
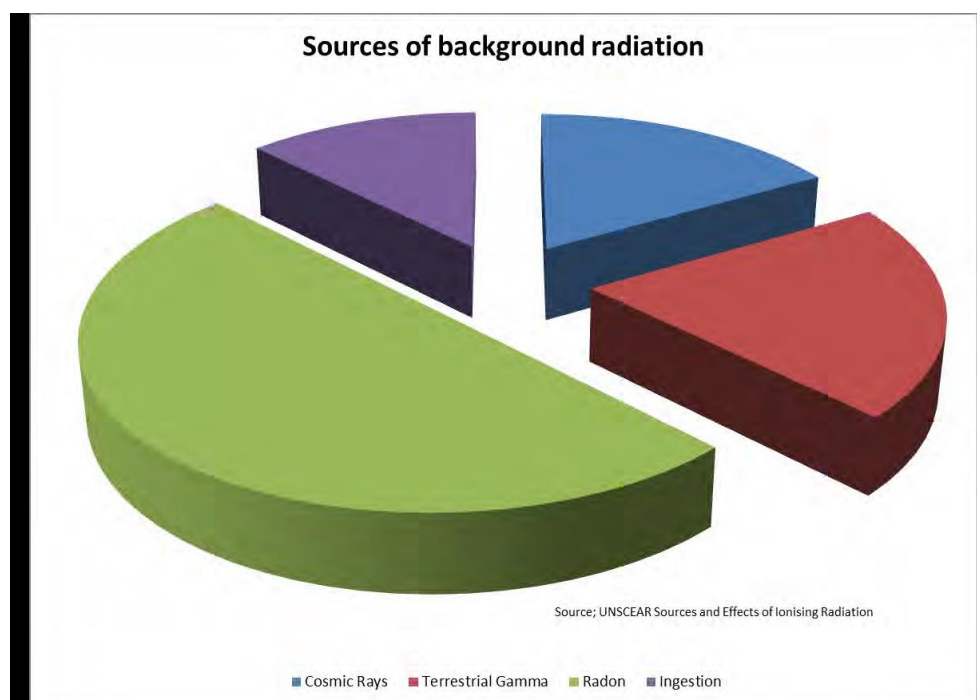
Figure 1.7. Sources of natural background radiation. Cosmic: ca. 17 %; Terrestrial gamma: ca. 20 %; Radon: ca. 51 %; Ingestion: ca. 12 %.

Internal radiation pathways

Naturally occurring radionuclides can enter the human body through inhalation and ingestion. The largest internal natural background dose generally comes from the inhalation of radon decay products. Radon is a member of the uranium decay series, being formed directly from the decay of radium in the soil. Being a noble gas (thus not attaching to surfaces), the radon can

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diffuse from the soil and enter the atmosphere, but normal atmospheric mixing keeps concentrations quite low. However if radon diffuses into an enclosed space, such as a house, from the soil below it, it may be trapped and build up to high levels. This is particularly so if there are cracks in floors or foundations, allowing easy access for the radon, and where houses are tightly sealed against the cold, thus retaining the radon.

The dose from inhaling radon itself is quite small, but radon decays to radon decay products (formerly called radon daughters) and if these are inhaled they may lodge in the lung, resulting in quite significant doses. Some houses in North America and Northern Europe have been found with radon decay product concentrations that are higher than would be permitted in modern uranium mines (ICRP, 2010). The other main pathway is ingestion, or swallowing of radioactive material that is present in food or drink. Plants will take up some radionuclides from the soil in which they grow. These radionuclides may then enter our food chain either directly, by eating the plants, or indirectly, by eating animals that have grazed on them. Similarly almost all surface and ground waters contain natural radionuclides derived from the surrounding soil. Consuming such food or water will result in an internal radiation dose. The largest contribution to internal dose from ingestion is usually from potassium-40 (^{40}K). Potassium is an essential element in the body, and the body will extract its requirements from food. As the body cannot distinguish between the radioactive potassium (^{40}K) and non-radioactive potassium isotopes, the body will always contain some ^{40}K. Other natural radionuclides, including uranium and thorium decay series isotopes will also be consumed with food and water and hence will be present in the body, and irradiate it. The world average natural background dose from all sources is about 2.4 mSv per year (UNSCEAR 2000). The average contribution of the different components is shown in the above Figure 1.7. As noted above, natural background can vary considerably in different places in the world. While the world average is 2.4mSv/y, the typical range is quoted as 1-10mSv/y. In any large population, about 65% would be expected to have annual doses of between 1 and 3 mSv. About 25% of the population would be expected to have annual doses of less than 1 mSv, and about 10% would be expected to have annual doses greater than 3 mSv. (IAEA, 2014)

Medical radiation
Another major source of radiation exposure to the general public is medical exposure. Radiation is used extensively for diagnosis and treatment of disease. The average annual radiation dose from diagnostic medical procedures in developed countries has been estimated to approximately 1.2 mSv/y (UNSCEAR 2000), although higher figures are stated by NCRP (2009).

1.7   Health effects of radiation

The health effects of radiation exposure (both internal and external) are well known. At high doses (several sieverts) significant numbers of cells in sensitive organs or tissues may be killed, leading to the breakdown of the organ or tissue, and possibly resulting in death. Other high dose effects include a reduction in the immune system and temporary sterility (in males). The doses required for these effects are similar to those received by fire fighters who attended the Chernobyl incident. Doses received during uranium mining and milling cannot approach these levels (and are generally more than 100 times less) so these high dose effects will not occur.

At lower doses health effects may arise from cells that are damaged by the radiation but not killed. There are cellular mechanisms that are capable of repairing this damage and there are other mechanisms that eliminate such damaged cells, but it is possible that damaged cells may develop the ability to proliferate without being subject to the normal controls on cell reproduction. This may be the initiating event for development of a cancer. Development of cancer is a multi-stage process, and some of the stages may take years to complete, so a cancer would not be expected to appear for some years after initiation. An individual cell that is damaged in this way has an extremely small chance that it may pass through all the different stages, and eventually develop into a cancer. Increasing the exposure and thus increasing the number of damaged cells leads to an increase in the risk of developing a cancer.

Alternatively, the damaged cells may be part of the reproductive line (egg cells, sperm or sperm generating cells. Again repair mechanisms exist and the damaged cells may not survive, however if they do, there is the chance that such damage may be carried over to the next generation and appear as hereditary disorders in the offspring.

A number of studies have found an increased risk of cancer among people exposed to moderate doses of radiation. The best known are the studies of the Japanese atomic bomb survivors, who have now been followed for 50 years. These studies have been able to determine the effects of a large range of doses on a large population over a long period (Preston, 2007). Other studies have included an international study of radiation workers who were generally exposed to low levels of radiation over a long period (Cardis et al., 2005).

The studies of miners exposed to radon decay products are of particular relevance to uranium mining. Early mines were often poorly ventilated, and as a result miners were often exposed to very high levels of radon decay products. Several groups have been studied, including both uranium and non-uranium miners (ICRP, 2010).

Both groups of studies show that there is a risk of increased cancer among those exposed to elevated levels of radiation, and that this risk increases as the radiation dose increases. The overall increase is approximately linear, that is doubling the dose doubles the risk (Brenner et al., 2003).

In general no studies have been able to measure increases in cancer risk from exposures to low doses of radiation (below about 50mSv). In this range, which includes the annual doses expected to be received by workers at Kvanefjeld, any increase in cancer risk has been too low to be detectable. However, it is still assumed that there is an increased risk, and the risk factors derived at higher doses are assumed to apply in this range.

There have also been studies looking for an increased rate of hereditary disorders in the offspring of parents exposed to radiation. No increased risk of hereditary disorders has been found in human studies, including those of the Japanese atomic bomb survivors. However increases have been found in animal studies (UNSCEAR 2000), and it is assumed that there are risks to humans of a similar magnitude to those found in animals. These risks are less than 5% of the cancer risk. The risks derived from these studies are used in the setting of radiation standards for exposure of workers and the general public.

In standard setting, the ICRP states 'it must be presumed that even small radiation doses may produce some deleterious effects' (ICRP, 1990). This is not to be confused with the often stated 'there is no safe level of radiation', which equates 'safety' with 'no risk at all'. This is not the normal use of the word 'safe'. For example, people recognise that there is some risk involved in

commercial air travel, but still regard it as 'safe', because they consider that the level of risk is so low that it is acceptable. Similarly for exposure to radiation: it can be considered 'safe' if the resulting doses are low enough to be considered acceptable.

Generally, worker doses can be minimised by considering time spent near sources, distance to sources, shielding against radiation from the sources and protective outfit (e.g., respiratory protection).

1.8   Radiation standards and limits

Sources of standards

The premier international body for radiation protection is the ICRP. The limits recommended by the ICRP have generally been adopted around the world. The recommended dose limits have changed over time as more information on the health effects of radiation has become available. However there has only been one major change to the recommended limits to workers in the past 50 years, in 1990 (ICRP, 1990).

The ICRP's most recent recommendations on standards and dose limits were published in 2008 (ICRP, 2008). These recommendations update the previous recommendations published in 1990 (ICRP, 1990), and maintain the three key elements of the "system of dose limitation" (see below) and the basic numerical dose limits.

ICRP recommendations

The ICRP recommends a "system of dose limitation" of which dose limits are only one part. The three key elements of this system are (ICRP, 1990; ICRP, 2008):

Justification – a practice involving exposure to radiation should only be adopted if the benefits of the practice outweigh the risks associated with the radiation exposure.

Optimisation – radiation doses received should be As Low As Reasonably Achievable, economic and social factors being taken into account (the ALARA principle).

Limitation – individuals should not receive radiation doses greater than the recommended limits.

