Uranium mining at Kvanefjeld

Source: Google Maps

Report based on the lectures by the author at the conferences at Nuuk (Greenland) and Copenhagen (Denmark), 22-25 March 2014

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Summary and findings

At Kvanefjeld/Kuannersuit large resources of rare earth elements (REEs) are present. The REE ores contain also substantial amounts of uranium and thorium, so the ores are radioactive. Uranium would be extracted as byproduct, thorium would be discarded in the mining waste.

As far as known the mine at Kvanefjeld/Kuannersuit would be the first uranium mine on top of a mountain and besides it is located in an arctic region. The consequences of these features are poorly understood and may pose unknown risks for the environment and quality of life of the local population.

Mining of the REE ores as intended by Greenland Minerals & Energy Ltd (GME) would produce massive amounts of mining waste, the tailings. The tailings, consisting of a slurry of finely ground rock suspended in water and a mix of chemicals, would be distributed over two residue storage facilities (RSFs).
The larger part of the tailings, counted in hundreds of millions of cubic meters, would be located in RSF1 in Lake Taseq and is less radioactive than the ores. Some constituents of the ores, for example fluoride, may be present in soluble form in RSF1.
The smaller one, counted in tens of millions of cubic meters, would be located in RSF2 in a natural basin east of the Nakalak range and is about ten times more radioactive than the ores. The radioactive contents, thorium, the majority of uranium and the decay products of both metals, are in soluble form, contrary to the original minerals.

There is a lack of knowledge on the physical behavior in the long run of the tailings in the RSFs in the local climate.
Major failures of the high embankments of the RSFs pose grave risks of very large mudflows of tailings slurry, containing massive amounts of (undisclosed) chemicals, radioactive elements and non-radioactive toxic elments. Contamination of soil and water is irreversible.

Seepage and spills of heavily contaminated water from the mining pit and from both RSFs are practically unavoidable. It is not known which chemical species, including radioactive elements, and at which rate will routinely enter the groundwater and rivers in the region, not only during the operational lifetime of the mine but also in the centuries following. Environmental and health effects are even less known.
A Risø study from the early 1980s identifies a number of non-radioactive elements released during mining as an environmental problem and concludes there is a great lack of knowledge.

In the view of the International Atomic Energy Agency (IAEA) the radioactivity of the mining waste of uranium mines are of minor importance. Economic factors are determining the method of ‘remediation’ of uranium mines. In practice no uranium mines in the world have ever been rehabilitated in an acceptable way: after depletion the mining sites are simply abandoned.

Exposure to radioactive materials, even at low levels, can cause a wide range of cancers, lethal and non-lethal diseases, genetic malformations, stillbirths, premature aging and inheritable diseases, often with long latency periods (years to decades).
Biological behavior and effects of radionuclides inside the human body are poorly understood. Effects of chronic exposure to a combination of radionuclides, by inhalation of dust and gaseous radionuclides and by ingestion via food and drinking water, are even less understood.

The IAEA does not recognise health effects with long latency periods as attributable to exposure to radioactive contamination. Only health effects caused by extremely high radiation doses (radiation sickness) are recognised as radiation-induced diseases. Radiation sickness is lethal and has short latency periods of hours to weeks.

The IAEA is not an independent scientific institute, for two reasons: it has promotion of nuclear energy in its mission statement and its official documents have to be approved by the 159 member states of the IAEA. Publications of the World Health Organization (WHO) on nuclear matters are not allowed to deviate from the view of the IAEA.

Uranium from Kvanefjeld/Kuannersuit would have only marginal importance for the world nuclear power generation. Due to the low uranium grade and the complex chemical composition of the ores, the recovery factor would be low and the specific energy consumption of the recovery would be high. As a result the energy balance of a nuclear power station fed with that uranium would approach zero (energy cliff) and the specific CO2 emission would rise to the level of fossil fuelled power stations (CO2 trap). The amount of ore to be mined and processed at Kvanefjeld/Kuannersuit would be as large as the amount of coal to be mined and burned to generate an equal amount of electricity (coal equivalence). The production cost of uranium from Kvanefjeld/Kuannersuit would fall in the highest cost category of the IAEA, three times higher than the current market price. As the uranium demand is expected to decrease in the long run, due to a decreasing world nuclear capacity, it is doubtful if uranium from Kvanefjeld/Kuannersuit could ever become cost-competitive.

Thorium will never become a substitute for uranium, because a thorium-based nuclear energy system is technically not feasible. Even if it would work as adverised, a thorium-based system would have a negative energy balance: it would consume more energy to run the system than it would generate.

Contents

Introduction

Questions are rasised by the plans to start mining ore deposits in South Greenland, internationally known as Kvanefjeld, in Greenlandic Kuannersuit. This report addresses issues regarding the uranium recovery and aims to provide the local population in Greenland and the Greenlandic and Danish politicians an independent view on the hazards posed by uranium mining, in addition to the information from companies and institutes with vested interests in uranium mining and nuclear power. In this way the policy makers may be able to base their decisions regarding uranium mining in Greenland on a balanced set of scientific and non-scientific arguments.

The ore deposits at Kvanefjeld/Kuannersuit contain different commodities. Important are a number of rare earth elements (REEs), zinc, fluorine and uranium. Rare earth elements are indispensable in our society for applications in electronic devices, LED's, etcetera. At this moment the world is largely dependent on China: more than 90% of the world demand is supplied by China. Geopolitically other large suppliers of rare earth elements might be of strategic importance.

The REE ores at Kvanefjeld/Kuannersuit contain also uranium and thorium. What is the importance of these metals? What to do with the uranium, thorium and the other radioactive elements present in the REE ore? What would be the environmental impact of the proposed mining of these deposits?
This report focuses on the uranium recovery, the thorium issue and the hazards posed by the radioactive elements in the ores. REE recovery will not be discussed here, to limit the scope.

1 Uranium resources at Kvanefjeld

The uranium occurence at Kvanefjeld/Kuannersuit are the largest known in Greenland and the only one which is described in great detail (MiMa 2014). Kvanefjeld is a unique type of uranium deposit where the majority of uranium is hosted by the complex phosphor-silicate mineral steenstrupine, containing 0.2-0.5% UO2. The host rock, lujavrite, contains 200-400 ppm U (grams uranium per ton rock) and 600-800 ppm Th (grams thorium per ton rock), the typical Th/U ratio lies between 2-3. Since 2007, the area has been explored for REE, and the current license-holder is Greenland Minerals and Energy Ltd (GME).

GME has published in its reports and on its website different figures regarding the uranium resources at Kvanefjeld/Kuannersuit. GME distinguishes three ore deposits at Ilimaussaq complex: Kvanefjeld, zone 2 (Sørensen) and zone 3. GME's most recent publication estimates the joint ore mass at 956 million metric tons, containing more than 220 thousand tons of uranium, at an average ore grade of 232 ppm U, parts per million, equivalent to 232 grams uranium per ton ore (GME 2014b). Other grade figures are also mentioned. In another publication (GME 2014a) GME claims a uranium resource of some 500 000 tons.

