Mining at Kvanefjeld

Source: Google Maps

Comments on:

Kvanefjeld Project. Environmental Impact Assessment,

Greenland Mineral and Energy Limited
Draft, October 2015, prepared by Orbicon A/S

by

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In the Ilimmaasaq geologic complex near Narsaq in the south of Greenland three ore deposits are identified, Kvanefjeld (Kuannersuit), Zone 2 (Sørensen) and Zone 3, with a joint mass of 1.01 billion metric tonnes of ore (as of June 2016), containing rare earth elements (REEs), zinc, tin, niobium, beryllium, fluorspar and the radioactive metals uranium and thorium.
The current license holder Greenland Minerals and Energy Ltd (GME) intents to apply for a mining license for recovery of the REEs, zinc and uranium, and asked Orbicon A/S to compile the Kvanefjeld Project Environmental Impact Assessment (EIA). The intended mine lies on top of a mountain a few kilometers uphill of an inhabited area, the Narsaq valley.
This report focuses on the presence of radioactive elements in the ores GME intents to exploit within the framework of its Kvanefjeld Project and assesses some environmental aspects and health hazards resulting from the mining activities as laid out by GME in the EIA draft report. Economic aspects are not addressed.

Prospects of uranium and thorium

Identified uranium resources
According to the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) the total amount of recoverable uranium is estimated at 221 000 tonnes at an average ore grade of 231 ppm U (gram U per tonne ore). Recent publications from Greenland Minerals and Energy Ltd (GME) point to slightly different figures: 228 000 tonnes of uranium at an average grade of 226 ppm U.
GME does not discuss the presence of thorium in the ores of the Kvanefjeld Project. Recent investigations estimated the typical thorium/uranium ratio in the host rock of the ore minerals at 2-3; this would mean an in situ resource of roughly 450 000 - 700 000 tonnes of thorium. Steenstrupine, the main ore mineral, contains about ten times as much thorium as uranium (2-7% respectively 0.2-0.7%).
The IAEA/NEA places the uranium resources of the Kvanefjeld project in the highest listed cost category of up to 260 USD/kg uranium; the current market price is some 50 USD/kg U. In view of the declining trend of the world nuclear capacity and the consequently declining uranium demand (in 2015 about 62 000 tonnes/year), it seems doubtful wether the price would rise to 260 USD/kg U or more in the foreseeable future, a price needed to make the uranium recovery profitable.

Energy cliff.
A thermodynamic analysis of the recovery of uranium from the earth‘s crust and subsequently its use as nuclear fuel proves that below a grade of some 200-100 gram uranium per tonne rock no net energy production from that ore is possible, this limit is called the *energy cliff.* The relationship between net energy production by nuclear power stations and ore grade is explained in Annex A. The quality of the uranium ores at the Kvanefjeld is very near the energy cliff, due to the low grade and the mineralogy of the ore.

Breeder systems and thorium reactors
Breeder reactor systems, that are said to fission 50-100 times more nuclei per kilogram uranium than the present reactors, are inherently unfeasible as follows from the Second Law of thermodynamics.
Thorium never can become a net energy source, as is proved by a thermodynamic analysis of the nuclear reactor systems that would be required.

Scope of the Kvanefjeld Project

From the EIA draft report follows that GME intends to mine ore only from the Kvanefjeld deposit. During a life span of 37 years the mine would process a total of 111 million tonnes of ore, slightly more than one tenth of the recoverable amount of 1.01 billion tonnes of ore reported to be present in the three deposits at the Ilimmaasaq complex and 16.5% of the Kvanefjeld deposit of 673 million tonnes of ore.
Orbicon does not make clear why only a minor part of the Kvanefjeld deposit would be mined nor wether GME considers exploitation in the future of the whole Kvanefjeld deposit and of the deposits of Zone 2 and Zone 3.

Layout of the mining facilities

Sequence of the mining processes
Mining of the Ilimmaasaq ores as proposed by GME involves the following steps:

- Removal of the overburden and waste rock to reach the ore bodies, by blasting with explosives, excavation and transport by dump trucks to the waste rock dump site.
- Mining of the ore in the same way and transport it to the mill where the rocks are crushed and ground into a fine powder, mixed with water; the resulting slurry is transported to the concentrator.
- In the concentrator the slurry is separated by means of flotation processes (sorting the mineral grains according to their specific density) into four fractions:
  - zinc sulphide, is exported abroad
  - fluorspar, is exported abroad
  - heavy minerals containing the REEs, uranium, thorium and other metals, this fraction comprises some 10% of the ore mass entering the concentrator; it is transported to the refinery
  - tailings, a slurry containing some 90% of the processed ore mass, the waste stream of the flotation separation processes is transported to the Flotation Tailings Storage Facility (FTSF)
- By means of a sequence of chemical separation processes in the refinery the slurry of heavy minerals is separated into four fractions:
  - uranium oxide, is exported abroad
  - light REE oxides, is exported abroad
  - mixed critical REE oxides, is exported abroad
  - chemical tailings, the waste stream of the chemical separation processes is transported to the Chemical Residue Storage Facility (CRSF).

Physical and chemical separation processes never go to completion, as follows from the Second Law of thermodynamics. As a result the flotation tailings still contain low concentrations of the desirable minerals, and the same holds true for the chemical tailings of the refinery. Nearly all undesirable heavy elements, such as thorium, end up in the chemical tailings or in the waste water discharged into Nordre Sermilik..

Mine products
The design production from the mined ore - REE oxides and -hydroxides, zinc sulphide and uranium oxide - is 38 057 tonnes per year, corresponding with 1.41 million tonnes during the operational life of the mine, including 557 tonnes per year of uranium oxide (= 472 tonnes uranium), respectively 20 609 tonnes (during mine lifetime) of uranium oxide (= 17 476 tonnes U). The present world uranium demand is about 62 000 tonnes uranium per year, but the demand is steadily declining.
In addition the mine produces fluorspar (16 2000 tonnes/year) and sodium hypochlorite (17 000 tonnes a year), reaction products from the ore processing plants.

Fresh water consumption

The mine would consume 3.5 million cubic meters of fresh water per year, sourced from the Narsaq river. This corresponds with 92 m^3 water per tonne product from ore (38 057 tonnes), or 49 m^3 per tonne product, if all mine products are taken into account (71 257 tonnes)

Consumables

From the figures given in the EIA report the specific consumption of consumables per tonne product can be deduced. If all mine products (71 257 tonnes) are taken into account, these quantities would be:

diesel + heavy oil	0.790 m^3
general freight + spares	0.656 tonnes
chemicals + reagents	3.11 tonnes.

These materials have to be imported from abroad and transported to the mine.

Waste water

The process water would be partly recycled, it would be separated into a waste stream that is discharged into Nordre Sermilik and a purified stream reentering the processes. The make up of fresh water, about 3.5 million m^3/year, would correspond with the volume of waste water discharged into Nordre Sermilik. The waste water would contain a gamut of chemical species, such as radionuclides, non-radioactive toxic elements (e.g. beryllium, barium, arsenicum), chemicals used in the ore processing plants. The EIA draft report does not mention the presence of thorium plus its decay products. It seems unlikely that these radionuclides would be not present in the waste water, in view of its 3-10 times higher concentration in the mined ores.

A dilution factor in the order of 2000 would be required to obtain Predicted No Effect Concentration (PNEC) for the most critical parameters. This would mean that the discharges of waste water during one year would have be diluted into 7 km^3 of seawater in the Nordre Sermilik and into 260 km^3 of seawater during the operational lifetime of the mine (37 years).

This observation raises the question if accumulation of the species from the waste water into the sediments and bioaccumulation into living organisms would not occur and could become a problem in the future.

Water from the mining pit and drain water from the waste rock piles would run off into Nordre Sermilik.

Undisclosed chemicals

A number of questions remain to be answered concerning the chemicals used in the ore processing plants. Many of these chemicals are mentioned only by their commercial brand name, so an assessment of the potential environmental impact and health effects by an independent chemist is hardly possible.

In its studies during the 1980s the Risø National Laboratory concluded that there is great lack of knowledge on several items essential for the environmental assessment. It is not clear if the findings of the Risø studies are implemented in the EIA draft report.

Mining wastes

The mine would be situated on top of a mountain a few kilometers uphill of an inhabited area, the Narsaq valley. Obviously this location would have important implications with respect to the environmental impact and the health hazards posed by the mining activities. Discharges into the air or surface water could reach the inhabited areas adjacent to the Ilimmaasaq complex and the coastal sea within a very short time period.