Justification is a necessary prerequisite for any decision regarding radiation exposure. Actions that alter the radiation exposure situation should do more good than harm. This means that by introducing a new radiation source, or a new practice involving radiation, one should achieve an overall societal or individual benefit that is higher than the detriment that the radiation exposure may cause. The benefits and detriments should be considered broadly, and often the radiation detriment will only be a small part of the total.

The ICRP sees the ALARA principle as a central element in radiation protection and, in the hierarchy of radiation protection measures it ranks ahead of the application of 'dose limits'. The principle requires that every practice involving radiation exposure should be examined, along with the potential protection measures. Protection measures that produce a net benefit (i.e. the benefit from reducing the exposure is greater than the cost of implementing that measure) should be implemented. This procedure should be continued until the costs of further reduction measures outweigh the potential benefits of the reduced exposure and at that stage, radiation protection can be considered to be optimised. The procedure should be implemented at the design stage, and carried on into operation of the practice.

Optimisation may include the use of "dose constraints", which are upper limits on the predicted doses used in the optimisation process. These are predetermined levels of dose for particular situations, generally imposed by regulatory authorities, above which it is unlikely that radiation protection is optimised. In the case of members of the public, dose constraints recognise the possibility that individuals may be exposed to radiation originating from more than one operation. In the case of uranium mines in remote locations this is unlikely to be the case. Dose constraints are not of themselves universal prescriptive regulatory limits.

The ALARA principle applies at all levels of exposure: if there are practical, cost-effective measures that can be applied to reduce radiation exposure, then they should be applied even if exposures are already well below the recommended dose limits. Indeed, the ICRP believes that proper application of this principle will generally result in doses that are well below the individual limits, and so those limits will only rarely need to be applied.

The limits recommended by the ICRP, which are of most relevance in the mining and mineral processing industries, are limits to the effective dose. These limits are also adopted by the IAEA (2014):

Annual limit to a worker 20mSv
Annual limit to a member of the public 1mSv

The doses received may be averaged over five years, but the dose to a worker in any one year must not exceed 50 mSv. Annual doses to members of the public should only be allowed to exceed 1 mSv in "special circumstances". There are other subsidiary limits (for doses to the lens of the eye, skin and hands or feet), but in uranium mining and processing these could only be exceeded in very unusual circumstances, which would almost certainly involve effective doses exceeding the main limits.

Further, it should be noted that a reference level for ^{222}Rn is set at a value that does not exceed an annual average activity air concentration of ^{222}Rn of 1000 Bq/m^3 (ICRP, 2010), with account taken of the prevailing social and economic circumstances. Employers shall ensure that the activity concentrations of ^{222}Rn in workplaces are as low as reasonably achievable below the reference level, and that protection is in general optimised. If, despite all reasonable efforts by the employer to reduce radon levels, the activity concentration of ^{222}Rn in the workplace remains above the reference level, the relevant requirements for occupational exposure in planned exposure situations shall apply.

Additional restrictions apply to occupational exposure for female workers who have notified pregnancy or are breast-feeding. Separate rules also apply to apprentices under the age of 18 years (IAEA, 2014).

The annual limits apply to the total dose received from operational sources including external gamma exposure and inhalation of radon decay products and dusts (with the doses from normal natural background being excluded). There are no exposure limits for the individual dose components. Likewise there are also no specific dose limits set for shorter periods (less than a year). This is because the likely health effects depend only on the total dose accumulated over a long period (possibly decades). In an operational situation, investigation and action levels are set for each pathway at levels that ensure continued exposure will not lead to doses above these long term limits, or other goals.

1.9   Radiological protection of the environment

Historically, the risk assessment and management of radionuclides entering or present in the environment has been based principally on human health considerations. The ICRP has stated that the standards of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species. Recently there has been increasing awareness of the vulnerability of the environment and of the need to be able to demonstrate that it is protected against the effects of industrial pollutants, including radionuclides. The ICRP, in its 2007 Recommendations (ICRP 2008) has given more emphasis to the protection of the environment. More detailed advice is given in ICRP Publication 91, 'A framework for assessing the impact of ionising radiation on non-human species' (ICRP, 2003) which reviews the various methods that have been developed for the assessment of radiological impacts with the objective of identifying and suggesting the best framework. It recommends making an initial assessment using primary (generic) reference organisms for flora and fauna to give an order of magnitude assessment of the probability and severity of likely effects of radiation exposure on the population. Organisms or situations that are not identified as being at negligible risk can then be subjected to a more detailed assessment, if necessary using situation or organism specific data. This approach has been adopted by the European Union as part of their ERICA project (Brown et al., 2008). Also UNSCEAR (2008) deals with these issues.

1.10 Legislation and regulatory requirements

The radiological aspects of the considered mining project at Kvanefjeld, Greenland are in lack of relevant national Greenlandic legislation.   However, regulatory aspects of the mining project will most probably be based on international recommendations of the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection ICRP). A number of documents are of particular interest in this context, including the following:

The document IAEA (2010) describes best practice in environmental management of uranium mining. This document describes principles of operation of social, environmental and economic nature. Best practice as described includes the active search, documentation and implementation of those practices that are most effective in improving the social, environmental and economic performance of an operation. The principles of best practice are universal, whereas their application is case specific.

The document IAEA (2014) sets the basic safety standards recommended by the IAEA. The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. The process of developing, reviewing and establishing the IAEA standards involves the IAEA Secretariat and all Member States, many of which are represented on the four IAEA safety standards committees and the IAEA Commission on Safety Standards.

The document IAEA (2004) gives the more specific recommendations on occupational radiation protection in the mining and processing of raw materials. The specific principles of dose limitation are stated, along with recommendations on radiation protection programmes including monitoring and dose assessment. The document also contains a section on engineering and

administrative protection measures, including ventilation, dust control, clean-up of spills, personal protective equipment, etc.

The document IAEA (2009) provides stakeholders with practical information and historical examples of experience gained from the introduction of uranium mining and processing operations in specific areas and the subsequent effects of mine closure. In addition, recommendations are offered to the primary stakeholders; namely government agencies, mining and processing companies, local communities, and environmental protection groups.

The document IAEA (2002) gives specific recommendations in relation to monitoring and surveillance of the residues from the mining and milling of uranium and thorium.

The document IAEA (2002a) gives specific recommendations in relation to management of radioactive waste from the mining and milling of ores.

The document OECD-NEA (2014) gives additional recommendations for managing environmental and health impacts of uranium mining.

As mentioned in the document IAEA (2010), a number of principles should be applied in assisting the development of such mining facilities:

- Sustainable development principles
- The ALARA principle
- Precautionary principle

Sustainable development can be defined through 4 points:
- Material and other needs for a better quality of life have to be fulfilled for people of this generation
- The process should be as equitable as possible
- Ecosystem limits should be respected
- A basis should be built on which future generations can meet their own needs

Sustainable development in the present context balances four main aspects: environment, social issues, economics and governance. Concentration on only one of these aspects will inevitably lead to conflict in relation to the others.

According to IAEA (2010), ten important principles for Sustainable Development Performance are:
- Implement and maintain ethical business practices and sound systems of corporate governance;
- Integrate sustainable development considerations within the corporate decision making process;
- Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others who are affected by our activities;
- Implement risk management strategies based on valid data and sound science;
- Seek continual improvement of our health and safety performance;
- Seek continual improvement of our environmental performance;
- Contribute to conservation of biodiversity and integrated approaches to land use planning;
- Facilitate and encourage responsible product design, use, reuse, recycling and disposal;
- Contribute to the social, economic and institutional development of the communities in which we operate;

- Implement effective and transparent engagement, communication and independently verified reporting arrangements with our stakeholders.

The ALARA principle is described above in section 1.8. In relation to the precautionary principle, the concept is that effective environmental management must anticipate, prevent and correct the causes of environmental degradation.

1.11 Radiation doses in uranium mines

The radiation doses that are received by workers in connection with uranium mining arise through three different pathways: external exposure (primarily from gamma radiation), inhalation of radon progeny, and inhalation and possible inadvertent digestion of mining dust. In connection with a number of other uranium mining projects both the total dose and the breakdown on different pathways has been assessed. The data is shown in Table 1.1 (Energy Resources of Australia, 2006; Rössing Uranium, 2014; Health Canada, 2007; AREVA Resources Canada, 2007, Mineral Council of Australia, 2014, Kutty et al., 2010, BHP Billiton, 2009, CNSC, 2009).

Table 1.1. Comparison of annual avg. radiation doses to mine workers at various uranium operations (mSv).