The IAEA (international Atomic Energy Agency) and OECD/NEA (Organisation for Economic Co-operation and Development/Nuclear Energy Agency) report a recoverable uranium resource of 134 000 tons, at an average ore grade of 218 ppm (Red Book 2011). Apparently only the Kvanefjeld deposit is listed. The Red Book is the authoritative report on the world uranium resources and is published once every 2-3 years. The IAEA/NEA assume a recovery factor of 65%. This recovery factor might be optimistic.
For reason of the complexity of the uranium recovery the IAEA/NEA places the uranium from Kvanefjeld in the highest cost category of up until 260 US dollars per kg uranium. The current (March 2014) market price is less than 80 USD/kgU.

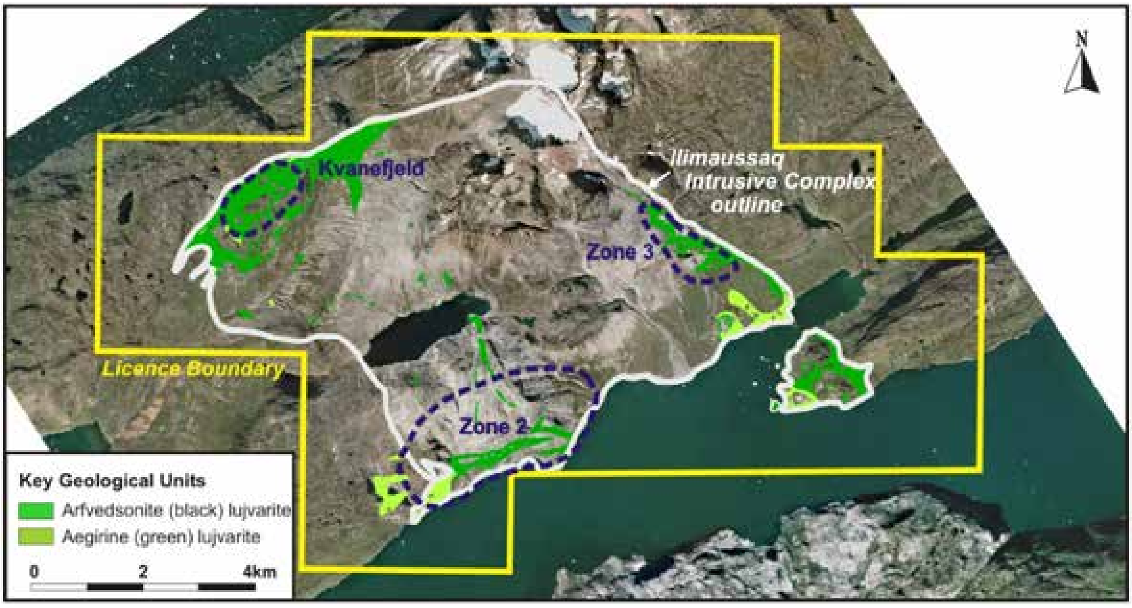


Figure 1

The Ilimaussaq complex and the three ore deposits as identified by GME. The ores are hosted in the black lujavrite rocks. Source: GME 2012.

There are inconsistences in the figures of the resources and ore grades as reported by GME. In addition there are disparities between the figures of GME and of the IAEA/NEA, particularly concerning the ore grades and cut-off grades. We found no explanation of the disparities.
Apparently GME does not distinguish between *in situ* resources and recoverable resources. The *in situ* resources are the amounts of uranium as present in the pristine rock and are not the same as recoverable resources. That are the amounts that can actually be recovered from the deposits. The fraction of the metal that can actually be recovered from an ore body depends on the ore grade and the chemical properties of the minerals containing the desired metal. This fraction is called the recovery yield or recovery factor.

From Table 2.6.1 in (GME 2012), may follow a recovery factor of 45% from ore at a grade of 364 ppm. Considering that the average grade is much lower than 364 ppm and in view of the complex chemical composition of the uranium-bearing minerals, the average recovery factor might be significantly lower than 45%. Based on previous studies this report estimates a figure of 40%, but a lower figure is likely. That would mean that the recoverable uranium resource of Kvanefjeld/Kuannersuit would be about 0.40•220 000 = 88 000 tons uranium. This amount would be produced during an operating lifetime of the mine of some 60 years, so the average annual production would be nearly 1500 tons per year. The current global uranium demand is 68 000 tons per year.

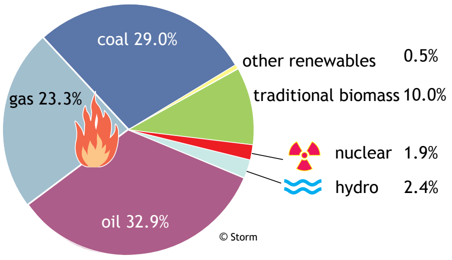
2 Importance of uranium in a global perspective

The following topics will be briefly addressed: coal equivalence, nuclear share of the world energy supply, energy costs energy: energy return on energy investments (EROEI), energy cliff and CO2 trap.

Coal equivalence

At a grade of about 200 ppm, 200 grams of uranium per ton rock, uranium ore has the same net energy content as coal. That means that to feed a nuclear power plant with uranium from that ore as much ore has to be mined and processed as the amount of coal needed to produce an equal amount of electricity.
The mentioned ore grades of Kvanefjeld/Kuannersuit are near at this limit: in one of its recent publications GME mentions an average grade of 218 ppm U.

Nuclear share



world energy consumption in 2010: ~515 EJ
traded energy: 463 EJ

Figure 2
World energy consumption in 2010. Traditional biomass and ‘other renewables’ are not traded and are usually omitted from the official energy statistics. In these statistics the amount of electricity produced by nuclear power is multoplied by a factor 2.8-3 to represent the amount of fossil fuels that would be needed to generate the same amount of electricity. However, the heat generated by a nuclear reactoir cannot be.applied as useful energy, contrary to the heat generated by fossil fuels. The only useful energy from nuclear power is electricity, just like the useful energy generated by hydropower, solar panels and wind power. The nuclear fraction of the world electricity generation was 13.0% in 2010.
Sources: BP 2011 and IEA 2010.

The nuclear contribution to the global energy supply was 1.9% in 2010 and is lower today. Even if nuclear power would be carbon-free, which it is not, the mitigation of the CO2 emission could be not more than 1.9%. If the world nuclear capacity remains level during the next decades, the nuclear share would decline to less than 1% by 2050, due to the increasing world energy demand. Besides, even a constant nuclear capacity would imply a massive construction programme, a nuclear renaissance, for the nearly the whole world nuclear fleet has to be replaced by new build by the year 2050.

During the last years the global nuclear capacity is declining and this trend is expected to accelerate in the future. This decline caused by the fact that more nuclear power plants are permanently shut down than new NPPs come on line. at an increasing rate. As a result the uranium demand will decline from the current demand of about 68 000 tons a year. For that reason it seems unlikely that the market price of uranium will rise in the future much above the current value of some 80 USD/kg U. Mines with high production costs have to suspend their mining activities already at this moment. The production costs of uranium from Kvanefjeld/Kuannersuit are placed in the highest cost category of up to 260 USD/kgU by the IAEA.