Tailings
Another point of concern is formed by the mill tailings, the waste streams of the ore processing, consisting of a semi-liquid slurry of finely ground ore mixed with water and a large number of added chemicals and reaction products. The massive waste streams of the concentrator and refinery are stored in the Flotation Tailings Storage Facility (FTSF), respectively the Chemical Residue Storage Facility (CRSF). The flotation tailings comprise some 90% of the processed ore mass and has a lower concentration of radioactive materials than the original ore, the chemical tailings comprise the remaining 10% of the processed ore mass and have a concentration of radioactive materials much higher than the original ore.

According to the design described in the EIA report both tailings storage facilities would be located in the Taseq basin. In previous reports GME intended to locate the FTSF in lake Taseq and the CRSF in a natural basin east of the Nakalak range at the other side of the Ilimmaasaq complex. Orbicon did not explain in the EIA draft report for what reason the size of the CRSF in the EIA report is much smaller than in the previous designs of GME.
The capacity of lake Taseq is far too low to accomodate the huge volumes of mud to be stored: after a number of years of mine operation the volumes are to be measured in tens of millions of cubic meters. For that reason a dam with a final height of nearly 60 meters would be constructed in the upper part of theTaseq basin to accomodate the chemical tailings, and a second dam of 60 meters height in the lower part of the Taseq basin to accomodate the flotation tailings.

Choice of the FSFT and CRSF concepts
Storage of mining wastes (tailings) in large ponds with artificial embankments is applied at nearly all open pit and underground mines of the world. A reason for this concept may be a practical one: how do you store some 1.4 million m^3 of slurry per year (in case of the Kvanefjeld project) during many years of mining operation.
The reason to choose for the Taseq basin might be financial: it might be the least costly solution to store the massive volumes of the tailings. Another argument of GME is the wish to keep the option open for reprocessing the residues from the tailings storage facilites in the future, and consequently to keep the tailings retrievable.

Tailings storage capacity limits mine operation
A rough estimate of the storage capacity in the Taseq basin as described in the EIA draft report comes to a storage volume in the order of 30 million m^3. It seems hardly possible to enlarge that capacity in the mountainous area, because of the huge embankments that would be required, that are already high in the current design. The limited storage capacity may limit the scope of the mine to the designed 37 years and the mining of 111 million tonnes, about 16.5% of the ores present at the Kvanefjeld deposit and 11% of the total identified resources at the Ilimmaasaq complex. Mining of the full resources, 1010 million tonnes, would generate a tailings volume about ten times larger than in the current design. It might be difficult to design a tailings storage facility with a capacity of some 300-500 million m^3 in the mountainous area around the Kvanefjeld.

Predictable environmental impact
Obviously the presence of a toxic slurry on the slope of a mountain poses environmental risks. Seepage, leaks and spills of liquids form the tailings will cause contamination of groundwater and rivers by radioactive and non-radioactive toxic chemical species. If the tailings by some unforeseen cause (such as leakages, technical problems, or other) would turn dry massive amounts of radioactive dust would blown away over vast distances. Orbicon does not discuss in the EIA draft report the possible consequences for the condition of the tailings and embankments of repeated freezing-thawing cycles.

Safety of the tailings

Control of the storage of the enormous volumes of toxic slurry, growing to some 30-50 million m^3 at the end of the operational phase, in ponds confined by 60 meters high artificial embankments on the slope of a mountain can only be offered by engineered safety. Safety is determined by the quality of the human-made design, the quality of the construction materials and method, and the quality of the maintenance during the operational lifetime of the mine and during the centuries thereafter.

With respect to the design and safety of the FTSF and CRSF Orbicon and GME seem to implicitely assume that:

- the behaviour of the tailings and of the chemical species in the mud through the years would be perfectly predictable
- the embankments (dams) would keep their as-designed integrity during centuries, and would not be subject to spontaneous degradation processes (Second Law of thermodynamics), nor to unforeseen phenomena.

From a physical viewpoint these assumptions are unrealistic. The question may be not if the dams would ever fail, the question might be: when would the dams fail.

Tailings dam failures

A worst case scenario is a major failure of the embankment. That could mean that tens of millions of cubic meters of a toxic and radioactive mud would come down the slopes into the Narsaq valley. Unfortunately there are examples of such disasters.

On 5 November 2015 a tailings dam of the Germano iron mine near the town of Mariana in Minas Gerais (Brazil) (owner Samarco) failed, releasing 30-60 million cubic meters of mud, containing toxic substances like Hg, As, Cr, Mn, causing 19 casualties and devastating a large inhabited area down the Rio Doce valley, reaching the Altantic Ocean 500 km from the mine. Taseq would ultimately contain a similar amount of mud.

Isolation of the minining wastes

Summarised, the storage of the tailings in the FTSF and CRSF in the Taseq basin would generate health hazards due to unavoidable events and phenomena, even if the dams would behave as designed and human actions would function as advertised. In addtion to the gradual contamination of the environment would come the risk for a disastrous failure of one or both dams. This risk would grow with time due to the spontaneous and unavoidable degadation processes following from the Second Law, the more so after the final closure phase of the mine when inspections and maintenance might come to an end. In the long term the dams will fail.

In order to limit the enviromental contamination and the risks for catastrophic dam failures to a minimum, the tailings should be isolated from the environment as effectively and as soon as possible after closure of the mine.

Broadly this would imply two basic processes:

- chemical fixation of the radionuclides and of other toxic non-radioactive species to make them insoluble in water
- storage of the waste in a way that minimalises the chance that the radioactive and toxic substances reenter the human environment.

The best way to achieve these goals may be to transport the tailings back into the mine, between thick layers of bentonite, after adding fixation chemicals. Bentonite is a clay mineral that retards the migration of ions. The waste rock would be also transported back into the mining pit, on top of the tailings. In this way a mimicry could be achieved of the pristine situation of the ore deposit.

Isolation of the mill tailings and rehabilitation of the mine area are issues not addressed in publications of the nuclear industry.
Groundwater and soil may remain contaminated for very long time periods by radionuclides, toxic non-radioactive elements from the ore (e.g. arsenicum, mercury) and chemicals used in the milling processes.

Orbicon and GME may be aware of above described isolation concept from previous publications of the author of this report, for the EIA draft report mentions the option to move the tailings from the Taseq basin back into the mining pit at mine closure, without further details with respect of isolation. However, Orbicon and GME reject this option for various reasons, summarised:

- it would be too expensive,
- it would be practically not possible to resuspend the slurry with water and pump it back into the mining pit,
- it would would prevent future recovery of residues from the tailings such as zirconium, thorium, gallium and heavy REEs.

The third reason seems contradictory to the first and second arguments: if the tailings would be retrieved in the future for reprocessing, the mass has to be resuspended and pumped back to the processing facilities. Such an action appears to be practically possible indeed and apparently the cost would be not too high for reprocessing. Another question is why GME does not intend to recover the mentioned metals (zirconium, thorium, gallium) in the first round of the ore processing, together with the other commodities, the production costs in a future second round would be much higher due to the retrieval of the tailings.
It is a fallacy to think advanced technology would make reprocessing of the tailings attractive in the future. Extraction of metals and minerals from ore is not a matter of advanced technology, it is a matter of processes governed by the Second Law of thermodynamics, and consequently a matter of investments of energy and dedicated effort. A higher extraction efficiency can only be achieved by higher investments. No technology can circumvent this fundamental law of nature.

Summarised, the arguments put forward by GME/Orbicon do not sound very solid and the conclusion might be that there is just one dominant reason for rejecting the isolation of the tailings in the mining pit as decribed above: the cost.

Environmental and health aspects

Radioactive materials in the tailings
Roughly estimated the ores contain 20-25 Bq/g (becquerel per gram ore) of uranium plus its decay products, including highly toxic radionuclides such as polonium, lead and radium. The decay products all end up in the tailings, comprising the major part of the radioactivity.
Because the Ilimmaasaq ores contain also thorium, in concentrations 3-10 times higher than uranium, the radioactivity of the tailings would be 3-10 times higher than might be expected based on the presence of uranium alone.
Seepages and spills from the FTSF and CRSF would be unavoidable, not to speak about incidental overflows, so it is important to know which chemicals could enter the groundwater and rivers of the Narsaq valley and at which rate the escape into the environment could happen during operation of the mine and during the centuries thereafter, in the post-closure phase.

Regulations and standards
Regulations concerning allowed contamination of air, water, soil, food and drinking water are recommended by the IAEA, but each country is free to set its own regulations. Generally they are not coupled to quantified

standards, and in practice they prove to be easily adaptable to economic needs or other interests.

Orbicon in the EIA draft report does not make clear which figures of concentration of species in the waters of rivers, groundwater and coastal sea are based on measurements and experiments, and which are based on model calculations, for instance the figures of the dispersion of dust from the mining activities, from waste rock dump and from the tailings in the case they would dry up.