Mine and worker type	Ore grade (%U_3O_8)	Total dose		Gamma		Radon		Dust	
		Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
Ranger mine worker	0.29	1.0	4.8	0.5	4.3	0.1	0.4	0.3	0.9
Rössing pit equipment operator	0.035	2.1	NA	0.6	NA	1.2	NA	0.4	NA
Rössing pit field staff	0.035	2.5	NA	1.0	NA	1.1	NA	0.4	NA
McLean Lake open pit workers	1.6	<1	NA	NA	NA	NA	NA	NA	NA
Canadian surface miners 2004	Various	1.1	<5	NA	NA	0.3	NA	NA	NA
Nabarlek open pit worker	2	6.6	NA	2.3	10	0.3	NA	4	NA
Olympic Dam	0.07	1.7	NA	NA	NA	NA	NA	NA	NA
Beverley mine	0.18	<1	<8	NA	NA	NA	NA	NA	NA
McArthur underground mine	16	1.2	NA	0.3	NA	0.6	NA	0.2	NA
Key Lake open pit mine	2.3	0.8	NA	0.4	NA	0.2	NA	0.2	NA
Cigar Lake underground mine	20	0.16	NA	0.03	NA	0.09	NA	0.04	NA
Rabbit Lake underground/open	0.22	2.0	NA	0.7	NA	0.8	NA	0.5	NA

'NA' = not available

Figure 1.8 shows the average and maximum effective dose trends for all Australian uranium mine workers over the period 2004-2013 (Mineral Council of Australia, 2014). Fig. 1.9 shows the average uranium mine worker, processor, etc. dose trend by work category (2004-2013). ANRDR stands for the Australian National Radiation Dose Register. Fig. 1.10 shows the annual

dose distribution for all Australian uranium mine workers (data from 2003; Mineral Council of Australia, 2014).
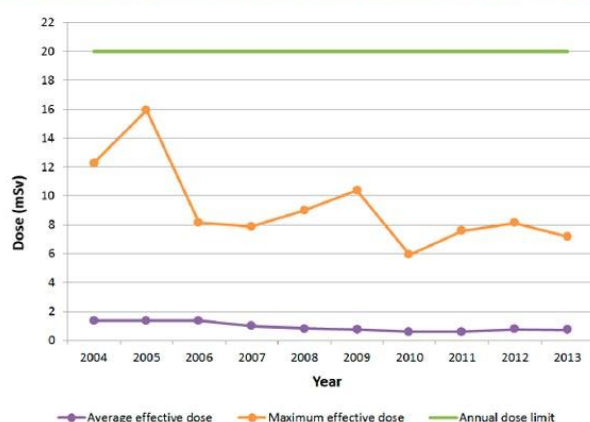
Figure 1.8. Average and maximum effective dose trends for all Australian uranium mine workers over the period 2004-2013.

Figure 1.9. Average effective dose trend by work category (2004-2013) for workers in the Australian mining business.

	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5	5-5.5	5.5-6	6-6.5	6.5-7	7-7.5	7.5-8
No. of workers	6073	1161	481	266	164	194	220	229	125	71	59	25	13	6	1	0
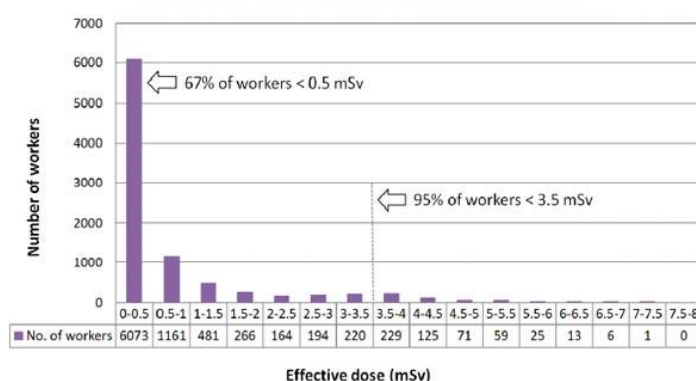
Figure 1.10. Annual dose distribution for all Australian uranium mine workers in 2013.

Predicted Radiation Exposure from Mining at Kvanefjeld

It should be noted that maximum and average doses decrease, presumably due to improved radiation protection (Fig. 1.8). In Fig. 1.9 the sudden increase in mining average is likely due to the addition of a new operator. Fig. 1.10 shows that very few persons receive higher doses (e.g., some mill maintenance workers).

1.12 Human health impact of likely worker dose levels in mining and processing

Judging from the measured data in Table 1.1 for worker doses from ongoing mining projects in different parts of the world, there seems to be a broad agreement. The Nabarlek open pit seems to give a somewhat higher dose than the rest, which coincides with a comparatively exceptionally high ore grade. It should also be noted that that particular ore body was completely mined out in one short campaign of about 4½ months. This mining campaign was carried out some 30 years ago. According to recent investigations (GMEL, 2014), the Kvanefjeld mine should contain U_3O_8 with a peak grade of 400 ppm, and with a thorium peak grade of 750 ppm Th. The Kvanefjeld peak ore grade thus ties in with the lower ore grades for the existing uranium mines referred to in Table 1.1. On this background, there would not be *expected* to be unusually high doses to workers at the Kvanefjeld, and since even the highest reported doses in Table 1.1 are well below the IAEA/ICRP limit for worker exposure of 20 mSv/y, it would on this background be expected that the doses to Kvanefjeld mining project workers would be well below the threshold value. According to the ICRP (2008), the risk to a 'typical' individual of an eventual fatal cancer is 0.00005 per mSv, so with an expected annual dose of a few mSv, the individual worker risk will be low. Equally, it would on the basis of Table 1.1 preliminarily be expected that the annual increase in doses to the public would be well below 1 mSv, as only the dust related dose component (rather than those related to gamma and radon) from the mining could possibly be of relevance in that context, and the distance to the nearest human population is some 8 km. However this is being analysed separately. Transportation of radionuclides in ground and surface water might possibly constitute an additional pathway of dose to the local population, meriting further examination.

1.13 Nuclear safeguards and security

International safeguards and security systems have been developed by the IAEA, and Greenland currently lacks specific rules and requirements in this area. The IAEA standards, which are adopted by most nations, would apply to the Kvanefjeld case.

Nuclear security deals with prevention against theft and diversion of nuclear materials and sabotage against nuclear materials or installations.

It is based on provisions of physical protection of nuclear materials and facilities complemented by:

- Provisions for accounting for and control to prevent and, where appropriate, detect loss, theft or diversion of nuclear materials;
- The nuclear safety provisions to protect nuclear materials and facilities against sabotage.

Safeguards are an extensive set of technical measures by which the IAEA Secretariat independently verifies the correctness and the completeness of the declarations made by States about their nuclear material and activities.

The aim of IAEA controls is to verify afterwards the respect for the declared use of materials or political commitments undertaken by States under the non-proliferation purpose.

An international *accounting system* is used to trace the movement of uranium from production to fuel fabrication and its introduction into the nuclear power reactor. The tracking continues when spent fuel is removed from the reactor and is reprocessed into more fuel, or stored and disposed of as waste. The tracking also covers plutonium produced from the uranium in the reactor. Essentially, this establishes a pool of uranium earmarked for power generation, and material can only be removed from this pool for use in civilian power reactors.

The requirements for *physical security* set minimum standards for ensuring that nuclear materials (including uranium) are protected from theft or hijacking. These include stringent measures to ensure security during transport, as well as how it is stored or processed in facilities.

Verification that the safeguards requirements are being properly implemented and complied with is obtained in several ways. These include auditing records of production transfer and use to ensure that there are no discrepancies, and physical inspection and accounting for nuclear material in facilities. Inspections can include physical inspection, measurements on for example amounts of material in storage, or the use of tamper proof cameras and the like to monitor operations in facilities.

1.14 References

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2 Review of Radiation Baseline Information

Greenland Minerals and Energy Limited (GMEL) holds an exploration lease over the Kvanefjeld plateau located in the south-western part of Greenland. GMEL have conducted exploration activities at the Kvanefjeld Project since 2007 to the present. During this time radiation monitoring activities have been conducted annually as an occupational safety requirement and for establishing an environmental baseline. Monitoring activities have included external dose-rate monitoring, passive radon and thoron monitoring, real time radon and thoron gas monitoring, radon daughter monitoring and dust monitoring. ^{210}Po has been analysed in a number of biological samples and a small number of water samples have been analysed for ^{226}Ra, ^{228}Ra and ^{210}Pb. The extent of monitoring and the parameters monitored has varied from year to year.

The locations investigated have been the Kvanefjeld Project area on the Kvanefjeld plateau, Narsaq town and the 'Critical group location' (also called the 'Representative Persons location') which is a farm situated roughly halfway between Narsaq and the Kvanefjeld Project area. Also the area between Narsaq and the Kvanefjeld Project area was included in the 2013 monitoring, as was the Narsaq river delta, the proposed plant area and the proposed accommodation area.

The methodology has included TLD and scintillation detectors for external dose-rate monitoring, CR-39 film with and without a thoron proof filter to enable combined radon + thoron gas and radon gas only measurements (two monitors at each station), electrostatic sampling combined with solid state alpha spectrometry for continuous radon and thoron gas monitoring, an Environmental Radon Daughter Monitor (ERDM) to specifically measure radon daughter progeny. The ERDM instrument was not further specified in the available material.

The monitoring has usually been conducted during the summer months each year but due to the strong seasonal changes winter monitoring of external dose-rate and radon using the passive detectors (TLD's and CR-39 film) were done in winter 2008/2009. To gain further understanding of the radon and thoron exposure over the winter months 36 monitors (CR-39) were located at 12 stations in the winter 2013-2014.

Radiation monitoring reports covering the monitoring between 2007-2013 have been issued for 2008-2011, 2012 and 2013 respectively (Breheny 2012a, 2012b, 2014).

2.1 External dose rate

Between 2008 and 2011 focus was on surveying the Kvanefjeld project area, Narsaq town and the Critical group location (WP 49), a farm situated approximately half-way between Narsaq and Kvanefjeld. Monitoring was done using TLD's which were exposed during summer months and during one winter (2008/2009). However, no travelling blank TLD's were employed to correct for exposure during transit between laboratory and measurement location. Apart from the TLD monitoring, measurements of external gamma background were also performed in Narsaq using a scintillation detector. In 2012 external radiation background recordings were obtained through TLD's worn by 8 workers in Narsaq only. In 2013 environmental gamma monitoring was entirely done using the scintillation detector (5 minutes counting per location). The survey covered the 25 locations in Narsaq from previous years and 89 locations (waypoints) between Narsaq and the Kvanefjeld project area.

Table 2.1. Summary of the number of measurements at each location for each year in connection with monitoring done on external dose-rate using TLD and scintillation detector based instruments. Deployment time (TLD) or integration time (scintillation detector) is shown in parenthesis.