Energy costs energy

Mining energy

The mining or ore and the extraction of a metal from that ore consumes energy: fossil fuels, chiefly diesel, and electricity. In the milling process lots of chemicals are consumed. The production and transport of those chemicals also cost energy. The energy requirements of uranium recovery increase steeply with declining ore grades. Recovery of 1 kg of uranium from ore with a content of 200 grams uranium per ton ore requires processing of at least five times as much ore than recovery from ore at 1000 grams uranium per ton ore (about the current world average). Because the recovery factor sharply declines at grades below 1000 g U/ton ore, the specific energy input per kg U increases correspondingly. The recovery of uranium from hard ores, such as the ores of Kvanefjeld/Kuannersuit, consumes 2-3 times as much energy as from soft ores at same grade (Storm 2012a & 2012b).

Nuclear process chain

A nuclear reactor is not a stand-alone system. Nuclear fuel is not found in nature but has to be prepared from natural uranium. Figure 3 represents a simplified outline of the complete system of industrial processes needed to generate nuclear power, from cradle to grave.

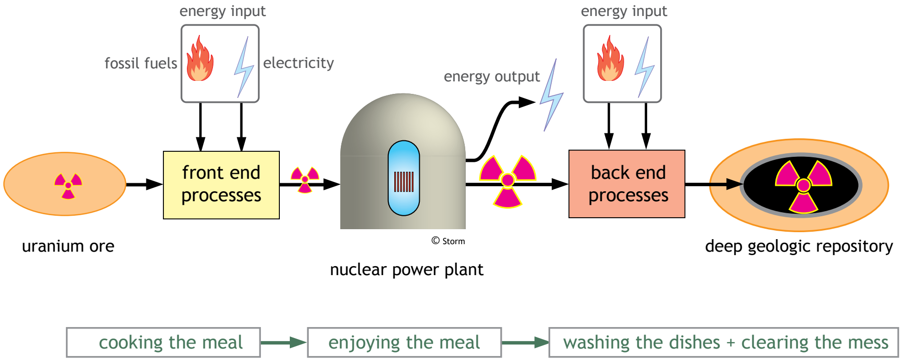


Figure 3

Simplified outline of the nuclear process chain as it ought to be. As almost every industrial process, and even household activities, the nuclear energy system consists of three main parts: preparation activities (front end), the intended activity and the cleanup of the waste (back end). In case of the nuclear system the wastes are piling up, because the back end processes are still being passed onto future generations. To calculate the EROEI of an energy sytem all activities from cradle to grave should be included, to make a fair comparison possible.

In the front-end processes – from ore to fuel – uranium is extracted from the earth's crust and is processed into nuclear fuel elements. In addition the construction of the nuclear reactor and the power plant is an important part of the front-end processes.

The back-end processes encompass all activities needed to safely handle the radioactive waste from the reactor. The most important back end processes still do not exist. All radioactive waste ever generated in the world since the 1940s is still awaiting safe and permanent isolation from the biosphere.

All components of the nuclear chain, except the fission process in the reactor, are essentially conventional industrial processes, consuming materials, electricity and fossil fuels. Consequently all processes of the nuclear chain, except the nuclear reactor itself, emit carbon dioxide CO_2. It is not possible to generate useful energy from uranium without the consumption of fossil fuels and the emission of CO_2, both in significant amounts. Jointly these processes and activities are called the nuclear process chain, the most complex technical system ever designed by man.

Energy return on energy investment (EROEI)

The energy return on energy investment (EROEI) is defined as the ratio of the net energy production of an energy system over the energy inputs needed to construct and to operate that energy system from cradle to grave. The energy input of the nuclear back end processes can be estimated based on a detailed life cycle assessment (LCA), for no advanced technology is needed to isolate all radioactive waste from the biosphere as effective as possible (Storm 2012a). The EROEI is convenient to compare different energy systems, for example nuclear power and solar power.

Energy cliff

As pointed out above, the recovery energy per kg uranium rises exponentially with decreasing ore grade. Consequently the net energy from 1 kg uranium as found in the earth's crust drops steeply with decreasing ore grade. This phenomenon is called the energy cliff. Beyond the energy cliff, corresponding with an ore grade of about 100-200 ppm uranium, a uranium resource cannot be a net energy resource anymore, but becomes a net energy sink.

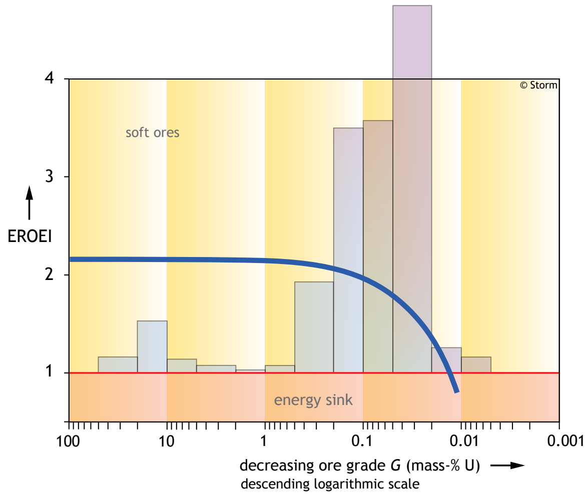


Figure 4

The energy cliff. EROEI of the nuclear energy system as function of the uranium ore grade. Note the descending logarithmic scale on the horizontal axis. For explanation see text. At uranium ore grades below 1% U (10 kg uranium per ton rock) the EROEI of nuclear power starts declining at an increasing rate and becomes zero at grades between 100 and 200 ppm. The bar diagram in the background represents the grade distribution of the world known uranium resources. The energy cliff is not dependent of the operational lifetime of a nuclear power plant. Source: Storm 2012a.

The graphic of Figure 4 shows the energy return on energy investment (EROEI) as function of the uranium ore grade. In the background the grade distribution of the known world uranium resources is represented by the bar diagram. This bar diagram shows a common geologic phenomenon: more uranium resources exist in the earth's crust as the ore grade is lower. This holds true for all metals. Below 200 ppm U (0.02% or 200 grams U per ton ore) practically no resources are listed in the official statistics of the nuclear industry. This is because at that low grades recovery is not economic anymore. A uranium-bearing rock is called an 'ore' only if recovery of uranium from that rock can be accomplished in an economically profitable way. From a geologic viewpoint there are large amounts of uranium at lower grades in the earth's crust, but those amounts are not called 'resources'. The ores of Kvanefjeld/Kuannersuit turn out to be near the bottom of the energy cliff.

CO_2 trap

As pointed out above, the nuclear process chain emits substantial amounts of CO2. Under the current conditions some 130 grams CO2 per kWh, assumed that all electricity consumed in the process chain is generated by the nuclear power plant itself.