Pathways of contamination

During the intended mining activities massive amounts of rock and ore are mobilised, ultimately 111 million tonnes, plus about an equal amount of waste rock. Unavoidably a fraction of the elements present in these excavated rocks would be released into the human environment via dust, aerosols, gases, and liquid discharges. In addition to authorised discharges also unintentional but unavoidable discharges might be expected caused by leaks, spills, seepages, accidents. As a consequence in the course of years a vast area around the mine would become contaminated by radioactive and non-radioactive materials from the mine, many of which may be highly toxic. People living in the contaminated area would be chronically exposed to radioactive and other toxic species via drinking water, food and air. Seafood would become contaminated as well, due to the substantial discharges of wastes into the coastal sea. Bioaccumulation of radionuclides and non-radioactive chemicals in the food chain may become a serious problem.

Health effects of REEs

A report of the US Environmental Protection Agency from 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. One of the key findings is:

"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."

Health effects of exposure to radioactivity

The radioactive materials released into the environment during the mining and processing of the ores contain a number of radionuclides: uranium + its decay products and thorium + its decay products, a mix of alpha, beta and gamma emitters. Gamma radiation is highy penetrating. The commonly used radiation counters can only detect gamma radiation, not alpha and beta radiation. Alpha radiation and most beta radiation do not penetrate the skin, and for that reason these kinds of radiation are classified as less hazardous in the radiological models used in the nuclear industry, that are based on radiation from sources outside the body. 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. On top of the intensive interaction of alpha and beta radiation with living matter come the biological properties of these radionuclides, such as accumulation in specific organs or tissues and incorporation in biomolecules.

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.

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

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

- inheritable diseases.

The latency periods of most of these diseases are long: often the radiogenetic diseases become observable only after years or even decades (e.g. inheritable diseases). A point is that many of these diseases are not labeled, they can be induced also by non-nuclear causes. Generally it is difficult to attribute a health effect in a particular case unambiguously to radioactive contamination. The relationship between health effects (always deleterious) and exposure to radioactivity can statistically be proved by epidemiological investigations, involving large numbers of people during an extended period.

Viewpoints of the nuclear industry

*Downplaying and denial of health effect*s

The International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO) deny that the above mentioned diseases can be attributed to radioactive contamination. Observed diseases and health effects in areas contaminated by radioactive materials are attributed to mental factors, explicitely excluding radioactivity as a possible cause. This viewpoint became clear after the nuclear disasters at Chernobyl and Fukushima, despite opposite evidence from independent studies, among other by the International Physicians for the Prevention of Nuclear War (IPPNW), who received the Nobel Peace Prize in 1985.

In their reports on the health effects of radioactivity the IAEA and WHO commit basic scientific flaws: observed health effects are systematically attributed to radiophobia, mental disorders and bad lifestyle without any proof and are ignored if they do not comply with the used radiological models. By definition models are simplified descriptions of phenomena and mechanisms in reality. The outcome of calculations based on a model are determined by the the input of data and the assumptions on which the model is based. If empirical evidence deviates from predictions based on a model, the model is not correct and the evidence should not be discarded as ‘outlier’ or ‘unreliable’.

Scientific epidemiological studies that might unambiguously prove the IAEA viewpoint remain undone by the IAEA and WHO.

Conflict of interests

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.

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.

Position of the WHO

According to an agreement between the International Atomic Energy Agency and the World Health Organization in 1959 the WHO cannot operate independently of the IAEA on nuclear matters. The WHO reports on the health effects of Chernobyl and Fukushima do not deviate from the IAEA viewpoints on that issue.

IAEA’s viewpoint on uranium mine rehabilitation

In a recent report the IAEA discusses what is called ‘environmental remediation’ of uranium mining and processing sites. Many sites of depleted uranium mines are ‘orphaned’ according to the report. As far as

known no uranium mining and processing site in the world has ever been rehabilitated in a way complying with acceptable environmental and health standards. The IAEA admits that little progress has been made in this respect. From the report follows that the IAEA health effects of radioactive residues from uranium mining considers to be of minor importance, the text boils down to a conclusion that economic factors are the driver of the mining waste management. The term ‘remediation’ in itself is noncommittal and is open to many interpretations.
This viewpoint is shared by the nuclear industry in its statements that mining and milling wastes are not classified as radioactive wastes.

Questions

With respect to responsibilities and liabilities a number of questions are remaining.

- Which independent institute would be responsible for inspections and quality checks of the construction and maintenance of the mine facilities, including the tailings storage facilities in the Taseq basin?
- And for monitoring the tailings in the post-closure phase?

- Which quality regulations would be applied?
  Which quantitatively defined standards form the basis of the regulations?

- Who is liable for the damages as a result of the mining operations, during all phases: construction phase, operation phase and closure phase, including dam failures?

- Would the funds set aside by the mining company (companies) for severe accidents be sufficient to cover the costs?
- What if not so? Who pays the bill?

- Who is liable for the damages as a result of the mining operations in the post-closure phase, including dam failures?
- Who would own the mining area after the definitive closure of the mine?
- What if serious shortcomings of construction and maintenance come to light in the post-closure phase?

Who pays the bill?

- If GME, or a possible buyer of its mining rights, would intent to reprocess the tailings in Taseq basin, would the company need to apply for a new mining license?

- What if a mining company applies for mining the remaining ore resources at the Ilimmaasaq complex?

- The EIA draft report concerns a mine at the Kvanefjeld with an operational lifetime of 37 years, during which 111 million tonnes of ore would be mined and processed. This mass is 16.5% of the ore resources identified at the Kvanefjeld and 11% of the total resources at the Ilimmaasaq complex. The listed amounts of resources in the report include those of Zone 2 (Sørensen) and Zone 3, suggesting that these resources would also be mined. In its preliminary reports GME mentions an operating lifespan of the mine of 60 years. In the White Paper of October 2015 GMe states that the life of the Kvanefjed mine Project is expected to go beyond 100 years.
- What are the long-term intentions of GME?

Annex A
Thermodynamic aspects

Recovery of uranium

Recovery of uranium from the Ilimmaasaq ores is complicated for several reasons:
- low uranium content of the ore
- presence of REEs, thorium and other metals
- refractory mineralogy of the ore and host rock.

Due to the low uranium content a large mass of ore has to be mined and processed to obtain a kilogram of uranium, the lower the content, the larger the required ore mass. This simple mathematical relationship is here called the dilution factor. The physical and chemical separation processes needed for extraction of uranium, or whatever metal, from its ore are governed by the basic natural laws of thermodynamics. From these laws follows that the extraction efficiency of the recovery of uranium from its host rock declines with declining uranium concentration, with increasing number of other chemical species in the matrix, with increasing chemical similarity of the species and with increasing refractoriness of the host minerals.
The high dilution factor and the low extraction efficiency result in a high specific consumption of energy and chemicals per kilogram recovered uranium. The relationship between the ore grade and the specific energy consumption, apart from other complicating factors, proves the existence of the energy cliff: at a grade of 200-100 ppm the recovery of 1 kg of uranium from its ore consumes as much energy as can by generated from that kilogram of uranium in the nuclear energy system. Consequently no net energy generation is possible from uranium resources at or below the critical grade of the energy cliff.

The thermodynamic quality of the uranium resources of Ilimmaasaq may be near the energy cliff. Due to the high specific energy consumption the recovery of uranium from these ores has also a high specific CO_2 emission. Nuclear power plants fed by uranium from these lean ores have a specific CO_2 emission (gCO_2/kWh) approaching the emission of fossil-fuelled power plants; this phenomenon is called the CO_2 trap. As a consequence the Ilimmaasaq uranium cannot contribute to mitigation of the anthropogenic climate change.

Closed-cycle reactor systems

A thermodynamic analysis of closed-cycle nuclear power systems, such as the uranium-plutonium breeder and the thorium-uranium breeder, proves that these concepts are inherently infeasible, because they are based on (implicite) assumptions that are in conflict with the Second Law of thermodynamics. As a consequence it is not possible to release significantly more useful energy from uranium than by means of the currently operational nuclear power plants. Another conclusion is that thorium resources never could become energy resources. Moreover the envisioned closed-cycle systems would have a negative energy balance: the operation of the closed cycle of reactor + reprocessing plant + fuel fabrication plant would consume more useful energy than could be generated by the system. The energy balance includes the dismantling of the closed down facilities. Apart from the technical infeasibility and the negative energy balance of the closed-cycle systems they would provoke serious threats of nuclear terrorism.

Long-term prospects of nuclear power

The main conclusion based on the thermodynamic analyses of nuclear systems is that in the foreseeable future nuclear power is only possible by means of the currently operational technology of thermal neutron reactors, and consequently will depend on conventional uranium resources, that are limited by the energy cliff.