Year	Narsaq (TLD)	Narsaq (Scintillation detector)	Critical group loc. (TLD)	Critical group loc. (Scintillation detector)	Kvanefjeld Project area (TLD)	Kvanefjeld Project area (Scintillation detector)
2008	4(117 d)	N/A	1(117 d)	N/A	25 (117 d)	N/A
2008/2009	1(275 d)	N/A	1(275 d)	N/A	8 (275 d)	N/A
2009	3(56d)	25 (3min)	2(47&54d)	N/A	30 (50-54d)	N/A
2010	N/A	25 (5min)	1(56 d)	N/A	11 (N/A) (*)	N/A
2011	3 (427) (A)	25 (5min)	1(427 d) (A)	N/A	16 (N/A) (*)	N/A
2012	N/A	N/A	N/A	N/A	N/A	N/A
2013	N/A	25 (5min)	N/A		N/A	10 (5min)

*) In 2010 and 2011 TLD's were not deployed in the Kvanefjeld project area but in the accommodation huts in the Kvanefjeld camp. The deployment period was not given.

A) TLD monitor placed at the Critical group location in 2011 remained over winter to 2012, a total of 427 days. Similarly TLD's were left in three houses in Narsaq over winter 2011/2012 during 427 days.

Table 2.2. Results (average and standard deviation of data, µGy/h) obtained at each location during monitoring of external dose rates 2008-2013.

Year	Narsaq (TLD)	Narsaq (Scintillation detector)	Critical group loc. (TLD)	Critical group loc. (Scintillation detector)	Kvanefjeld Project area (TLD)	Kvanefjeld Project area (Scintillation detector)
	(µGy/h)	(µGy/h)	(µGy/h)	(µGy/h)	(µGy/h)	(µGy/h)
2008	0.16 ± 0.04	N/A	0.3 [*]	N/A	1.3 ± 0.73	N/A
2008/2009	0.1 [*]	N/A	0.2 [*]	N/A	0.54 ± 0.38	N/A
2009	0.09 ± 0.02	0.15 ± 0.06	0.19 & 0.26	N/A	1.46 ± 1.36	N/A
2010	N/A	0.24 ± 0.05	0.46 [*]	N/A	0.6 ± 0.09	N/A
2011	0.16 ± 0.004 [(A)]	0.45 ± 0.09	0.27 [*(A)]	N/A	0.4 ± 0.2	N/A
2012	N/A	N/A	N/A	N/A	N/A	N/A
2013	N/A	0.43 ± 0.08	N/A	0.55 ± 0.07	N/A	N/A

*) Only one monitor used.

A) Used during winter 2011/2012, a total of 427 days.

Predicted Radiation Exposure from Mining at Kvanefjeld

Other areas surveyed were the Narsaq river delta (2 locations), the Accommodation site (2 locations), proposed Production Plant site (7 locations), Tailings site (4 locations), along the pipe to the Tailings site (5 locations), Effluent line (2 locations) and 4 locations on the Project area. Gamma measurements were also recorded at 7 locations where passive radon monitors were deployed. Further 10 locations on the Kvanefjeld plateau across the Project area established in 2008 were repeated.
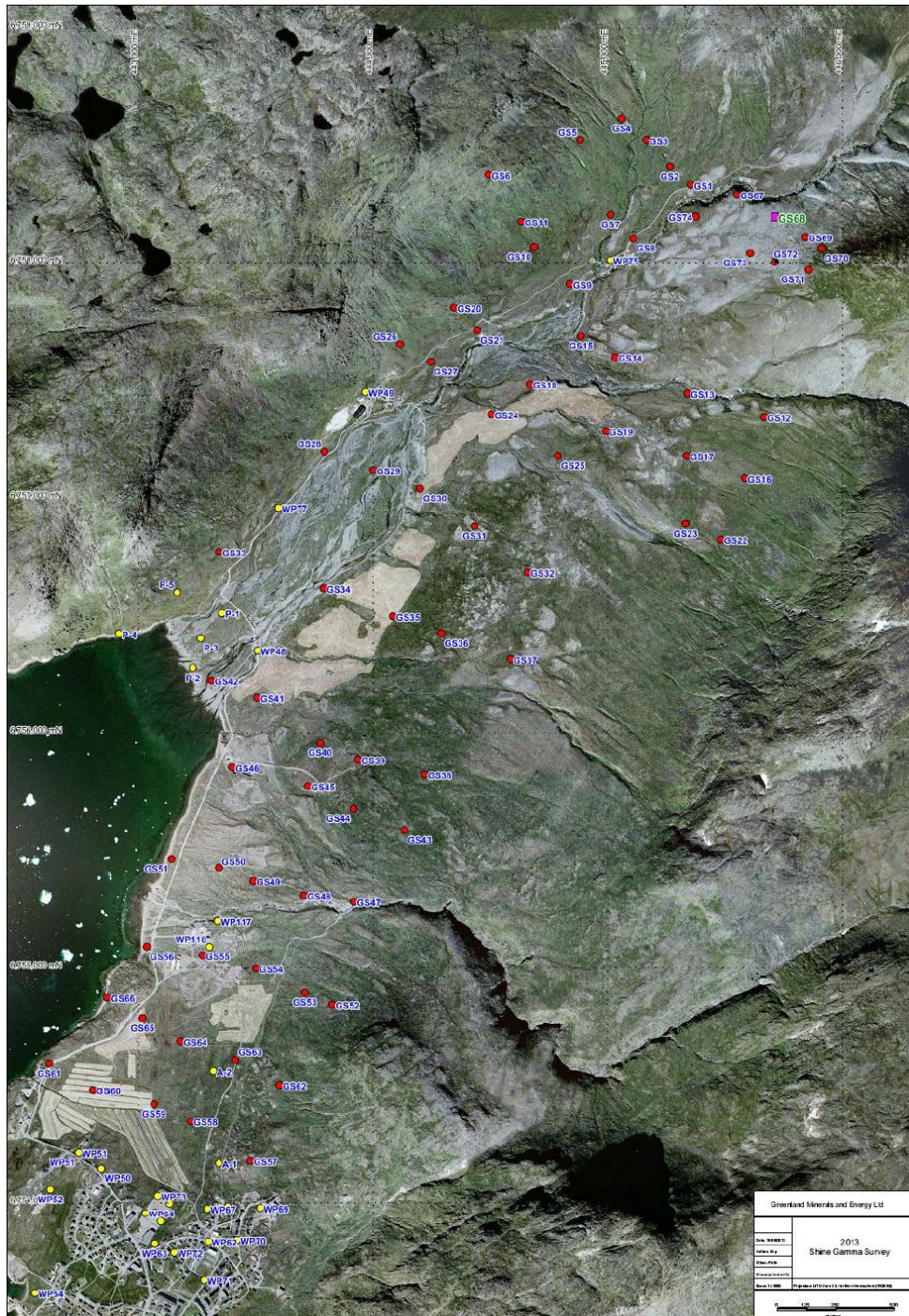
Figure 2.11. Overview of Narsaq town, the proposed accommodation area and the Narsaq river delta.

In 2013 environmental gamma monitoring was entirely done using the scintillation detector (5 minutes counting per location). The survey covered the 25 locations in Narsaq from previous years and 89 locations (waypoints) between Narsaq and the Kvanefjeld project area. Other areas surveyed were the port (5 locations), the Accommodation site (2 locations, 0.40 ± 0.04 µGy/h), proposed Production Plant site (7 locations), Tailings site (2 locations), along the pipe to the Tailings site (3 locations), Effluent line (2 locations) and 4 locations on the Project area. Gamma measurements were also recorded at 7 locations where passive radon monitors were deployed. Further 10 locations on the Kvanefjeld plateau across the Project area established in 2008 were repeated.

Table 2.3: Summary of dose-rate data obtained at various locations using the scintillation based hand instrument during a survey in 2013

Location	(µGy/h)	No of measurement locations
Area between Narsaq and Kvanefjeld plateau	1.04 ± 0.78	89
Proposed accommodation area	0.40 ± 0.04	2
Narsaq river delta	0.87 ± 0.41	5
Production plant site	0.39 ± 0.06	7
Tailings area	1.24 ± 0.007	2
Proposed tailings pipeline route	1.55 ± 0.36	3
Proposed effluent line	0.31 ± 0.02	2

Bøtter-Jensen et.al. (1978) give data on external exposure rates measured at Kvanefjeld using LiF TLD's, high-pressurized ionization chambers and energy-compensated plastic scintillators. TLD's were sandwiched between 1mm aluminium sheets to obtain electron equilibrium and placed in the field for 3 months. Corrections for the transit dose to the TLD's due to transport Greenland-Denmark were determined on separate TLD's. This may be an important contribution to the TLD dose in case of low received doses in the field since dose rates at flight altitudes are typically 10-50 times higher than on ground but recordings on a TLD will depend on its construction material (sensitivity to neutrons). The total dose (external gamma + cosmic contribution) measured using the TLD's are shown in Table 2.4.

Table 2.4: TLD based dose rates at various locations in the Kvanefjeld area as determined in 1977.

Area-1	Area-2	Area-3	Area-4	Narsaq
Medium active, coarse-grained luvjavrite, (n=9)	Low-active gabbro (n=9)	Medium-active, homogeneous luvjavrite(n=9)	High-active, heterogeneous luvjavrite(n=9)	(n=5)
(µGy/h)	(µGy/h)	(µGy/h)	(µGy/h)	(µGy/h)
2.2±0.5	0.22±0.02	2.2±0.3	5.0±0.7	0.085±0.01

Dose rates for Narsaq are comparable to results obtained using TLD by GMEL but results obtained using scintillator based instruments show higher values. This has been pointed out in a memorandum (Stager, 2014). The dose rates derived from measurements using the pancake scintillator-based detector are 3-4 times higher than corresponding TLD doses in Narsaq which are in the same range as those measured by Bøtter-Jensen. It is thus recommended to primarily

rely on dose rates based on TLD's for the environmental exposure but the TLD measurements should be accompanied by a transparent QA/QC protocol including duplicate units and travel blanks to correct for contributions obtained between measurement location and read-out laboratory. It should be noted however, that the data indicate that corrections for exposure of travelling blank TLD's are low since there is reasonable agreement between the low gamma dose rates measured in Nasaq town by GMEL and Bøtter-Jensen.