Higher energy consumption per kg extracted uranium means higher consumption of fossil fuels and consequently to a higher specific CO2 emission (grams CO2 per kWh). Due to the exponentially rising energy consumption with declining ore grade, the specific CO2 emission of nuclear power will rise sharply and surpass that of gas-fired power stations within the lifetime of new nuclear build.

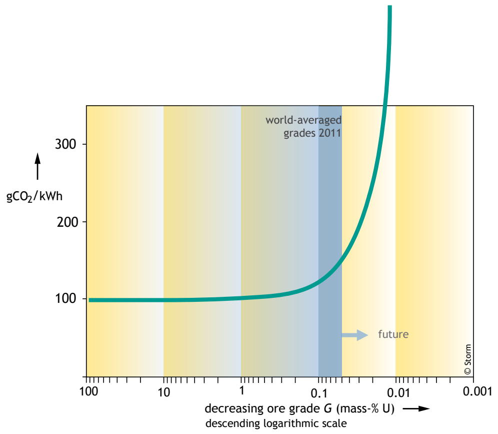


Figure 5

CO2 trap. CO2 emission of the nuclear energy system as function of the uranium ore grade. At present the world-averaged ore grade is 0.1-0.05% U (1000-500 grams U per ton rock). The average ore grade is declining because the richest ores are mined first and no new rich ore resources are found. Source: Storm 2012a.

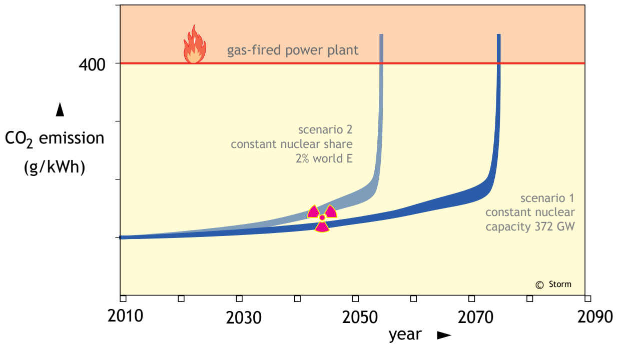


Figure 6

The CO_2 trap: the nuclear CO_2 emission over time. The specific CO_2 emission of nuclear power rises with time due to decreasing quality of the available uranium ores. Within the lifetime of new nuclear build the specific CO_2 emission surpasses that of fossil-fuelled electricity generation. The colored bands represent the uncertainty ranges regarding ore quality. Source: Storm 2012a.

Conclusion

Nuclear power provides a tiny and declining contribution to the world energy supply and is approaching the energy cliff and the CO2 trap. For these reasons nuclear power is an outdated means to generate useful

energy and we do not need it,
- not for climate control
- not for energy security
- not for geopolitical stability.

3 Mining flowsheet

Uranium recovery from ore

The recovery of uranium and the other metals from ore is done in a chain of physical and chemical separation processes. The general outline of this process chain (flowsheet) is as follows.

- After removing the overburden of the ore deposit as waste rock, the ore is mined. This is done by large excavators after blasting the rock with dynamite. The ore chunks are transported by large dump trucks to the next phase.
- Before transporting the ore to the mill, the ore is scanned by radiation counters. At a uranium grade below a given value, the cut-off grade, the ore is discarded and stored in a separate waste rock dump. The lowest cut-off grade GME mentiones is 127 ppm uranium.
- Then the remaining ore rock is crushed and milled into fine grains and mixed with water and chemicals.
- The next phase is the beneficiation: in a physical separation process (flotation) the heavy ore grains are separated from the lighter host rock grains. The ore fraction is transported to the refinery for the following phases.
- In the first phase of the refinery, the leaching phase, the ore grains are dissolved by means of a mixture of chemicals into a solution containing many different metal compounds.
- From the resulting solution, called the pregnant liquor, uranium is extracted by chemical separation processes.
- The remaining solution goes through a number of other chemical separation processes to extract the REEs and other metals.
- In the last phases the extracted metals are purified, by means of additional separation processes.

The processes of the flowsheet will not be discussed here in detail.

Waste streams

In each separation process a waste stream is generated, inevitably containing a fraction of the desired metals. From the fundamental laws of nature follows that a separation process never goes to completion. In a separation process the mixture is separated into two fractions:

Fraction 1 is enriched in the desired metal(s), but contaminated with unwanted chemical species.

Fraction 2 contains most of the unwanted species and also a small fraction of the desired species. This fraction is the waste stream of the separation process.

Usually the waste streams of the various separation processes after the milling and leaching are mixed into one waste stream called the mill tailings and are discarded in the mill tailings pond. The tailings of a mine at Kvanefjeld/Kuannersuit would be dumped in two separate storage facilities (see Chapter 7). The tailings consist of a slurry of mineral powder, chemicals and water, and contains an assortment of dissolved metals from the processed ore.

Uranium recovery factor

From the fundamental laws of nature follows that any separation is less complete as the content of the desired species in the mixture is lower and the mixture contains more different species.

The uranium content of the ores at Kvanefjeld/Kuannersuit is low and the minerals have a complex chemical composition, containing many different metals, so the separation losses would be high and consequently the recovery factor would be low. As pointed out in Chapter 1, a uranium recovery factor of 40% or less might be expected.

The consumption of energy and chemicals per kilogram recovered uranium would be high, the more so because the uranium-containing minerals at Kvanefjeld/Kuannersuit are difficult to bring into solution. Because uranium would be a byproduct at Kvanefjeld/Kuannersuit, only a part of the input of energy and chemicals of the mine could be attributed to the production of uranium.

Health effects of REEs

Although this report focuses on the radioactive contents of the ores at Kvanefjeld/Kuannersuit, other pollutants might be also important (Risø 1990). A report of the US Environmental Protection Agency (EPA 2012) mentions several primary pollutants of concern, associated with REE mining, such as radiologicals, metals, mine drainage (acid, alkaline or neutral), organics, dust and associated pollutants. The report discusses documented human health and ecological effects from exposure to REE. Two quotes from the Key Findings:

> "The most significant environmental impact from contaminant sources associated with hardrock mining is to surface water and ground water quality. However, documented impacts also have occurred to sediments, soils, and air. Mining for rare earth mineral ores and processing those ores into the final products can be compared to other hardrock metal mining and processing operations, and similar environmental impacts and risks would be expected.
> The specific health effects of elevated concentrations of REEs in the environment from mining and processing REE-containing ores are not well understood. From the limited literature review, it appears that most available epidemiological data are for mixtures of REEs rather than individual elements. These data indicate that pulmonary toxicity of REEs in humans may be a concern."

4 Radioactive elements in the mining waste

Thorium resources

Only a few times in its publications GME mentions the presence of thorium in the ore minerals. In its Prefeasibility Report (GME 2012) GME presents a table 'Significant Ore Minerals' and the commodities they contain: uranium, REEs, tin, niobium, beryllium and zinc. However, all mentioned uranium-bearing minerals contain also thorium. In addition two minerals that are not classified by GME as uranium ores also contain thorium, for example monazite.