1 Mineral resources at the Ilimmaasaq complex

Uranium resources

The uranium occurence at Kvanefjeld 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 occurs in the complex phosphor-silicate mineral steenstrupine. The host rock, lujavrite, contains 200-400 ppm U (grams uranium per tonne rock) and 600-800 ppm Th, the typical Th/U ratio lies between 2 and 3.
Since 2007, the area has been explored for rare earth elements (REEs), and the current license-holder is Greenland Minerals and Energy Ltd (GME, or GMEL). GME identified three ore deposits at the Ilimmaasaq complex: Kvanefjeld, zone 2 (Sørensen) and zone 3. The contained recoverable masses of metals at the three deposits are summarised in Table 1 below. These figures are from the *June 2016 Quarterly Report* [GMEL-qrJune 2016],that are the same as in the *September 2016 Quarterly Report* [GME-qrSept 2016], but different from the figures given by [GMEL 2016]. The figures of the Kvanefjeld deposit are dated February 2015, those of Sørensen March 2012 and of Zone 3 May 2012.

Table 1
Contained metals in the three ore deposits of the Ilimmaasaq complex, with a total ore mass of 1.01 billion tonnes, at a cut-off grade of 150 ppm U_3O_8, corresponding with 127 ppm U. Mt = million metric tonnes, Mlbs = million pounds, 1 lb = 0.4536 kg, 1 kg U_3O_8 = 0.848 kg U. Source: [GMEL-qrJune 2016].

deposit	ore mass Mt	TREO * Mt	zinc Mt	U_3O_8 Mlbs	uranium 1000 tonnes	average ppm U **
Kvanefjeld	673	7.34	1.53	368.02	141.56	210
Zone 2 (Sørensen)	242	2.67	0.63	162.18	62,38	258
Zone 3	95	1.11	0.26	63.00	24.23	255
grand total	1010	10.33	2.25	592.84	228.04	226

* TREO = Total Rare Earth Oxide
** calculated by author: average grade = uranium mass/ore mass

The IAEA (international Atomic Energy Agency) and OECD/NEA (Organisation for Economic Co-operation and Development/Nuclear Energy Agency) report in [Red Book 2014] (the most recent edition) a recoverable uranium resource of 221 000 metric tons from 956 million tons of ore, this corresponds with an average ore grade 221000/956 000 000 = 231 ppm U. Apparently not only the Kvanefjeld deposit is listed, but the sum of the three deposit zones of the Ilimmaasaq complex. The IAEA and NEA assume a recovery factor of 65%. This recovery factor might be optimistic. In [Red Book 2011] other figures are mentioned: 135 000 tons of U from 619 million tons of ore, corresponding with an average grade of 218 ppm U.

In some publications of GME there may be confusion 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 that GME assumes a recovery factor of 45% from ore at a grade of 364 ppm. Considering that the average grade of the processed ore may be significantly lower than 364 ppm (see Table 1) and in view of the refractory and chemically complex composition of the uranium-bearing minerals, the average recovery factor might be significantly lower than 45%. Based on previous studies this report estimates a recovery factor of 40%, but the practical figure might be even lower. A recovery factor of 40% would mean that the recoverable uranium resources of Kvanefjeld + Zone 2 + Zone 3 would be about 0.40•(228 000/0.65) = 140 000 tonnes of uranium.
The current global uranium demand is some 62000 tonnes per year.

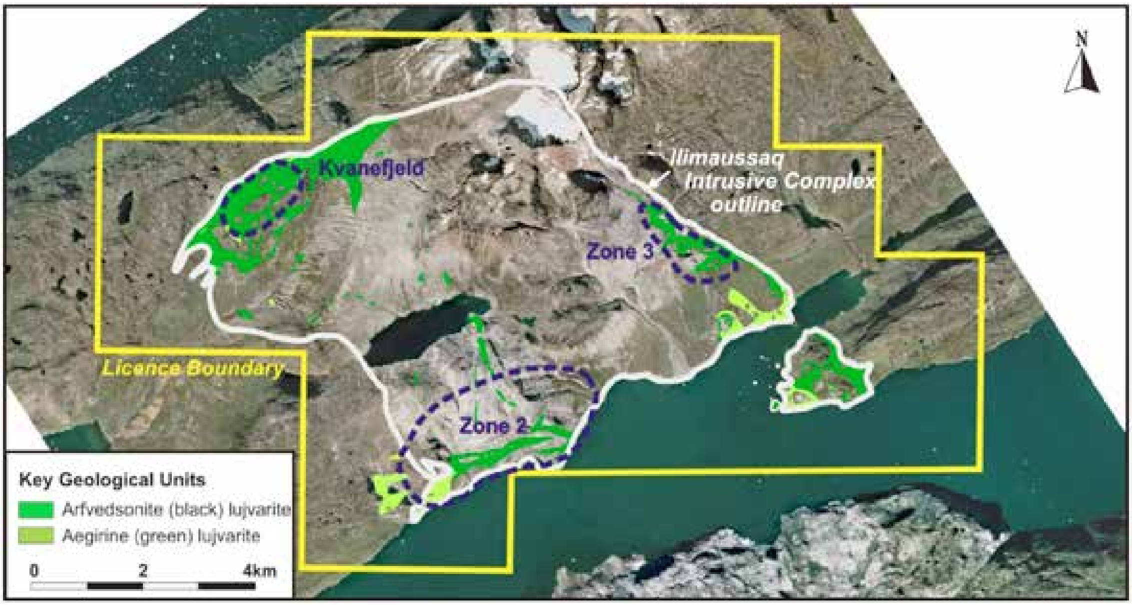

Figure 1
Overview of GMEL's 100% controlled license EL2010/02, with the Ilimmaasaq complex and the three ore deposits as identified by GMEL. The ores are hosted in the black lujavrite rocks. Source: [GME 2012]. A similar map is published in [GMEL-qrSept 2016].

Thorium resources

Thorium (Th) is a radioactive metal found in small quantities in most rocks and soils; its crustal abundance is 3-5 times that of uranium. Thorium in mineral form occurs as oxides, silicates and phosphates, often with rare earth elements (REEs), niobium and tantalum.
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, a well known REE ore mineral.

According to a report of Risø National Laboratory [Risø 1966] the mineral steenstrupine, the main ore mineral of Kvanefjeld, contains thorium at a grade ten times the uranium grade (2-7% resp. 0.2-0.7%).
According to [MiMa 2014] lujavrite, the host rock of the resources at the Ilimmaasaq intrusion complex, contains 200-400 ppm U and 600-800 ppm Th, the typical Th/U ratio lies between 2-3. This implies that the thorium resources would be 2-3 times the uranium resources: roughly 440 000 - 660 000 tons, if the

same recovery criteria would be employed as with the recovery of uranium. According to [Red Book 2014] a preliminary estimate of the thorium resources at Kvanefjeld comes at 86 000 - 93 000 tons *in situ*, but it could be some 400 000 tons according to [Red Book 2011]. As pointed out above '*in situ* resources' are not the same as 'recoverable resources'.

The by-product nature of the occurrence of thorium and the lack of economic interest has meant that thorium resources have seldom, if ever, been accurately defined. This observation may explain the large difference between the figures mentioned above.

Uranium for sale?

The mineralogy of the Kvanefjeld ore points to a so called hard ore, requiring significantly more energy to extract a kilogram uranium from it than from soft ores at the same grade. This observation plus the low grade are two causes of the high cost of uranium from Kvanefjeld. Uranium recovery from the Kvanefjeld ores is chemically complicated, due to the presence of thorium, REEs and other elements.

For above mentioned reasons the IAEA/NEA Red Book places the uranium from Kvanefjeld in the highest cost category of up to 260 US dollars per kg uranium, and there are no Kvanefjeld uranium resources in lower cost categories listed in the IAEA statistics. The market price in October 2016 was about 53 USD/kgU. At this moment there seems to be no market for the Kvanefjeld uranium and in view of the steadily declining demand, it is doubtful wether the price will rise to 260 USD/kgU in the future.

It is unlikely that GME does not know these facts. A possible explanation is that the uranium has to be removed anyway from the ore mass together with the thorium, to make further separation steps of the REEs possible; the sulphur acid leaching first step in the refinery may point to this assumption. The cost of this first separation step after the flotation step might be largely allocated to the REEs recovery.

In one scenario the whole fraction containing uranium + thorium would be discarded into the Chemical Residue Storage Facility (CRSF). In another scenario GME would separate uranium from thorium and sell the uranium at a price of say 50 USD/kgU. In both scenarios thorium plus its decay products would be discarded into the chemical tailings.