2.2 Radon monitoring

In 2008 passive radon monitors (CR-39 film) were used to determine levels of radon in air during summer time. The CR-39 film monitor is integrated in the same dosimeter/device as the TLD used to record background gamma exposure. Locations for recording of integrated radon concentrations and external gamma exposure were thus the same (Kvanefjeld project area, Narsaq and the Critical group location). Exposure time during the summer months was 117 days and during winter 275 days. At the Kvanefjeld project area and at the Critical group location measurements of ^{222}Rn were also done over a 15h period using a Durridge RAD-7 instrument, utilizing electrostatic collection of short-lived radon daughters followed by alpha spectrometry using a PIPS detector. In 2009 the same type of passive monitors (CR-39 film) as during 2008 were used at approximately the same locations. In 2010 and 2011 both radon and thoron was measured in the Kvanefjeld camp (CR-39 with and without thoron filter). The RAD-7 instrument was used to monitor both radon and thoron gas short time fluctuations in the camp, for radon the maximum concentrations occurred in the late morning, following a diurnal trend. In 2012 Environmental radon and thoron gas monitoring was carried out mainly around Narsaq. Limited radon gas monitoring was undertaken on the Kvanefjeld plateau.

Table 2.5. Summary of the number of radon measurements.

Year	Narsaq (CR-39)	Narsaq (Durridge RAD-7)[B]	Critical group loc. (CR-39)	Critical group loc. (Durridge RAD-7)[B]	Kvanefjeld Project area (CR-39)	Kvanefjeld Project area (Durridge RAD-7)[B]
2008	4 (117 d)	N/A	1(117 d)	1 (not given)	25 (117 days)	19 (15h)
2008/2009	1 (275 d)	N/A	1(275 d)	N/A	8 (275 days)	N/A
2009	3(56d)	N/A	2(47&54d)	N/A	30 (50-54d)	N/A
2010	N/A	N/A	1(56 d)	N/A	11 (N/A) [A]	6 (8-24h)
2011	N/A	N/A	1(427 d) [(C)]	N/A	16 (N/A) [A]	2 (6-19h)
2012	N/A	5 (4d)	N/A	1 (4d)	N/A	N/A
2013	5 (98d)	4(48h)	2 (98d)	1(48h)	9 (98d)	1(48h)

A. In 2010 CR-39 radon monitors were not deployed in the Kvanefjeld project area but in the accommodation huts in the Kvanefjeld camp. The deployment period was not given.
B. Continuous measurements of thoron (^{220}Rn) with the Durridge RAD-7 instrument were done in 2010 and 2011 in parallel with radon at Kvanefjeld plateau and in Narsaq and the Critical group location in 2012.
C. CR-39 radon monitor placed at the Critical group location in 2011 remained over winter to 2012.
D.

2.3   Radon results

Additional data during 2013 was obtained for radon and thoron on the road between Narsaq and the Project area (three locations, ^{222}Rn: 30±7 Bq/m^3, ^{220}Rn: 53±11 Bq/m^3) and Lake Taseq (one location, ^{222}Rn: 40±8 Bq/m^3, ^{220}Rn: 14±7 Bq/m^3).

Table 2.6. Data on radon concentrations obtained using integrated and real-time measurements (Bq/m^3).

Year	Narsaq (Bq/m^3) CR-39	Narsaq (Bq/m^3) Durridge RAD-7	Critical group loc. (Bq/m^3) CR-39	Critical group loc. (Bq/m^3) Durridge RAD-7	Kvanefjeld Project area (Bq/m^3) CR-39	Kvanefjeld Project area (Bq/m^3) Durridge RAD-7
2008	21 ± 2	N/A	64[A]	1 (not given)	78 ± 35	86 ± 50
2008/2009	126 ± 10	N/A	139[A]	N/A	233 ± 100	N/A
2009	92 ± 12	N/A	81 & 249	N/A	126 ± 50	N/A
2010	N/A	N/A	52[A]	N/A	60 ± 12 [B]	29 ± 16
2011	53 ± 18[C,D]	N/A	187[A,C]	N/A	34 ± 22 [B]	30 ± 8
2012	N/A	4.8 ± 1	N/A	21 ± 1	N/A	N/A
2013	20 ± 4	13 ± 4	76 ± 0.4	45 ± 9	341 ± 392[E]	17 ± 4

   A.   Only one monitor used
   B.   Accommodation huts in the Kvanefjeld camp
   C.   Deployed during winter 2011/2012
   D.   In GMEL personnel dwellings in Narsaq
   E.   Questionable data. Possibly some detectors snow covered part of time.

2.4   Thoron

Table 2.7. Data on thoron concentrations obtained using integrated and real-time measurements (Bq/m^3).

Year	Narsaq (Bq/m^3)	Narsaq (Bq/m^3)	Critical group loc. (Bq/m^3)	Critical group loc. (Bq/m^3)	Kvanefjeld Project area (Bq/m^3)	Kvanefjeld Project area (Bq/m^3)
2008	N/A		N/A			N/A
2008/2009	N/A		N/A			N/A
2009	N/A		N/A			N/A
2010	N/A		N/A			53 ± 50
2011	N/A		N/A			32 ± 17
2012	N/A	43 ± 65	N/A	24 ± 3	N/A	N/A
2013	16 ± 3	47 ± 11	50 ± 4	32 ± 11	50 ± 31	12 ± 4

Continuous measurements of thoron (^{220}Rn) with the Durridge RAD-7 instrument were done in 2010 and 2011 in parallel with radon at Kvanefjeld plateau and in Narsaq and the Critical group location in 2012. For number of measurements and duration refer to Table 2.5.

2.5   Environmental radon daughter monitoring

During 2013 concentrations of radon daughters were measured for the first time in the Kvanefjeld area. Due to the many factors influencing the concentrations of radon gas and its daughters, radon daughter monitoring is usually done in parallel with measurements of radon gas. It is usually expressed as the potential alpha energy concentration (PAEC), A PAEC of 1 J/m^3 is dosimetrically equivalent to a radon concentration of 1.8*10^8 Bq/m^3 in equilibrium with its progeny. Measurements of both radon and its progeny enable calculation of an equilibrium factor. Measurement of the PAEC alone is less useful. It is not clear from the current data in 2013 if the measurements of radon gas and daughters were done simultaneously. From data available radon was measured at 5 out of the 12 stations were radon daughters were analysed. It should be noted, however, that radon decay products may originate from sources some distance away as radon is released from soils and ores and some time is taken for the decay products to build up.

Table 2.8. Data on radon daughter concentrations.

Location	PAEC [µJ/m^3]	Number of measurements
Narsaq	0.089 ± 0.055	3
Critical group location	0.028 ± 0.022	1
Kvanefjeld Project area	0.07 ± 0.05	2
Road Narsaq-Kvanefjeld	0.033 ± 0.034	5

2.6   Soil & water

Table 2.9. Results of analyses of radioisotopes in water samples.

Sample ID	Narsaq River delta	First bridge	Kvanefjeld stream	Old bridge	Accommodation area
U [mg/L]	0.0011	0.0014	0.0082	0.00082	<0.0005
Th [mg/L]	<0.0005	<0.0005	0.0017	<0.0005	<0.0005
^{226}Ra [Bq/L]	<0.043	<0.048	0.047 ± 0.022	<0.057	0.048 ± 0.028
^{228}Ra [Bq/L]	<0.011	<0.12	<0.10	<0.12	<0.12
^{210}Pb [Bq/L]	0.10 ± 0.13	<0.22	0.16 ± 0.08	0.20 ± 0.07	0.11 ± 0.07
Total alpha [Bq/L]	0.34 ± 0.02	0.036 ± 0.015	0.20 ± 0.02	<0.034	<0.034
Total beta [Bq/L]	<0.15	<0.15	0.17 ± 0.06	<0.15	<0.15

In 2009 water was sampled from the lake behind the camp, used for drinking, cleaning and showering. Radon concentrations in the lake water were 23 ± 3 Bq/L. In 2013 water (8 samples) and soil (6 samples) were collected for radiometric analysis to establish a baseline of

radioisotope concentrations around Narsaq and Kvanefjeld. For the solid samples only elemental uranium and thorium was reported while for water samples data are shown in Table 2.9.

Table 2.9 (continued)

Sample ID	Waste area	Waste area	River from glacier	River coming down from lake
U [mg/L]	<0.0005	<0.0005	0.0032	0.00092
Th [mg/L]	<0.0005	<0.0005	<0.0005	<0.0005
^{226}Ra [Bq/L]	<0.055	<0.046	<0.043	0.022 ± 0.020
^{228}Ra [Bq/L]	<0.12	<0.10	<0.11	<0.12
^{210}Pb [Bq/L]	0.08 ± 0.13	<0.27	0.16 ± 0.11	0.11 ± 0.13
Total alpha [Bq/L]	<0.034	<0.034	0.074 ± 0.017	<0.034
Total beta [Bq/L]	<0.15	<0.15	0.11 ± 0.06	<0.15

Table 2.10. Results of analysis of radioisotopes in solid samples (soil/sediment).

	Elemental uranium [mg/kg]	Elemental thorium [mg/kg]
Narasq river delta	10.2	22
First bridge	35	49.6
Kvanefjeld stream	26.9	25.5
Old bridge	25	35.6
Accommodation area	2	3.2
River from glacier	66	110

2.7   Polonium-210 in environmental samples

Table 2.11. Results from ^{210}Po measurements in biota for samples collected 2007-2009.