According to a report of Risø National Laboratory (Risø 1966) the mineral steenstrupine, the main ore mineral of Kvanefjeld/Kuannersuit, contains thorium at a grade ten times the uranium grade (2-7% resp. 0.2-0.7%). According to the IAEA (Red Book 2011) a preliminary estimate of the thorium resources *in situ* comes at 86 000 – 93 000 tons thorium, but it could be some 400 000 tons. These are rough estimates, because the thorium resources are not systematically investigated like the uranium resources, at least such investigations have not been published at this moment.

Thorium is not a commodity

Thorium has virtually no industrial applications. The nuclear industry claims it would be possible to develop a thorium-based nuclear energy system, with an almost limitless energy potential. However, thorium is not fissile, like uranium-235, but has to be converted into uranium-233 in a very complex breeder system. Based on a fundamental law of nature (Second Law of thermodynamics) it can be proved that such a system can only exist in cyberspace and is practically unfeasible (Storm 2012c).

Although thorium is basicly not a commodity, like uranium, its presence in the ore is important for its radioactivity. The thorium in the processed ores would end up in the mining waste. In view of its high concentration in the main ore mineral steenstrupine, thorium is a reason of concern with regard to the safe handling of the mining waste.

Radioactive elements in the ore

Uranium and thorium are radioactive elements. What does that mean?

Firstly that means that these metals emit nuclear radiation.

Secondly it means that uranium and thorium atoms spontaneously decay into other atoms; this decay is coupled to the emission of radiation. The atoms resulting from the radioactive decay, called decay daughters or decay products, are also radioactive and so a series of other radioactive elements comes into being.

As a result of this phenomenon minerals containing uranium and thorium also contain a number of radioactive isotopes of various other elements, for example, radium, radon, radioactive lead and polonium. All these radionuclides are highly dangerous when inhaled or ingested. The mixture emits all kinds of nuclear radiation: alpha, beta and gamma radiation.

5 Health hazards of radioactive elements

Exposure to radioactivity

It makes a big difference if you are exposed to radiation from radioactive sources outside of your body or from radioactive atoms inside your body. Gamma radiation is very penetrating. Alpha and most beta radiation usually do not penetrate your skin. That is the reason why usually only gamma-emitting radioactive substances are measured to assess health risks posed by radioactive contamination. Besides, the commonly used radiation counters can only detect gamma radiation, not alpha and beta radiation.

However, alpha and beta emitters are highly dangerous inside the body. Especially alpha emitters inflict serious biological damage inside living cells, due to the high energy of the alpha rays. Alpha and beta emitting radionuclides can enter the body via inhalation of radioactive dust or via ingestion of dissolved radionuclides in food and drinking water.

Health effects of radioactivity

Damage to the biomolecules in living cells can cause a wide variety of diseases (IPPNW 2011), such as:

- cancers,
- lethal and non-lethal non-cancer diseases,
- premature senescence
- stillbirths
- genetic malformations
- inheritable diseases.

The latency period of these disease are long: often the diseases become observable only after years or even decades. A point is that most of diseases can be induced also by non-nuclear causes. So in most cases it is hardly possible to attribute a given disease contracted by a given individual unambiguously to radioactive contamination.

The International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO) deny that such diseases can be attributed to radioactive contamination. This viewpoint became clear after the nuclear disasters at Chernobyl and Fukushima (Chernobyl Forum 2006 & 2008, WHO 2005), despite opposite evidence from independent studies (Yablokov 2010, Paulitz 2012).

The relationship between adverse health effects and exposure to radioactivity can statisticaly be proved by epidemiological investigations, involving large numbers of people. This kind of studies remain undone by the IAEA and WHO. However, independent German (KiKK 2007) and French (Geocap 2012) studies proved a strong connection between the incidence of child cancer and the living distance from a normally operating nuclear power station. In those cases the exposure to radioactivity was very low compared to exposure in contaminated areas after Chernobyl and Fukushima. According to the standards of the IAEA the exposure doses in the vicinity of nuclear power plants are by far too low to cause any observable health effect.

Weak knowledge base on health effects of radioactivity

Very little is known on chronic exposure to a variety of radionuclides via the food chain and drinking water. Little is known on the biological behavior of radioactive substances inside the human body. Very little is known on the combined action of a number of different kinds of radionuclides together in the body.

Empirical evidence proves young childern and women to be more sensitive to radiadion than men and foetuses to be exceedingly radiosensitive. Essential knowledge with regard to radiation risks for embryos and fetuses is absent (Fairlie 2009).

Bioaccumulation

A number of the radioactive pollutants tend to cumulate in seaweed, crustaceans and shellfish and other organisms. In this way those radionuclides will enter the food chain at high concentrations. Little is understood about this phenomenon, which is poorly investigated. There are reports of crustaceans caught near the coast of Norway that contained so much heavy radionuclides that consumption had to be discouraged. These radionuclides originated from the reprocessing plants in La Hague in France and/or Sellafield in the UK.

6 Entanglement of interests

Dominance of the IAEA

The International Atomic Energy Agency is an organisation that seeks to promote the peaceful use of nuclear energy, and to inhibit its use for any military purpose, including nuclear weapons. The IAEA was established as an autonomous organization on 29 July 1957. Established independently of the United Nations through its own international treaty, the IAEA Statute (http://www.iaea.org/About/statute.html), the IAEA reports to both the UN General Assembly and Security Council; its total Membership counts 159 states (http://www.iaea.org/About/Policy/MemberStates/). Official publications of the IAEA have to be approved by all member states of the IAEA. The globally authoritative status on nuclear matters of the IAEA follows from above mentioned facts.

The IAEA is often called the 'nuclear watchdog', due to the frequent publicity regarding surveillance and inspections of nuclear installations in less stable countries which could be used for the production of nuclear weapons. IAEA's promotional activities are much less visible in the media..

It is a misconception to regard the IAEA as an independent scientific institute, for two reasons:

- the IAEA, has the promotion of nuclear power in its mission statement,
- its official publications have to be approved by all member states of the IAEA.

It is a task of politicians to be aware of these promotional and political features and to be prepared for biased or incomplete information from the IAEA.

Information on nuclear matters to the public and politicians originates almost exclusively from institutions with vested interests in nuclear power, such as: IAEA, World Nuclear Association (WNA, the official representative of the Western nuclear industry), Nuclear Energy Institute (NEI) in the US. The views of the Nuclear Energy Agency (OECD-NEA) rely heavily on the IAEA and the WNA. The IAEA plays a dominant role in the statements of the nuclear world concerning nuclear security and health effects of dispersion of radioactive materials into the human environment.

ICRP

The International Commission on Radiological Protection is an advisory body providing recommendations and guidance on radiation protection. It was founded by the International Society of Radiology (ISR) in 1928 and was restructured and given its present name in 1950. The ICRP has more than 200 volunteer members from about 30 countries.