With regard to the radioactivity of the tailings discharged into the CRSF scenario 1 and 2 would hardly make any difference, because the thorium content is 2-3 times higher than the uranium content, and all decay products of uranium would end up in the tailings anyway; the activity of the uranium itself is only a minor fraction of the total activity.

Kvanefjeld uranium and thorium as energy sources

A thermodynamic analysis of the recovery of uranium from the earth's crust and subsequently its use as nuclear fuel proves that below a grade of some 200-100 gram uranium per tonne rock no net energy production from that ore is possible, this limit is called *the energy cliff*. The relationship between net energy production by nuclear power stations and ore grade is explained in Annex A. The quality of the uranium ores at the Kvanefjeld is very near the energy cliff, due to the low grade and the mineralogy of the ore.

Breeder reactor systems, that are said to fission 50-100 times more nuclei per kilogram uranium than the present reactors, inherently unfeasible following from the Second Law of thermodynamics, see Annex A.

Thorium never can become a net energy source, as is proved by a thermodynamic analysis of the nuclear reactor systems that would be required.

2 Layout of the Kvanefjeld mining facilities

Scope of the Kvanefjeld Project: 11% of the resources

GME proposes the following time schedule of the Kvanefjeld Project:

Table 2
Time line of the Kvanefjeld Project. Source: [Orbicon 2015].

	duration	year	period
construction phase	2-3 years	–	2017 -2020
operation phase	37 years	0 -37	2021 - 2058
closure phase	6 years	38 - 43	2059 - 2065
post-closure phase	–	44 -	2066 -

Some things concerning the mining plans are noticeable, such as:

- Previous reports of GME, e.g. [GME 2012], make mention of an operational phase of 60 years. This figure is absent in the EIA report.
- In the White Paper of October 1025 [GME-SIA 2015] GME states:
  "The life of the Kvanefjeld mine Project is expected to go beyond 100 years."
  This figure is also absent in the EIA report.
- In the EIA draft report no mention is made of exploiting the ore deposits of Zone 2 (Sørensen) and Zone 3, together containing half as much as the Kvanefjeld deposit (see Table 1).
- The mine would treat 3.0 million tonnes of ore per year (crusher feed) to extract products of Rare Earth Elements, uranium, zinc and fluorspar [Orbicon 2015].

From the EIA draft report follows that GME intends to mine ore only from the Kvanefjeld deposit. During a life span of 37 years the mine would process a total of 111 million tonnes of ore, slightly more than one tenth of the recoverable amount of 1.01 billion tonnes of ore reported to be present in the three deposits at the Ilimmaasaq complex and 16.5% of the Kvanefjeld deposit of 673 million tonnes of ore (see Table 1).

Orbicon does not make clear why only a minor part of the Kvanefjeld deposit would be mined nor wether GME considers exploitation in the future of the whole Kvanefjeld deposit and of the deposits of Zone 2 and Zone 3,
A possible reason may be related with the storage of the mining wastes: it might be a problem to store more wastes in this mountainous area. In the present plans about 111 million tonnes of mining waste (tailings) would have to be stored; if all three deposits would be fully mined that mass would be nearly ten times as much. Tailings will be discussed in the following chapter.

Mine layout according to EIA 2015

.
The ore is mined in an open pit on top of the Kvanefjeld by blasting, excavation and haulage of the rocks. The overburden (rock not containng the desirable minerals) and the waste rock with a grade below a given standard, is dumped near the mine. The ore is transported by dump truck to the ore processing area.

After crushing and grinding the finely ground ore mass, mixed with water and chemicals, is separated by means of flotation processes into a small fraction enriched in ore minerals and a large fraction depleted in ore minerals; this is called the concentrator or beneficiation step. The larger fraction, the flotation tailings, is pumped as as a slurry to the Flotation Tailings Storage Facility (FTSF) in the lower part of lake Taseq. In the concentrator the light zinc mineral is separated from the heavy other minerals, in addition fluorspar is produced by reaction of calcium chloride with fluorides in the process water.
The smaller fraction, some 10% of the processed ore mass, containing the heavy ore minerals, is transported to the chemical processing plant where it is separated into several fractions, see Figure 2 below. The waste streams of the chemical processing, the chemical tailings, also a slurry, are pumped to the Chemical Residue Storage Facility (CRSF) in the upper part of the Taseq basin.

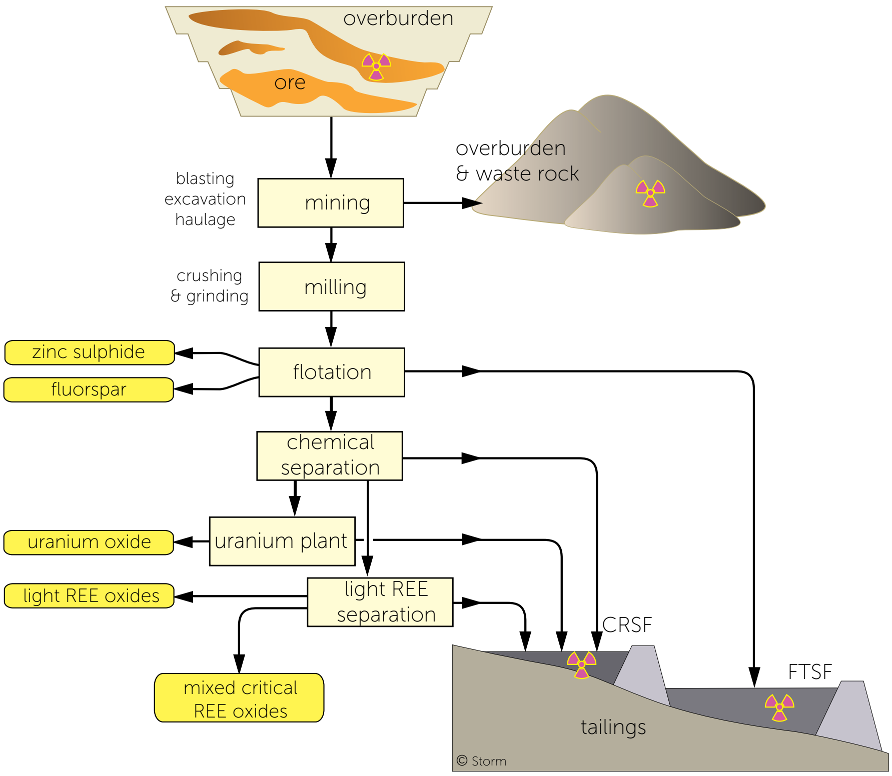

Figure 2

Flowsheet of the planned Kvanefjeld mining project of GMEL based on Figure 5-4 and other data from the EIA draft report [Orbicon 2015]. CRSF = Chemical Residue Storage Facility, FTSF = Flotation Tailings Storage Facility.

Fluorspar is formed in the water treatment from calcium chloride to remove fluoride dissolved from the ore into the waste water, down to 100 ppm before discharge into the sea.

The light rare earth elements (REEs) are: lanthanum La and cerium Ce, the critical REEs are: praseodymium Pr, neodymium Nd, europium Eu, terbium Tb and dysprosium Dy [GMEL-qrJune 2016]; the fraction 'critical REEs' includes yttrium Y, although Y is strictly not a REE. The fractions of the light REEs and the critical REEs are exported abroad for further separation and purification, this requires a very complex processing. Likely the fraction 'critical REEs' contains also other, not mentioned REEs, for all REEs are chemically very similar.

The layout of the proposed mining facilities is illustrated by the map of Figure 3; this map deviates from previous publications, as illustrated by Figure 4. Following public consultations the 'East Scenario', involving waste rock and tailings deposition in the Ipiutaq area, was abandoned and the development of the mine design was focused on the Narsaq Valley - Narsap Ilua area [Orbicon 2015].