Sample type	^{210}Po Bq/kg (fw)	^{210}Po Bq/kg (dw)
Marine fish	1.2 ± 1.8 (n=6)	-
Blue mussel	79 ± 34 (n=15)	-
Seal meat	38 ± 30 (n=12)	-
Seal liver	155 ± 95 (n=7)	-
Freshwater fish	1.2 ± 0.4 (n=2)	-
Lichen	-	740 ± 333 (n=12)
Salix	-	61 ± 61 (n=12)
Grass	-	150 ± 156 (n=11)

Environmental samples were collected in August-September 2007-2009 from the Kvanefjeld area in Greenland and delivered to the Radiation Research Department at Risø DTU, Denmark, for analysis of ^{210}Po. Sample types comprised marine fish, mussels, seaweed, seal meat, seal liver, freshwater fish, lichen, salix and grass. Results for the analysed samples are shown in Table 2.11. All data refer to the sampling date but due to ^{210}Pb not being analysed the actual

Predicted Radiation Exposure from Mining at Kvanefjeld

levels of [210]Po in these samples may be lower or higher depending on the [210]Po/^{210}Pb ratio at the time of sampling and the delay between sampling and analysis. Typical delay between sampling and analysis was between 1-2 months, sometimes even longer. However, uncertainty due to delay between sampling and analysis and lack of information on ^{210}Pb is believed to be minor compared to the variability across sample types which in some cases exceed 100% (e.g. for marine fish and grass).

2.8 Dust monitoring

During 2009-2011 dust sampling was conducted using a small battery-operated dust sampling pump. Due to the low volumes collected in 2009 and 2010, no data on dust was obtained for these years.

Table 2.12. Results of PM_{10} concentrations and radioisotopes in dust collected at three locations

Sample code	Sampling period	Location	Days	Volume (m^3)	PM_{10} µg/m^3	[232]Th (ng/m^3)	[238]U (ng/m^3)	[210]Po (mBq/m^3)
KP001_01	aug-2011	Sheep farm	29	79.45	4.0	0.33	0.052	0.23
KP010_10	oct-2011	Sheep farm	28	77.16	2.1	0.046	0.0029	0.26
KP013_32	nov-2011	Sheep farm	25	68.2	2.0	0.057	0.0093	0.41
KP002_02	aug-2011	Narsaq town	29	79.33	4.3	0.14	0.01	0.14
KP011_11	oct-2011	Narsaq town	29	79.18	1.0	0.085	0.0025	0.04
KP014_33	nov-2011	Narsaq town	30	82.68	0.8	0.069	0.0011	0.06
KP003_03	aug-2011	Narsaq point	30	81.47	2.8	0.088	0.0078	0.13
KP012_12	oct-2011	Narsaq point	28	77.2	2.1	0.089	0.0077	0.27
KP015_31	nov-2011	Narsaq point	28	76.57	1.9	0.026	0.0027	0.26

A baseline dust and pollutant monitoring programme in the surroundings of the proposed Kvanefjeld mine and the town of Narsaq was run from 1 August 2011 to 31 August 2012 (Clark, 2013). Apart from meteorological parameters the baseline monitoring included monthly PM_{10} dust concentrations in ambient air with elemental composition and [210]Po on selected monthly samples. Among the elements determined were uranium and thorium. Results of the analyses are shown in Table 2.12 together with locations period of sampling and duration. Uncertainties of the radioisotope analyses are about 10%. The conversion between mass and activity for Th is roughly 4 µBq/ng and for U 12 µBq/ng.

2.9 Conclusions

Data on external exposure based on measurements done with TLD should constitute the base for the current gamma exposure situation. The methodology of using TLD as a detector for the integrated dose is well established. Reported data based on scintillator detectors are probably overestimated and both the instrumentation itself and the handling have the risk of inducing sources of error that should be avoided. If such type of instrumentation is used it is essential that staff are well trained in handling of instruments and know about inherent artefacts. Data on radon shows relatively high concentrations in outdoor air. It is suggested that the monitoring using integrated detectors continue.

It is suggested that the monitoring of the area includes regular measurements of radioactivity in precipitation since this is a very simple and sensitive way of monitoring dust in the atmosphere. The monitoring activities should also include air sampling on a weekly or monthly basis (high volume air sampling) and have fixed stations for selected biological samples collected annually. Such samples should preferably be analysed by gamma spectrometry and ^{210}Pb-^{210}Po using radiochemical methods. Previous data on ^{210}Po alone in biological samples are incomplete due to the dynamic development of polonium as a consequence of decay and ingrowth from ^{210}Pb. To avoid difficulties arising from long waiting times between sampling, transportation and analysis the initial chemical separation of polonium and lead should be done directly in the field. Lack of information on levels of ^{210}Pb in samples is believed to be of minor importance compared to the considerable variability in ^{210}Po levels across samples for each type of sample.

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3 Predicted Radiation Doses to Workers

3.1 Radiation in mining and processing

There are three principal ways in which radiation exposure can occur in uranium mining and processing:

- <u>External gamma exposure</u> – gamma rays emitted from uranium and thorium ores and concentrates can result in radiation doses to those nearby. The gamma radiation originates mainly from a few decay products of U-238 and Th-232, particularly Pb-214, Bi-214, Ac-228 and Tl-208.

- <u>Inhalation of radioactive dusts</u> – dust from uranium and thorium ore, concentrates and wastes contain radionuclides. If inhaled, they may be retained in the lungs, or transported by body fluids and deposited in other organs. Subsequent radioactive decay may result in doses to organs. The long-lived alpha emitting radionuclides (U-238, U-234, Th-230, Ra-226, Po-210 and Th-232, Th-228) and beta emitters (Pb-210, Ra-228) are the most important for this type of exposure.

- <u>Inhalation of radon decay products</u> (RnDP) – one of the uranium (U-238) decay products is the radioactive gas, radon (Rn-222), which can diffuse out of the ore in which it is formed, and into the atmosphere. Inhalation of radon itself does not result in a significant radiation dose, because very little is retained in the lungs as it is an inert gas. However, radon decays to short-lived decay products (RnDPs – Po-218, Pb-214, Bi-214 and Po-214). These attach quickly to particles and if inhaled they lodge in the lung, and in high concentrations can result in large radiation doses from the alpha particles they emit. Also one of the Th-232 decay products, thoron (Rn-220), is gaseous and can diffuse from the ore and contribute to RnDP in the air. Due to the short half-life of thoron (55s), this contribution is usually relatively minor compared to that of U-238 decay products.

There are two other ways that internal exposure may arise from mining or processing operations:

- Ingestion (swallowing) – this may arise in occupational exposure by hand-to-mouth transfer when eating, drinking or smoking with contaminated hands.
- Wound contamination – radioactive material can enter the body via wounds.

These pathways are minor, and simple measures (e.g. personal hygiene and covering of wounds) can usually reduce them further.

3.2 Methodology

The radiation exposures of workers expected to result from the proposed mining operations are estimated from a number of assumptions. Concentrations of uranium and thorium vary across the Kvanefjeld ore but for the purpose of estimating radiation exposures, a peak uranium grade of 400 ppm U_3O_8 (340 ppm U) and a peak thorium grade of 750 ppm have been selected for calculations. These peak grades are on the high side and therefore will give a more conservative radiation exposure estimate.

The radioactivity from the ^{235}U decay chain, which occurs naturally within the ^{238}U decay chain, is not usually considered as its impact is small, less than 3%.

3.3 Predicted exposures in the mine

Information on working conditions was provided by GMEL (2014). The operators and trades people (electricians, welders and mechanics) will all work a two weeks on and then 1 week off roster. While on shift they will be working 12 hours per day. Annual leave will be four weeks per year plus 5 days sick/compassionate leave. This is the equivalent of 50 hours per week of work exposure time. This would be a maximum exposure period as approximately 2 hours of work breaks away from working areas would be included in the 12 hour shift. Only about 50% of the working shift will be in the operation plant environment corresponding to about 1000 h/y.

All work clothing worn by the employees will consist of long sleeve shirts and pants made from cotton. A dust mask will be provided to employees in specific areas where dusting is a hazard. Hard hats, safety boots, eye protection glasses and hearing protection will be provided as standard to all employees. Clothes are laundered (washed) at the refinery/concentrator plant site to ensure no potentially radioactive materials are brought into their private living accommodation. A change room and laundry facilities are provided at both the concentrator and refinery sites.

All employees will be provided with gamma radiation dose badges. These are typically worn for a period of one month before being collected and sent off for analysis. The badges are replaced with another new dose measuring badge so that analysis is continuous. Safety officers on site will monitor the radiation measurements for each employee to ensure that no one employee is receiving a high dose. Workers which are seeing an increase in dose will be investigated and possibly moved to a different section of the plant if required. Areas where elevated radioactivity is expected will have engineering measures (shielding, distance) and procedural controls (exposure time, worker rotation and personal protective equipment) to minimise radiation dose to ensure the total dose is acceptable.

The proposed mining technique for the Kvanefjeld project is an open pit. Figure 3.1 shows the exposure pathways for an open pit mine covering gamma radiation from the pit floor and pit walls, inhalation of radioactive dust and inhalation of radon and radon decay products. For purposes of calculating doses to workers, the mine pit depth has been assumed at 50 m and the width across at 250 m (GMEL, 2014).

3.4 Gamma exposure

The gamma dose rate from an extended source can be calculated using conversion factors for uranium and thorium (Saito and Jacob, 1994). In the open pit there would be a slight increase in exposure due to radiation from the walls. However, there would generally be some reduction due to shielding from equipment.