The International System of Radiological Protection that is used across Europe and worldwide is based on the recommendations of the ICRP and the International Commission on Radiation Units and Measurements (ICRU), according to SCENIHR 2012. These recommendations are based on three fundamental, essentially economic, principles:

- justification
- optimisation
- dose limitation.

The main task of the ICRP seems to be the formulation of a legal framework for authorities and politicians how to cope with financial liabilities which may arise by exposure of people to radiation and/or radioactive materials (see ICRP 103 2007 and ICRP 111 2009).

UNSCEAR

The United Nations Scientific Committee on the Effects of Atomic Radiation has been established 3 December 1955. The United Nations General Assembly has designated 27 States as members of the Scientific Committee. The mandate can be read in UNSCEAR 2010 Report. The work of UNSCEAR seems to be focused on exposure to external radiation chiefly from natural sources.

There are reports on the strong connections between the IAEA and UNSCEAR and ICRP (Bertell 2002).

Dependent position of the WHO

How independent are the reports on the consequences of radioactive contamination for the local inhabitants, for example after the disasters of Chernobyl and Fukushima?

According to an agreement between the International Atomic Energy Agency and the World Health Organization (UN Res. WHA12-40, 28 May 1959) the WHO cannot operate independently of the IAEA on nuclear matters, see also the preface of the report WHO 2013a. The WHO reports on the health effects of Chernobyl and Fukushima do not deviate from the IAEA reports on that issue.

Reliance on models

The IAEA and WHO assess the health hazards posed by radioactive materials by means of radiological models. These mathematical models are based on studies from the 1940s and 1950s and have inherent imperfections and large uncertainties (CERRIE 2004). The reliance on the official models is so strong that observed health effects that are in conflict with the models are principally and without proof attributed to non-nuclear causes, for example radiophobia or other mental disorders (see for example WHO 2005).

The radiological models can easily be adapted to the economic needs in a given region at a given condition in accordance with the recommendations of the ICRP.

7 Environment and uranium mining

If the Kvanefjeld deposits would be mined, the mill tailings would be radioactive in any case, wether uranium is recovered or not. So at issue is not: can uranium safely be mined? At issue Is how safe is the mining of the Kvanefjeld deposits at all? In addition to the radioactive elements the mill tailings contain also an assortment of non-radioactive toxic elements from the ores, such as fluoride and a number of heavy metals, plus the chemicals added in the recovery processes. All these aspects should be thouroughly investigated before a mining license is to be granted.
To give some insight in the environmental implications uranium mining can have, a schematic outline of the activities from discovery of the ore deposits through rehabilitation of the mining site is discussed below.

Pristine situation

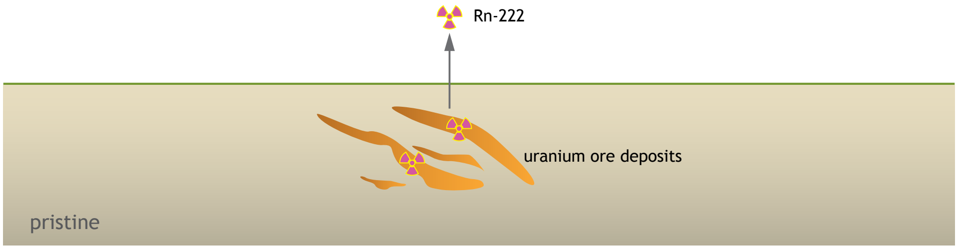


Figure 7
Schematic presentation of uranium ore bodies in the ground. Generally uranium ores are geologically very old formations. There are also rocks containing uranium at concentrations too low to be exploited as uranium ore. Granite for example contains generally about 4-8 ppm uranium, but some kinds of granite may contain higher levels of uranium.

The many radioactive elements present in the ores, uranium, thorium and their decay products, are chemically tightly bound in the minerals in the rock. Usually the ore bodies are covered by thick layers of soil and rock with a composition different from the uranium-bearing rock. Such ore bodies can be discovered at the surface by measurement of the radioactive noble gas radon, which diffuses through the rock and soil and emits easily detectable gamma radiation. If the uranium-bearing rock outcrops, weathering of the insoluble minerals at the surface will set free tiny amounts of the radioactive elements, generally as insoluble compounds. This is not to say this phenomenon is harmless to inhabitants, on the contrary. Areas with uranium-bearing minerals in the ground are not the best places to live, as indigenous people in Australia and the USA can tell you.

Mining and milling

In the mining and milling processes the ore minerals containing the desired metals are brought into solution (leaching). In case of Kvanefjeld/Kuannersuit that are the minerals containing rare earth elements *and* the radioactive elements. If uranium is not recovered all radioactive elements are discarded as waste in the mill tailings, which are as a consequence radioactive. If uranium is recovered from the pregnant liquor, still a major fraction of it would remain in the mill tailings, due to the incomplete separation. The mill tailings would be hardly less radioactive, because the recovered fraction of uranium would represent only a tiny fraction of the radioactivity in the minerals.

In the mill tailings the radioactive elements are in a water-soluble form and could easily enter the biosphere, the food chain, drinking water and the seawater near the coast of Greenland. Spills, leaks and seepages of the radioactive solution inevitably will occur during the lifetime of the mine. No chemical plant is perfect. For

that reason we can be sure that radioactive materials will enter the food chain and drinking water.
A worst case scenario is the break of the dam enclosing the mill tailings, see below. Such events actually did occur at some uranium mines in the past. In case of a mine at Kvanefjeld/Kuannersuit that would have disastrous consequences, because the mill tailings would be located uphill and very near inhabitated areas.

If the mill tailings turn dry, radioactive dust will be blown by the wind over very long distances. A serious health hazard associated with this dust is lung cancer due to inhaling uranium, thorium and their decay products.
Studies have shown (EPA 2012) that inhaling or ingesting thorium causes an increased risk of developing lung cancer and cancer of the pancreas. Bone cancer risk is also increased because thorium may be stored in the bones.
The only volatile radioactive element is radon. This noble gas will escape into the air anyway and cannot be retained in the mill tailings.
The mining operations will generate large amounts of dust. A Risø study (Risø 1990) estimates some 1000 tons of dust per year might be released into the air, if no suppression actions are taken. Another point of concern might be the large volumes of water seeping from the mining pit.