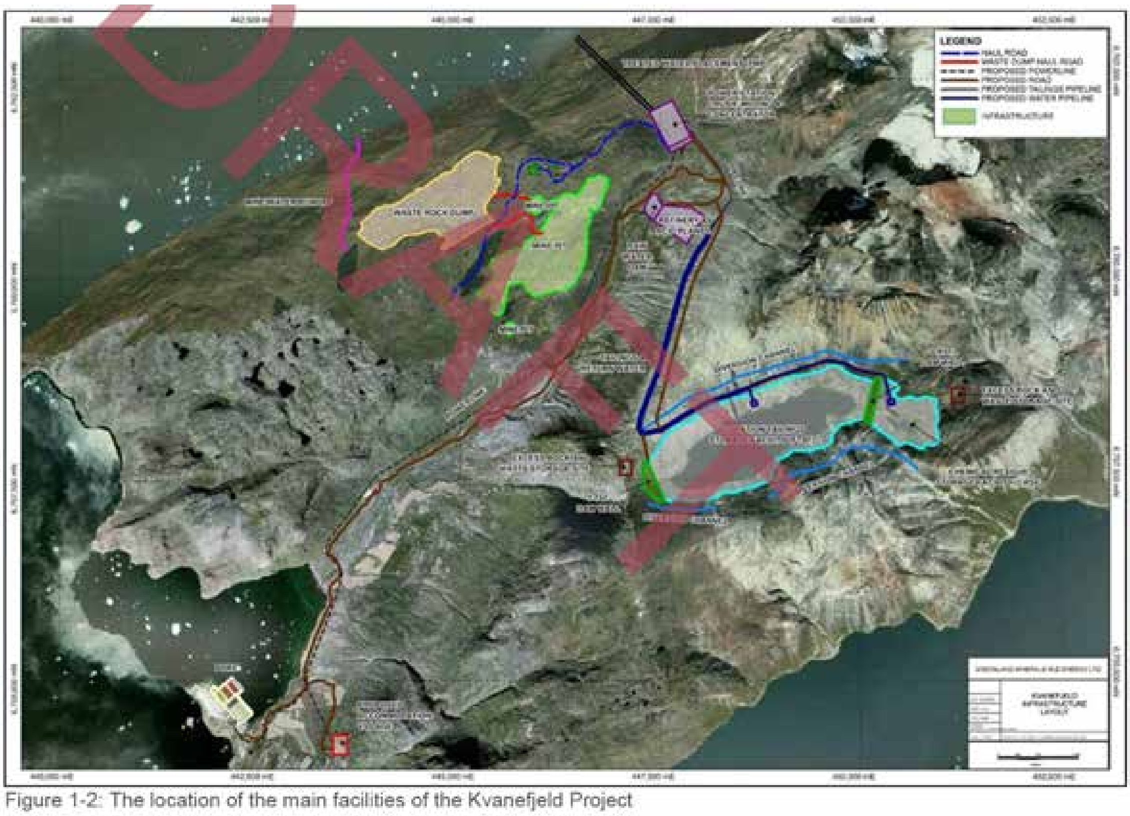

Figure 3
Outlay of the facilities of the Kvanefjeld Project, source: [Orbicon 2015].

Figure 4
Residue Storage Facility (RSF) options considered by GME in 2012. 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, had been chosen as the preferred location for RSF2 (chemical tailings). This location would allow RSF2 to be located alongside the proposed processing plant/refinery and at a similar elevation. Source: [GME 2012].

Mine products

According to the EIA draft report the Kvanefjeld mine would export REEs oxides and hydroxides, zinc sulphide concentrate and uranium oxide; other metals from the ore are not recovered. In addition to the metals reaction products of the ore processing plants are exported: fluorspar and sodium hypochlorite. Fluorspar is the reaction product of calcium chloride, imported from abroad, and the fluorides from the ores that are dissolved in the process water. Sodium hypochlorite is a reaction product of undisclosed chemical reactions in the ore processing plants, involving chemicals that are also imported from abroad.

Table 3
Mine products of the Kvanefjeld Project, transported to the harbour. Data from Table 5-4 [Orbicon 2015].

	annual production tonnes/year	total production during 37 years tonnes
mixed critical rare earth oxides	7850	290 450
cerium hydroxide	6950	257 150
lanthanum oxide	4300	159 100
lanthanum/cerium oxide	3900	144 300
sum REEs	23 000	851 000
zinc concentrate, ZnS	14 500	536 500
uranium oxide, U_3O_8	557	20 609
sum metals	38 057	1 408 109
fluorspar, CaF_2	16 200	599 400
sodium hypochlorite	17 000	629 000
grand total	71 257	2 636 509

Fresh water consumption

Large volumes of fresh water are used in ore processing. Water for the Concentrator and Refinery would be provided by two sources:

- Narsaq river
- recycled water from the two tailings storage facilities in the Taseq basin

The decant water from Taseq would be purified and the purified fraction recycled into the separation processes. The waste stream of this purification process is discharged into Nordre Sermilik.

Around 400 m^3/hour (9600 m^3/day, 3.5 million m^3/year) of fresh water would be sourced from Narsaq River [Orbicon 2015]. This water can be seen as the make up of the cyclic fresh water system, so the discharges of waste water into Nordre Sermilik might have the same volume.
The specific fresh water consumption (make up) would be 3 500 000/71257 = 49 m^3/tonne if alle products are accounted for. If only the typical mine products (zinc, REEs, uranium), with a total mass of 38 057 tonnes, are accounted for, the specific consumption would be 92 m^3/tonne product.

Consumables

The expected annual consumption of consumables by the mine during operationis summarised in Table 4 below. These materials have to be imported from abroad and transported to the mine.

Table 4
Consumables required for the Kvanefjeld Project. Data from Table 5-3 [Orbicon 2015]. The fresh water consumption (make up of the purification cycle) equals the waste water discharges into Nordre Sermilik.

	unit	per year	per tonne product	during 37 years
diesel (mining)	m^3	6300	0.166 *	233 100
heavy fuel oil (power plant)	m^3	50 000	0.702 **	1 850 000
general freight + spares	tonne	46 750	0.656 **	1 729 750
chemicals + reagents	tonne	221 675	3.11 **	8 201 975
fresh water, make up = waste water discharge	m^3	3 500 000	92 *, 49 **	129 500 000

* allocated to products from mining only, 38 057 tonnes/year
** allocated to total products, 71 257 tonnes/year

Waste water

In the purification process the processs water is separated into two fractions: a large volume fraction at lower concentrations of unwanted species and a smaller volume fraction at a higher concentration of unwanted chemical species than the process water entering the purification process. Some species can be removed from the waste water by precipitation, e.g. fluoride can be precipitated as fluorspar by adding calcium chloride to the waste water.
The smaller volume fraction, the waste stream, is to be discharged into the sea; it is enriched in unwanted chemical species, such as radionuclides, non-radioactive toxic elements (e.g. beryllium, barium, arsenicum), chemicals used in the ore processing plants. It contains also desirable species: REEs, zinc, uranium, because separation processes never go to completion.
The EIA draft report does not mention the presence of thorium plus its decay products. It seems unlikely that these radionuclides would be not present in the waste water, in view of its 3-10 times higher concentration in the mined ores.
According to the EIA draft report a dilution factor in the order of 2000 would be required to obtain Predicted No Effect Concentration (PNEC) for the most critical parameters. This would mean that the discharges of waste water during one year (see Table 4) would have be diluted into 7 km^3 of seawater in the Nordre Sermilik and into 260 km^3 of seawater during the operational lifetime of the mine (37 years).

This observation raises the question if accumulation of the species from the waste water into the sediments and bioaccumulation into living organisms would not occur and could become a problem in the future.

Water from the mining pit and drain water from the waste rock piles would run off into Nordre Sermilik.

Questions regarding undisclosed chemical aspects of ore processing

Numerous chemicals are needed to perform the separation processes in the flotation concentrator and the chemical refinery. Table 5-2 of the EIA draft report [Orbicon 2015] gives a list of chemicals needed for the refinery, with a total mass of 20925 tonnes a year. A large number of these chemicals – such as flocculents, coagulants, extractants, biocides, inhibitors, etcetera – are listed only with their technical brand names, without their chemical composition.
For that reason it is difficult to an independent chemist to judge the environmental impact and health effects of those chemicals. Lack of knowledge hampers also assessment of the possible reaction products from the separation processes that are discharged into the tailings. A number of questions remain to be answered, such as:

- Which chemical species will end up in the tailings, not only unused added chemicals but also reaction products formed in the separation processes?
- Which reactions are conceivable in the long run between all present species in the tailings: the artificial chemicals mutually and reactions with species from the processed ore, such as REEs, uranium and thorium plus their decay products, fluorides and other elements mobilised from the ore?
- What is known about the toxicity of the chemical species present in the tailings?
- What is known about the biochemical behaviour of the chemical species, escaping into the environment via seepage and overflows into groundwater and rivers?
- What is known about the biochemical behaviour of the chemical species in the waste water discharged into the sea (Nordre Sermilik)?
- Which chemical species might enter the drinking water and the food chain, via fresh water and via the sea?

Risø study

During the 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 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.

Risø investigated alkaline leaching under pressure and at elevated temperatures of the main ore mineral of Kvanefjeld, 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 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.