Applying the conversion factors to the uranium and thorium grades (340 ppm U and 750 ppm Th) for ore material gives annual doses from exposure during 2000 h/y, of about 7.6 mSv.

In practice it is unlikely that an individual would work full time on ore, so the value of 7.6 mSv/y represents a significant overestimate. If we assume that the highest exposure work groups would spend no more than 1000 h/y on ore, this would then give a maximum dose of about 3.8 mSv/y.
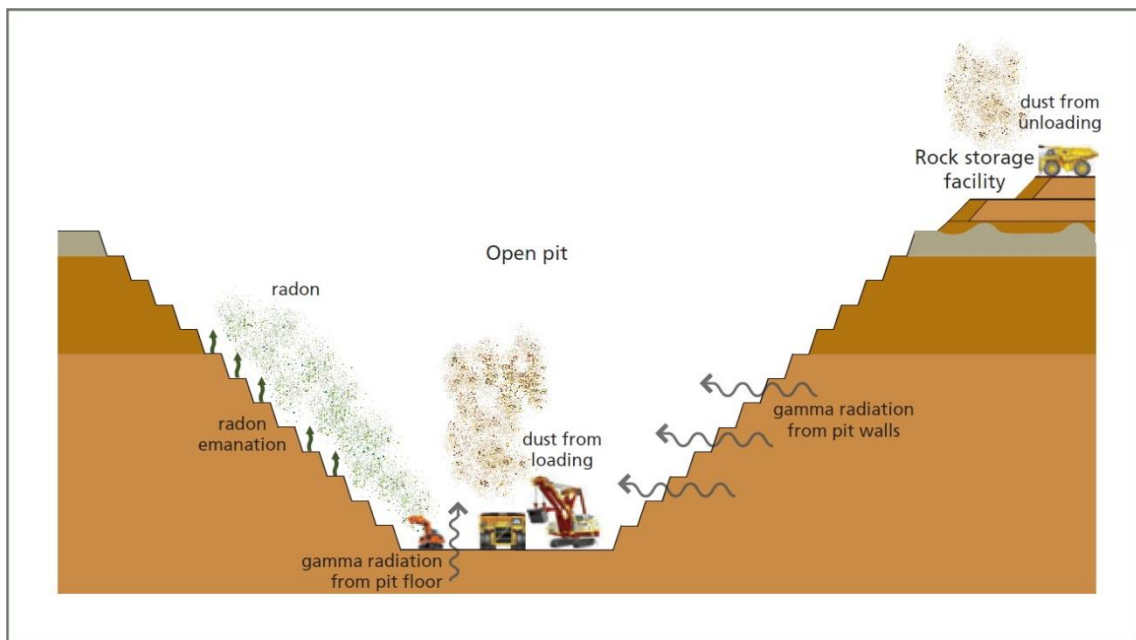
Figure 3.12 Open pit exposure pathways (BHP Billiton, 2009)

To compare this theoretical calculation with that observed in real situations, a review of operations at the open pit Ranger uranium mine in the Northern Territory in Australia was undertaken. The gamma doses to open pit workers at Ranger are given in Table 1.1. This shows an average worker receives 0.5 mSv/y gamma dose with a maximum of 4.3 mSv/y (Energy Resources of Australia, 2006). The ore grade of the Ranger pit has an average of 2600 ppm uranium, about 7 times greater than that predicted for the proposed Kvanefjeld project. As gamma dose is proportional with ore grade, which indicates that the doses predicted from theoretical calculations are likely to be considerably overestimated.

Based on this information, the annual doses to workers in the proposed Kvanefjeld project from gamma exposure in the open pit are expected to average less than 1 mSv ranging up to about 4 mSv.

3.4.1   Radon decay product exposures

Radon is exhaled continuously from ore into the atmosphere decaying into short-lived radon decay products (RnDP). Radon and RnDP are present in the atmosphere everywhere, but due to enhanced concentrations of uranium and radium in the ore, radon concentrations in the open pit atmosphere will also be enhanced. Concentrations will depend strongly on meteorological conditions: high wind speeds will quickly remove enhanced levels of radon and RnDP while low wind speeds will allow concentrations of radon and RnDP to build up in the pit atmosphere. Worst case scenarios are prolonged stable situations with stagnant wind and a temperature inversion layer formed above the base of the pit allowing radon and RnDP concentrations to build up. Such stable situations occur generally in winter during night when the sun is not available to generate local turbulence. A meteorological study at Kvanefjeld during 1979-1983 found weather conditions with wind speeds above 1 m/s during 75% of the time while stable conditions could account for the remaining 25% (Sørensen, 1983). However, experience from

mining operations in Northern Canada shows that during stable conditions the turbulence and heat from the movement of ore haul trucks typically eliminates the issue.

The rate of exhalation of radon from the Kvanefjeld ore to atmosphere was measured in a horizontal bore hole in the mining area. The rate of exhalation obtained by scaling to an average uranium grade of 340 ppm gave a value of 0.037 Bq/m^2/s (Sørensen, 1983). Atmospheric concentrations of radon in the pit have been estimated from the size of the pit, the rate of radon exhalation and the rate of ventilation of air in the pit due to wind. Assuming that air in the pit is exchanged one time per hour results in an average radon concentration of about 10 Bq/m^3. In this case an equilibrium factor of 0.4 would be assumed. Based on these assumptions, a worker spending 1000 h/y in the pit would receive an estimated annual dose from radon decay products of 0.03 mSv.

Under atmospheric stable conditions with no ventilation of air in the pit, radon and radon decay product concentrations will build up during 24 h to about 200 Bq/m^3. Under such stable conditions an equilibrium factor of 1 can be assumed. A worker spending 250 h/y in the pit under stable conditions and 750 h/y under ventilated conditions will receive an estimated annual dose from radon decay products of 0.4 mSv.

3.4.2   Dust exposures

The pit will be evacuated prior to blasting until the blast and dust clouds have subsided. Water trucks will be used to keep the entire mining area and road wet to suppress dust. Therefore, dust exposures of workers in the open pit area are expected to be small.

Data from open pit mines show average concentrations of dust in the air of about 1-2 mg/m^3 (Ghose and Majee, 2001). Selecting a conservative average concentration of 3 mg/m^3 in the open pit on Kvanefjeld and 1000 h/y in the operating pit environment results in an estimated annual radiation dose of 1.0 mSv from uranium and thorium in dust inhaled.

3.4.3   Estimated total dose to mine workers

The total maximum dose to workers in the open pit is thus estimated to be less than 5.4 mSv/y, consisting of 4 mSv/y from gamma exposure, 0.4 mSv/y from inhalation of radon decay products and 1 mSv/y from inhalation of radioactive dusts. The average dose to workers in the open pit is expected to be much smaller and below 2 mSv/y. These doses are a small fraction of the internationally recognized dose limit to workers of 20 mSv/y.

The results of these estimated doses are in broad agreement with actual doses to workers in uranium mines (Table 1.1).

Mine workers in the open pit mining area will be mainly located within the air-conditioned cabins of mining equipment. The cabins will have air filters which will remove almost all dust and will be replaced on a regular basis. Any time outside of the vehicles will be limited and the mine pit area will require special access requirements and require the use of a dust mask. During blasting when significant dusting can occur, the pit will be evacuated until the blast and dust cloud have subsided. Fog (fine water mist) generating machines will be used during the blast to minimize dust. Water trucks will be used to keep the entire mining area and road wet to suppress dust. A vehicle washing bay will be used to remove the mine dirt/dust from all vehicles which leave the mining area.

3.5 Predicted exposures in the processing plant

3.5.1 Mineral Concentrator

The most common area in mining operations which see elevated radioactivity is the crushing circuit, which is located in the mineral concentrator. Here the ore is crushed to fine pebbles in the dry conditioning before wet grinding. As the coarse rocks from the mine are reduced in size any trapped radon gas which has built up over time is released. As a precaution the ventilation rate for the crushing building at the refinery is considerably higher than in other areas. The crusher building air is turned over 10 times per hour compared to 4 times per hour in other parts of the process plant buildings. As a comparison domestic buildings and offices the air is turned over 1 time per hour. The crusher building has a volume of 12,000 m^3.

Assuming that 3 million tonnes of ore are treated annually, that the average plant availability is 90% and that 20% of the radon is released from the ore gives an average concentration of radon in the crushing building of about 3000 Bq/m^3. Furthermore, an equilibrium factor of 0.4 for radon and radon decay products is assumed in the building due to the high ventilation rate resulting in an estimated dose rate due to inhalation of radon decay products of 8 µSv/h. The calculated radon concentration is well above the reference concentration of 1000 Bq/m^3 recommended for workplaces (IAEA, 2014) which is also reflected in the estimated dose rate that in 1000 h would result in a dose of 8 mSv.

Furthermore, if account is also taken to release of thoron from ore in the crushing building and assumptions similar to those of radon, then the average thoron concentration in air will be about 400 Bq/m^3 resulting in a dose rate contribution of 5 µSv/h. The additional dose rate contribution from thoron emphasises that work in this area should be limited and monitored carefully to ensure that total dose is acceptable.

Crushing of ore to fine pebbles in dry conditions will give rise to enhanced concentrations of radioactive dust in the crushing building. Assuming that dust concentrations will remain at an average level of 3 mg/m^3 this will correspond to an annual radiation dose from inhalation during 1000 h/y of 1 mSv. Hence the exposure pathway of inhalation of dust will be much less restrictive than that from inhalation of radon decay products.

After the ore is crushed it is contacted with water to produce slurry inside a grinding mill. This effectively converts the dry fine rocks into a mixture of water and powdered ore. From this point onward the solids/ore are not allowed to dry out (i.e. maintained in a water suspension or cover). The water cover dramatically reduces the emissions of radon, alpha and beta radiation. It is all effectively absorbed by the water. Gamma radiation however is still emitted through the water layer.