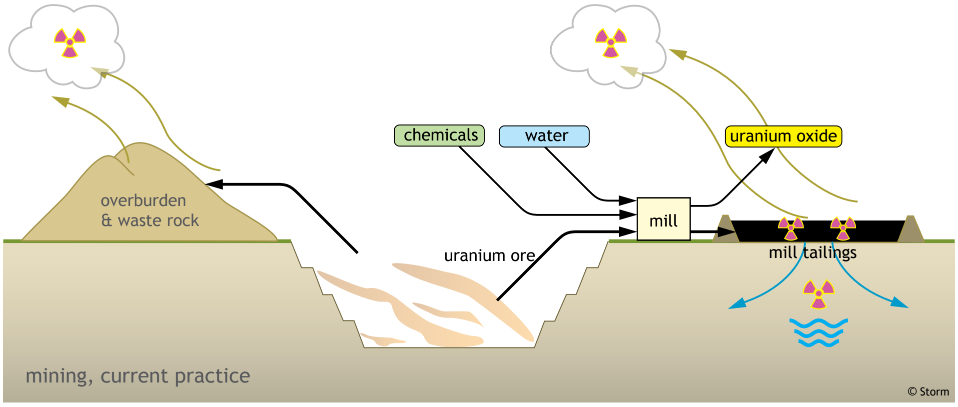


Figure 8
Generic outline of uranium mining activities. The overburden and waste rock is removed and the uranium ore is transported to the mill. The mill consumes large volumes of fresh water and chemicals. After extraction of the uranium from the ore the remaining mass, mixed with water and chemicals is stored in a mill tailings pond, sometimes also called a mill tailings dam. The radionuclides are in a chemically soluble form and will migrate into the groundwater. If the tailings turn dry, dust containing radioactive elements will be blown over long distances. Radioactive dust is also released by the mining operations. Source: Storm 2012a & 2012b.

mine rehabilitation

What happens with the mill tailings if a uranium mine is abandoned, for example after depletion of the ores? Few, if any, uranium mines in the world have been rehabilitated. Common practice is that when the last kilogram of uranium leaves the mine, the lights are turned off and the gate is closed. In some cases the mill tailings may have been covered by a layer of soil.

The first phase to minimize the hazards posed by the mill tailings would be chemical immobilisation of the radioactive and other toxic elements as soon as possible after the waste leaves the refinery. The seond phase would be the isolation of the immobilised elements from the biosphere in the most effective way.
Chemical immobilisation can be achieved by fixing the radioactive and other toxic elements into insoluble compounds by adding appropiate chemicals. This conversion should not be done after years storage of the mill tailings in a pond, because in the meantime large amounts of the unwanted elements could enter the

groundwater table and the coastal sea.
Isolation of the immobilised wastes might be done by storing them between thick layers of bentonite in the mining pit and cover them with the non-radioactive waste rock removed during mining. Bentonite is a special clay mineral which can form a practically impermeable barrier to the migration of dissolved chemical species. The contamination of the groundwater is irreversible

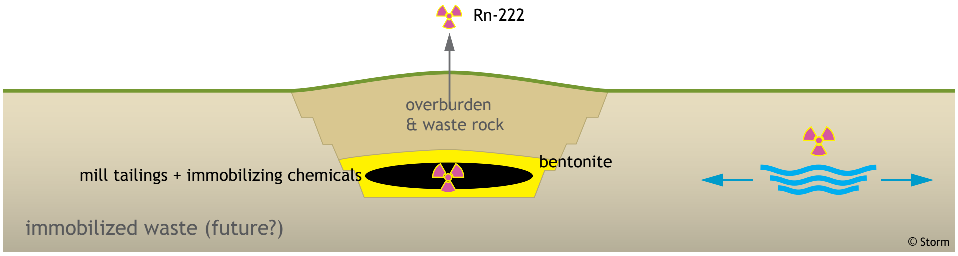


Figure 9
Generic outline of a rehabilitated uranium mine.in a flat region. The situation at Kvanefjeld/Kuannersuit would be different, because the mine is located at the top of a mountain.

Risø study

During the early 1980s the Risø National Laboratory performed studies (Risø 1990) on the environmental impact of uranium mining at Kvanefjeld. At that time only uranium recovery from the Kvanefjeld/Kuannersuit ore deposit was addressed. Recovery of rare earth elements (REEs) was not considered, likely because at that time these elements were little more than a chemical curiosity without important commercial applications. According to the report the mineable uranium resource at Kvanefjeld is 56 million tons ore at a mill feed grade of 365 ppm U, containing about 20500 tons uranium. It is not clear which fraction of this amount Risø expected to be recoverable.

Risø investigated alkaline leaching under pressure and at elevated temperatures of the main ore mineral of Kvanefjeld/Kuannersuit, steenstrupine. By this method uranium is preferentially dissolved and can be extracted. Thorium and the REEs remain largely insoluble and would be discarded in the tailings. It is not clear what would happen with the other radioactive elements in the ore.
Pollution of the rivers in the Narsaq area by a number of non-radioactive elements, particularly fluoride, were seen seen as a major problem.
The radioactive elements were found to have a higher mobility in the tailings than in the ore. The investigators suggested to make radium insoluble by adding chemicals to the tailings slurry and to cover the tailings with water to retard the emanation of radon.
Risø concluded that there is great lack of knowledge on several items essential for the environmental assessment. The technical design of the mine should be adjusted to the environmental requirements.

Intended GME flowsheet

GME switched to another processing chain than Risø investigated, in view of recovering uranium as well as REEs. After crushing and milling the ground ore mass is separated by means of flotation processes into a small fraction enriched in ore minerals and a large fraction depleted in ore minerals, as pointed out in Chapter 3. This is called the concentrator or beneficiation step. The large fraction is storaged in Residue Storage Facility 1 (RSF1). For more details see GME 2012.

After the concentrator step the mineral grains in the enriched fraction are transported to the refinery and leached by sulphuric acid at atmospheric pressure and 95°C. From the resulting solution (pregnant liquor) uranium and the REEs are extracted by various means. The waste streams of the separation processes in the refinery are pumped to RSF2.

GME considers Lake Taseq as the most favourable location of RSF1. Being a natural, impermeable basin it requires the least volume of rockfill to form a suitable embankment, and it has the capacity to contain the concentrator flotation residue for the life of mine. As the residues from the concentrator contain lower levels of radionuclides than that found naturally in the Kvanefjeld, and as the ore has not been chemically processed at this stage it is considered suitable for storing in Taseq. The residue will be covered by water hence radon emissions will be safely managed, according to GME.

Figure 10

Residue Storage Facility (RSF) options considered by GME. Site option A, Taseq was identified as the most favourable option for the permanent storage of concentrator flotation residues, RSF1. Option D, the natural basin east of the Nakalak range, has been chosen as the preferred location for RSF2. This location allows RSF2 to be located alongside the proposed processing plant/refinery and at a similar elevation. Source: GME 2012.

The natural basin east of the Nakalak range has been chosen as the preferred location for RSF2. The refinery will produce a residue slurry with 22% w/w solids content suitable for pumping to RSF2. Due to the nature of the refinery residue, allowance has been made to fully line RSF2 so as to create an impermeable barrier. The initial embankment height for RSF2 will be in the order of 20m with subsequent lifts of between 1m and 5m. The final embankment height is expected to be in the order of 62m (GME 2012).