3 Mining wastes: tailings in the Taseq basin

Waste streams of the ore processing

In each separation process a waste stream is generated, inevitably containing a fraction of the desirable metals. From the fundamental laws of nature follows that a separation process never goes to completion. In any separation process a mixture is separated into two fractions:
One fraction is enriched in the desirable metal(s), but contaminated with unwanted chemical species.
The other fraction contains most of the unwanted species and also a small fraction of the desirable species; this fraction is the waste stream of the separation process.
The waste streams of the ore processing, called tailings, are discarded and stored in large ponds. The tailings of a mine at Kvanefjeld would be dumped into two separate storage facilities: the tailings from concentrator into the Flotation Tailings Storage Facility (FTSF), and the tailings from the chemical processing into the Chemical Residue Storage Facility (CRSF), see also Figure 2.
Tailings consist of a slurry of mineral powder and water, and contains an assortment of dissolved species from the processed ore plus the chemicals added in the separation processes and their reaction products with chemical species in the ore.

Flotation Tailings Storage Facility (FTSF)

The volumes of the concentrator tailings, to be stored in flotation tailings storage facility (FTSF) in the Taseq basin would be large. During the operational lifetime of the mine (37 years) 111 million tonnes of ore are to be mined and processed, based on the current plans. About 90% of the mined mass would be discarded into the FTSF, or some 100 million tonnes, the remaining part, about 11 million tonnes, into the CRSF. These figures may be compared with the 216 million tonnes of the total mass of uranium mill tailings in Canada at the end of 2013 [LLRWMO-2013].
Assumed the slurry from the concentrator would have a density of about 2 tonne/m^3, the volume would be about 50 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 indicated in Figure 5-7 of the EIA draft report. The lake would effectively be displaced by the mud from the concentrator.

The tailings in the FTSF would be less radioactive than the original rocks, because the majority of the minerals containing radioactive elements are separated from ground ore mass in the flotation step. GME seems to suggests that these flotation tailings are harmless for that reason. However, the separation of minerals by the flotation process is not perfect, and consequently a significant part of the radioactive minerals will end up in the flotation tailings. In addition 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.

Chemical Residue Storage Facility (CRSF)

At the end of the operational phase of the mine the volume of the chemical tailings from the refinery would be some 5 millions of cubic meters that are the stored in Chemical Residue Storage Facility CRSF, situated in the upper part of lake Taseq. Contrary to the tailings stored in FTSF, the tailings in CRSF are stronger radioactive than the ore from which they originated: about ten times as high. Moreover the radionuclides

and many other non-radioactive toxic elements from the ore minerals [Risø 1990] are in a soluble form and consequently highly mobile in the environment.
The problems and unknowns concerning FTSF addressed above, apply just as much to CRSF, 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 Narsaq valley, the rivers and the fjords and at which rate during operation of the mine and during the centuries thereafter.

Noteable is the large difference in size of the CRSF in the upper part of Taseq as presented in the EIA draft report and the original plans from 2012 for the chemical tailings storage, at that time called RSF2, at a preferred location in a basin near the Nakalak range, see Figures 3 and 4.

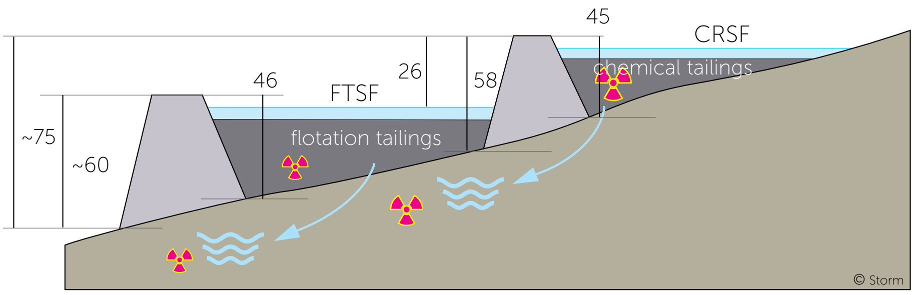

Figure 5
Schematic representation of the two tailings ponds in lake Taseq, the Chemical Residue Storage Facility (CRSF) and the Flotation Tailings Storage Facility (FTSF). The drawing (not to scale) is based on Figure 5-8 in the EIA draft report [Orbicon 2015]. The heights are measured in meters. Seepage, leaks and spills will cause contamination of groundwater and rivers by radioactive and non-radioactive toxic chemical species. During operation the tailings are covered by several meters of water.

Choice for the FSFT and CRSF concepts

The confinement by artificial embarkments of the enormous volumes of toxic slurry, growing to some 30-50 million m^3 at the end of the operational phase, offers only engineered safety. One reason to apply this concept may be the cost: it might be the least costly solution to store the massive volumes of the tailings generated, more than 1 million m^3 per year. Another argument of GME is the wish to keep the option open for reprocessing the residues from the tailings storage facilites in the future [GME 2012] and [Orbicon 2015], and consequently to keep the tailings retrievable.
It is a fallacy to think advanced technology would make reprocessing of the tailings attractive in the future. Extraction of metals and minerals from ore is not a matter of advanced technology, it is a matter of processes governed by the Second Law of thermodynamics, and consequently a matter of investments of energy and dedicated effort. A higher extraction efficiency can only be achieved by higher investments of materials and energy. No technology can circumvent this fundamental law of nature.

Tailings storage capacity limits mine operation

A rough estimate of the storage capacity in the Taseq basin as described in the EIA draft report comes to a storage volume in the order of 30 million m^3. It seems hardly possible to enlarge that capacity in the mountainous area, because of the huge embankments that would be required, that are already high in the current design. The limited storage capacity may limit the scope of the mine to the designed 37 years and the mining of 111 million tonnes, about 16.5% of the ores present at the Kvanefjeld. Mining of the full resources, 1010 million tonnes, would generate a tailings volume about ten times larger than in the current design. It might be difficult to design a tailings storage facility with a capacity of some 300-500 million m^3 in the mountainous area around the Kvanefjeld.

Radioactivity of the tailings

All radionuclides present in the tailings of a uranium mine pose a serious long term environmental risk [NRC 1996], [Andriesse 1994], [Lipschutz 1980], [INFCE-7 1980] all the more so because the elements are chemically mobile after the milling process. The publications by [Blanchard et al. 1982], [WISE-U 2006] and [Diehl 2006] deepen that worries.
Averaged over its full operational lifetime a nuclear power plant of 1 GWe consumes 26 g/kWh of uranium ore at a grade of 0.1% U, this would correspond with 150-200 g/kWh of Ilimmaasaq ore and would displace a similar mass of waste rock, a part of which is weakly radioactive. By processing the uranium ore, some 3900 Bq/kWh (becquerel per kilowatthour) of highly toxic radioactive elements (U, Th, Po, Bi, Pb, Rn, Ra and Pa) are mobilised from their host rock and could enter the environment as dust or dissolved in groundwater [Diehl 2011]. Because the Ilimmaasaq ores contain also thorium, in concentrations 3-10 times higher than uranium, the radioactivity of the tailings would be 3-10 times higher than might be expected based on the presence of uranium alone.

Mine rehabilitation should be included in the nuclear process chain, if the nuclear industry were to claim nuclear power is ‘clean’. Striking is the following statement of the nuclear industry [WNA 2016a]:

> ‘Strictly speaking these [.. mining and milling wastes ..] are not classified as radioactive wastes’.

Until the present day, mill tailings and other waste of the uranium mining industry are being discharged into the environment. Obviously this practice cannot be reconciled with any sustainability definition. To make sure that this part of the nuclear cycle will become less harmful to the environment and to future generations, the mining and milling waste should be isolated from the biosphere. Broadly this would imply two basic processes:

- chemical fixation of the radionuclides (if possible) and of other toxic, non-radioactive species into a water-insoluble chemical compound
- physical isolation of the waste from the biosphere, minimalizing the chance that the radioactive and toxic substances reenter the human environment.

The problem of the mill tailings and the rehabilitation of the mine area are not addressed in any other study. This study assumes that the uranium mining area is restored to green field conditions after depletion of the ore deposit, to comply with sustainability criteria as well as possible. There is no or very limited practical experience with mine reclamation, so no empirical data are available. To make possible a rough estimation of the input of energy and materials of mine reclamation, a fictive but plausible procedure is adopted in this study for the immobilisation and isolation from the biosphere of the radioactive wastes of the mining activities.
The groundwater and soil remain contaminated for very long times by radionuclides, toxic non-radioactive elements from the ore (e.g. arsenicum, barium, beryllium) and chemicals used in the milling process. It is not clear if, and if so to what extent this contamination could be remediated.
As far as known no depleted uranium mine in the world has ever been rehabilitated in a way that would comply with elementary sustainability criteria.

Stability of the tailings storage facilities

Seepages and spills from the FTSF and CRSF would be unavoidable, not to speak about incidental overflows, so it is important to know which chemicals would enter the groundwater and rivers of the Narsaq valley and at which rate the escape into the environment could happen during operation of the mine and during the centuries thereafter, in the post-closure phase.