During 2012 approximately 16 tonnes of ore was sampled from the old mining stockpiles near Narsaq. Of this 16 tonnes, approximately 8 tonnes was transported to Perth, Western Australia for metallurgical test work. Pilot plant operations were performed to examine the performance of the concentrator in a flotation circuit. The plant treated 4.5 tonnes of ore which produced around 300 kg of rare earth phosphate mineral concentrate. This concentrate chemical assay was typically 15% rare earth oxides, 0.8% thorium and 0.25% U_3O_8. The concentrate was mainly used for hydrometallurgical pilot plant work to test the performance of the refinery process.

A gamma radiation survey of the pilot plant was carried out. The results show dose rates from a number of survey points in the pilot flotation circuit in the range 0.3-1.2 µSv/h at 1 m distance from equipment with an average value of 0.5 µSv/h. Combining this with the fact that the amount of ore located in the concentrator will be considerably less than that in the open pit shows that annual gamma doses from working 1000 h/y in the concentrator will be small, probably about 1 mSv/y, and much less restrictive than doses from inhalation of radon decay products.

The tailings stream from the concentrator contains uranium and thorium in secular equilibrium. These tailings contain the original unaffected minerals which have been reduced to powder size. The percentage of solids in the tailings stream is 60% by weight. The head of chain radionuclide composition is expected to be about 170 ppm uranium and 290 ppm thorium, which corresponds to about half of the average grades in the ore. Therefore, gamma dose rates from the tailings will be low. The tailings are stored under water in the Taseq Lake which is located a few kilometres from Kvanefjeld.

3.5.2   Refinery

The rare earth phosphate mineral concentrate is processed in the refinery where further separation of rare earth oxides and uranium is carried out. This is accomplished from a range of chemical treatments of the concentrate isolating the rare earths and uranium. These treatments also affect the radioactive decay products from the uranium and thorium decay chains so that these decay products end up in the waste stream generated by the refinery. The solids are not allowed to dry out, i.e. they are maintained in a water suspension or covered by water. Therefore, there will be no generation of radioactive dusts and release of radon will be minimal. The main exposure of workers to radiation in the refinery will be external gamma radiation from processing and storage tanks and other equipment holding impurities with uranium/thorium decay products.

Radiation doses to workers in the refinery are expected to be of the same order of magnitude as in the material concentrator, i.e. about 1 mSv/y from exposure to gamma radiation.

3.6   Predicted doses to administration personnel

Office based workers will only have intermittent process plant exposure and therefore doses much lower than workers in the open mining area or in processing areas.

3.7   Predicted doses from transportation

Uranium oxide is the only radioactive product which will be transported from the mining operations. It will be transported in solid form as the chemical uranium peroxide, UO_4. It will be packaged into 200-L steel drums and then strapped into standard 20–foot sea containers. Handling and transportation of uranium oxide will be carried out according to IAEA guidelines, which ensure that doses to workers are well below dose limits.

Figure 3.13. Filled Uranium Oxide Drums Strapped inside a Sea Container

3.8   Conclusion

Radiation doses to workers in the proposed Kvanefjeld mine and processing plant have been predicted from exposure to gamma radiation and from inhalation of radon decay products and radioactive dusts. The predicted gamma radiation levels and concentrations in air of radioactive dusts and radon decay products are low in general ensuring that the predicted radiation doses are also low and well below limits recommended internationally for radiation workers. However, concentrations in air of radon and radon decay products in the ore crushing building are predicted to be above the reference concentration for workplaces recommended by the IAEA. Work in the crushing building should be limited to ensure that total individual doses are acceptable.

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Appendix

A. Gamma exposure

Conversion factors are available for uranium and thorium in the ground and effective dose (Saito and Jacob, 1994). These conversion factors are calculated using a Monte Carlo method assuming that natural radionuclides are uniformly distributed in the ground.

Decay chain	Conversion factor (nGy/h per Bq/kg)	Conversion factor (nGy/h per ppm)
U-238	0.46	5.8
Th-232	0.60	2.5

Applying these to the uranium and thorium grades (340 ppm U and 750 ppm Th) for ore material gives annual doses from exposure during 2000 h/y, of about 7.6 mSv.

B. Exposure to radon decay products

International Basis Safety Standards from the IAEA (2014) gives the relation between exposure to radon decay products and effective dose as follows:

On the assumption of an equilibrium factor for ^{222}Rn of 0.4 and an annual occupancy of 2000 h, the value of activity concentration due to ^{222}Rn of 1000 Bq/m^3 corresponds to an annual effective dose of the order of 10 mSv.

The equilibrium factor for radon is the ratio between the activity of the short-lived radon decay products (which are responsible for most of radon's biological effects), and the activity that would be at equilibrium with the radon parent. If a closed air volume is constantly supplied with radon, the concentration of short-lived isotopes will increase until equilibrium is reached where the rate of decay of each decay product will equal that of the radon itself. The equilibrium factor is 1 when both activities are equal, meaning that the decay products have stayed close to the radon parent long enough for the equilibrium to be reached, within 2-3 hours. The equilibrium factor is typically 0.4 in outdoor air.

IAEA (2004) gives data from which the following operational conversion factors may be derived. For an equilibrium factor of 0.4 the conversion factor from radon exposure to dose may be expressed as 0.003 µSv m^3/(Bq h). For an equilibrium factor of 1, the conversion factor from exposure to dose may be expressed as 0.008 µSv m^3/(Bq h).

Conversion factors may also be derived for inhalation of thoron and thoron decay products. For an equilibrium factor of 0.4 the conversion factor from thoron exposure to dose may be expressed as 0.015 µSv m^3/(Bq h) and for an equilibrium factor of 1, the conversion factor may be expressed as 0.036 µSv m^3/(Bq h). Due to the short half-life of thoron (55 s half-life), calculations of thoron and thoron decay product concentrations in air are less reliable than those for the longer-lived radon (3.8 d half-life).

C. Doses from dust inhalation

The highest expected grade of uranium would amount to some 400 ppm U_3O_8 corresponding to 340 ppm U = $3.4 \cdot 10^{-4}$ g U / g dust. This agrees well with older findings by Pilegaard (1990), who only found this high grade in the ore (as opposed to the scale and tailings). Kissell (2003) described various highly dust generating mining operations (e.g., by stageloader-crusher, shields and shearer), and found that the most dusty operations could result in air concentrations of as much as 8.8 mg/m^3 (upper recorded limit). At such high concentrations, dust control would according to Kissell be required to make working conditions tolerable (e.g., ventilation and spray water). If a very high air concentration of dust material of 10 mg/m^3 is thus highly conservatively assumed in connection with work in Kvanefjeld operations, it would be rather unpleasant to work in without respiratory protection and tight fitting safety glasses. The uranium concentration in the air would then be as high as $3.4 \cdot 10^{-4}$ g U / g dust * 10 mg dust / m^3 = 3.4 µg U / m^3. According to ICRP (1994), an average human breathing rate during *heavy* work is of the order of $8 \cdot 10^{-4}$ m^{3}s^{-1}, which would mean that a worker might inhale as much as 3.4 µg U / m^3 * $8 \cdot 10^{-4}$ m^{3}s^{-1} = 10 µg U /h. With a specific activity for U-238 of 12.4 kBq/g, this amounts to 0.12 Bq/h.

Referring to IAEA (2004), for each Bq U-238 inhaled, the resulting dose from inhalation of all radionuclides at equilibrium in both uranium decay chains would result in an inhalation dose of $2.9 \cdot 10^{-5}$ Sv. That is assuming that the dust inhaled can be adequately represented as having an AMAD of 5 µm, as is the default recommendation for worker exposure studies, where more exact information is not available (ICRP, 1994; Dorrian & Bailey, 1995). It should be noted that the deposition in the alveolar-interstitial region of the respiratory tract is several orders of magnitude less for 20 µm aerosols than for 5 µm aerosols (Valentin, 2002). It is further assumed that the chemical form of each radionuclide in the dust inhaled is that corresponding to the slowest absorption class specified by ICRP (1995).

This means that the worker dose from inhalation of uranium in dust over one hour could amount to as much as 0.12 Bq/h * $2.9 \cdot 10^{-5}$ Sv/Bq = 3.5 µSv, or over a work year with 1000 effective hours in the mine: ca. 3.5 mSv. Similarly, peak thorium grades were reported by GMEL (2014) to be as high as 750 ppm. With a specific activity for Th-232 of 4.07 kBq/g, and a dose from the Th-232 decay chain of $4.8 \cdot 10^{-5}$ Sv/Bq (IAEA, 2004), it can be established with the same methodology and assumptions that the worker dose over one hour could amount to as much as 0.09 Bq/h * $4.8 \cdot 10^{-5}$ Sv/Bq = 4.3 µSv, or over a work year with 1000 effective hours in the mine: ca. 4.3 mSv. The total annual dose from inhalation of dust with these assumptions is 7.8 mSv.

This can be compared with the effective dose limits of 20 mSv per year averaged over five consecutive years, and of 50 mSv in any single year (IAEA, 2014).

The above dose estimate is highly conservative, and in any case, individuals' working hours over a year in such dust generating operations could presumably easily be reduced substantially. Also forced ventilation and water mists might be applied (Kissell, 2003). Techniques to change local airflow patterns can also be helpful, on the basis of airflow analyses. If desired, Powered Air Purifying Respirators (PAPR), which would also ease the breathing while working if the dust air concentrations would be anywhere near 10 mg/m^3, could reduce inhalation doses by several orders of magnitude. Specific recommendations have been given by the IAEA (2004) in Appendix V in relation to use of protective respiratory equipment by professionals in mining.

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