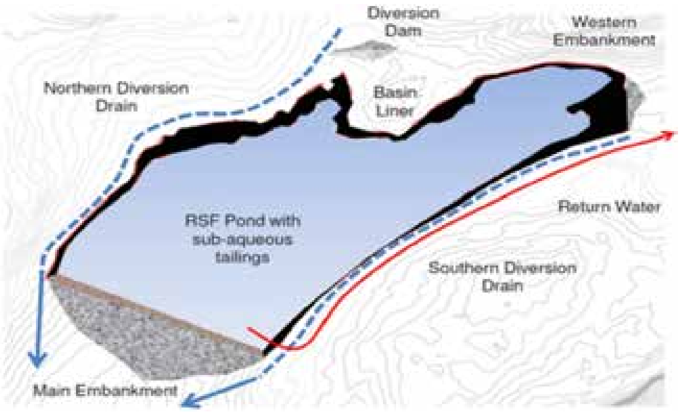


Figure 11

Residue Storage Facility RSF2 for the chemically treated mill tailings. Source: GME 2012

RSF1

The volumes of the concentrator tailings, to be stored in RSF1 (Taseq) would be huge. During the operational lifetime of the mine (about 60 years) 956 million tons ore are to be mined and processed, based on the presently known resources. If the beneficiation would work as advertised, 91,5% of the mined mass would be discarded in RSF1, or some 875 million tons. Assumed the slurry from the concentrator would have a density of about 2 ton/m^3, the volume would be about 440 million m^3. By draining the water the volume would decrease substantially. The valley of Taseq has to be blocked off by a large embankment to accomodate this amount, as actually indicated in Figure 10. The lake would effectively be displaced by the mud from the concentrator.

The tailings in Taseq would be less radioactive than the original rocks, because the majority of the minerals containing radioactive elements are separated from it. GME seems to suggests that these tailings are harmless for that reason. However the tailings would contain large amounts of various, undisclosed chemicals, which are needed in the flotation processes of the concentrator, for example barium chloride and various organics. A number of those chemicals may be toxic. Seepages and spills from RSF1 would be unavoidable, so it is important to know which chemicals would enter the groundwater and rivers of the Narsaq valley and at which rate during operation of the mine and the centuries thereafter,

Another point of concern might be the physical behavior and consistency of the tailings through the years. Would the slurry settle to a compact clay-like mass or would it remain a semi-liquid mud? What consequences could be expected from freezing and thawing during the winters and summers, year after year, decade after decade, century after century?

What could happen if the tailings turn dry and the wind is blowing the dust over long distances?

A worst case scenario is a major failure of the embankment. Would that mean that millions of cubic meters of a toxic mud would come down the slopes into the Narsaq valley?

RSF2

The volume of the tailings from the refinery would be counted in tens of millions of cubic meters and stored in RSF2. Contrary to the tailings stored in RSF1, the tailings in RSF2 are radioactive: about ten times as high as the ore rocks. Moreover the radionuclides and many other non-radioactive toxic elements from the ore minerals (see Risø 1990) are in a soluble form and consequently very mobile.

The problems and unknowns concerning RSF1 addressed above, apply just as much to RSF2, exacerbated by the high mobility of the radioactive and non-radioactive toxic species. Evidently it is important to know which chemicals would enter the groundwater of the Nakalak region and the fjords and at which rate during operation of the mine and the centuries thereafter,

According to GME allowance has been made to fully line RSF2 so as to create an impermeable barrier. How impermeable and for how long? By what means intends GME to create such a barrier?
For how long a period the tailings could be safely stored at RSF2?
How safe are the mill tailings during the winter, with snow, ice and very low temperatures, repeated freezing-thawing cycles?
The final embankment height of RSF2 is expected to be some 62 meters. Obviously the integrity of an embankment of that height will not last forever. What consequences could a major failure of the embankment have? Radioactive contamination is irreversible

GME intends to keep the option open for reprocessing the residues in RSF1 and RSF2 in the future (GME 2012):

> "It is important to note that the residues generated from both the Concentrator and the Refinery still contain elements that may have a significant commercial value in the future. Both Residue Storage Facilities have been designed to safely store the residues and whilst long term closure plans have been provided for in the design and cost estimates there may be potential to recover the residues for further processing at a later stage. The options chosen for the location of RSF1 and RSF2, whilst preferred, are not the only options available for the Project and further investigations and design work is planned for in the next phase of studies."

This statement implies that any kind of permanent disposal of the tailings, such as schematically described in the previous section, is no option. The high financial cost of a permanent isolation of radioactive mining waste might be a strong argument to keep other options open.

Mining: some questions

As far as known the mine at Kvanefjeld/Kuannersuit would be the first uranium mining pit on top of a mountain, a geologic situation different from any other uranium mine. What environmental and operational consequences could be expected?
Mining water and spills from the processing of the ore would run off the slopes and would reach inhabitated areas within a very short time. Leakages and spills will occur, technical failures during decades of operation are unavoidable. Dust from the mining pit could reach inhabitated areas within minutes.
The Kvanefjeld plateau would be mined as an open pit mine, but it is not clear how GME thinks to mine Zone 2 (Sørensen) and Zone 3: also as open pit, or by underground mining?

What consequences would the artic climate have for the operation of the uranium mine?
Could the mining activities continue during the winter?
Would it be possible to avoid radioactive dust generation during mining at temperatures far below the freezing point?
What are the consequences of freezing temperatures for the handling of the very large volumes of liquid wastes, which are ten times more radioactive than the ore?
To keep all machines, equipment and separation plant running during severe cold periods, large amounts of energy would be needed, likely to be supplied as diesel oil. Even if the plant is shut down during winter, significant amounts of energy would be needed to prevent freezing of vulnerable equipment.

IAEA's viewpoint on uranium mine rehabilitation

A recent report (IAEA-1630 2014) the IAEA discusses what is called 'environmental remediation' of uranium mining and processing sites. Remarkable are the following quotes from the Summary:

> "Many of these sites throughout the world have become orphaned, and are waiting for remediation. The publication notes that little progress has been made in the management of some of these sites, particularly in the understanding of associated environmental and health risks, and the ability to apply prediction to future environmental and health standards."
>
> "It is noted that remediation objectives will ideally be defined a priori, i.e. before the design of any technical solution, and it is crucial to recognize that remediation activities are not just determined by radiological or health risks. In many cases, other factors will prevail in the definition of the adopted strategy, and public perception will always be a key driver."

The term 'orphaned' in the first quote is an euphemism for 'abandoned'. As far as known no uranium mining and processing site in the world has ever been rehabilitated in an acceptable way.

The second quote indicates that the IAEA considers health effects of radioactive residues from uranium mining to be of minor importance. Remediation strategy will be determined by economic factors and public perception, However, because the great majority of the currently operating uranium mines in the world are located in uninhabitated or sparsely inhabitated regions, the factor 'public perception' will generally not carry much weight. Another interpretation of the statement on 'public perception' fits in with the opinion of the IAEA that observed health effects in areas contaminated with radioactive materials, for example after the disaster at Chernobyl and Fukushima, cannot be attributed to radioactivity but have mental causes, as pointed out in Chapter 6.

So economic factors remain as driver.

The report discusses a number of recommendations for activities that could be done or should be done, dependent on the local conditions, but no examples of what has been achieved in practice.

The term 'remediation' in itself is noncommittal and is open to many interpretations. .

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