Orbicon and GME in their EIA draft report seem to (implicitely) assume that:

- There will be no diffusion from deeper layers of the tailings into water on top of it, nor into the groundwater.
- There will be no fissures or other phenomena, such as freezing and thawing cycles, through which heavily contaminated water could enter the environment.
- During operation of the mine and the centuries after closure the tailings will not turn dry by leakages or by other causes, with the result that the fine powder would be blown by the wind over vast distances.
- The embankments (dams) will maintain a 100% integrity, without erosion and spontaneous degrading mechanisms.

It is an illusion to think that at the end of the 6 year closure phase the hazards and dangers would be definitively eliminated, on the contrary. Degradation of the human-made structures by spontaneous processes governed by the Second Law is unavoidable. The tailings in Taseq form an inherently unsafe situation: safety depends on engineered safety, on human competence and perfect maintenance during centuries following the closure of the project. Are unforeseen conditions out of the question?
From a physical viewpoint the question is not: *if* the dams would fail, the question might be: *when* would the dams fail?

The hazards posed by the tailings to the safety of the people living in the Narsaq valley, to the environment on land and to the sea around the peninsula depend on the quality of the storage facilities: the stability of the embankments and the permeability of the bottom of the facilities and of the embankments.

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 could it transform into a semi-liquid mud by a sudden movement or by a change in conditions?

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?

Dam failure

A worst case scenario is a major failure of the embankment. That could mean that tens of millions of cubic meters of a toxic and radioactive mud would come down the slopes into the Narsaq valley. Unfortunately there are examples of such disasters.
On 5 November 2015 a tailings dam of the Germano iron mine near the town of Mariana in Minas Gerais, south eastern Brazil (owner Samarco) failed, releasing 30-60 million cubic meters of mud, containing toxic substances like Hg, As, Cr, Mn, causing 19 casualties and devastating a large inhabited area down the Rio Doce valley, reaching the Altantic Ocean 500 km from the mine, see photos in Figures 7 and 8. Taseq would ultimately contain a similar amount of mud.

Figure 6
Devastation after the dam burst of the Samarco mine. Photo by: Reuters. Source: http://www.miningweekly.com/article/brazil-to-sue-bhp-vale-for-5bn-in-damages-for-dam-burst-2015-11-29

Figure 7
Devastation after the dam burst of the Samarco mine. Samarco dam failures via Estadao
http://blogs.agu.org/landslideblog/2015/11/08/samarco-1/

4 Isolation of the tailings from the human environment

Concept proposed in this report

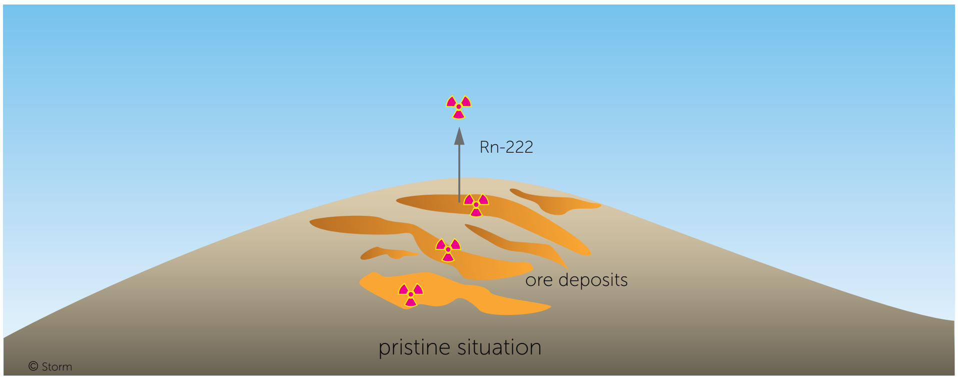

Figure 8
Schematic presentation of ore bodies at the Kvanefjeld, a geologically very old formation, before the mining activities.

The many radioactive elements present in the ores, uranium, thorium and their decay products, are chemically tightly bound in the minerals in the rock. The ore bodies at Kvanefjeld are covered by rock with a composition different from the uranium-bearing rock. These 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. That 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.

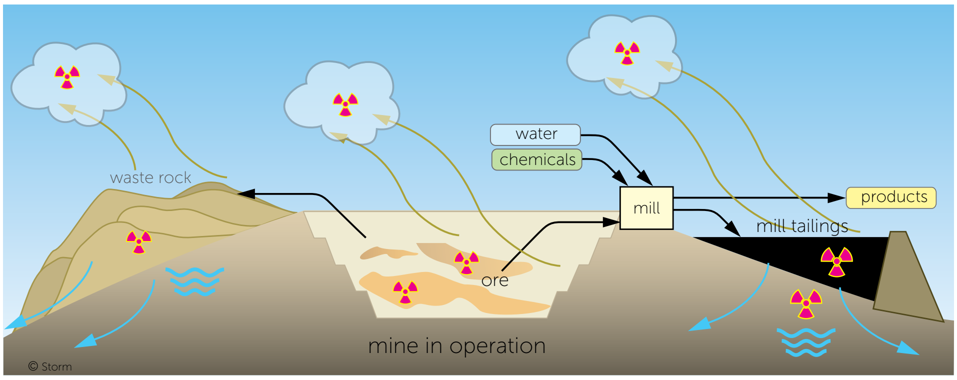

Figure 9
Generic outline of mining activities at the Kvanefjeld. The overburden and waste rock are removed and stored at a dump site. The ore is transported to the mill that grounds the rock into powder. The processing of the ground ore consumes large volumes of fresh water and chemicals. After extraction of the zinc, REEs and uranium from the ore the remaining mass, mixed with water and chemicals is stored in lake Taseq. Many 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 during the mining operations and from the waste rock piles.

Mine rehabilitation

What happens with the mill tailings if a uranium mine is abandoned, 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 a few cases the mill tailings may have been covered by a layer of soil.

The previous chapter discussed the inherently unsafe way of storage of the mining wastes in lake Taseq. From a physical/chemical point of view the least hazardous way to manage the mining wastes might be to isolate it from the human environment as discussed below.

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 second 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 insoluble 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. This situation mimics the pristine situation of the ores (Figure 10). The presence of the radioactive elements may be detected by gamma radiation from radon-222, the only gaseous decay product of uranium, that may diffuse through the layers isolating the tailings. Radon-220, the gaseous decay product of thorium, has a half-life too short to reach the surface.

Contamination of the groundwater is irreversible, so after isolation of the mill tailings in the above mentioned way, creeks, rivers and lakes may still be fed by water contaminated by radioactive elements and other toxic, non-radioactive chemical species. The extent of contamination depends on the condition of the rock, e.g. permeability and fissures, and of the top soil.

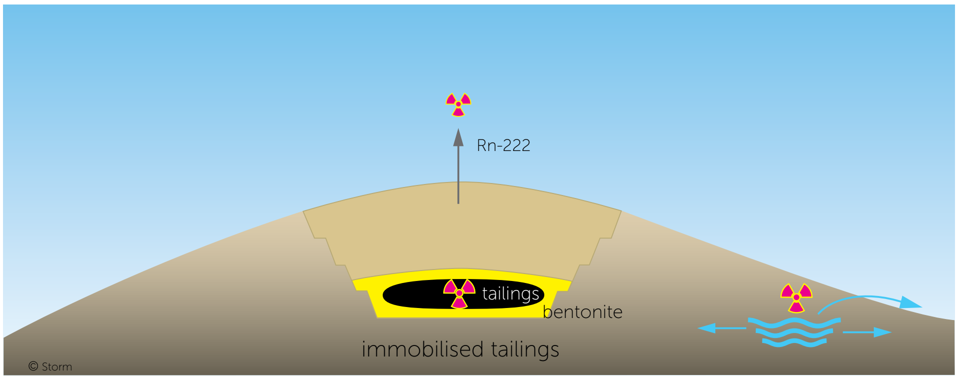

Figure 10
Generic outline of the rehabilitated mine at Kvanefjeld, according to a concept proposed by the author of this report. The radioactive and toxic tailings from CRSF and FTRF are isolated from the biosphere in the best conceivable way. The contaminated groundwater cannot be remediated.

View of GME

The EIA draft report (p.233-234) he option of moving the tailings back into the mine The report states:

> ‘However, since the tailings can only be removed with water it would require that the solids are re-suspended into slurry and pumped through a pipeline to the pit. This option is not practically possible for the following reasons:
>
> 1. After 37 years of deposition the tailings have compacted considerably making their re-suspension very difficult. It is estimated that the tailings are 70%+ solids with high viscosity and are therefore not in a pumpable condition.
> 2. Even if the tailings at the bottom of the Taseq basin are able to be pumped it will take a long time and considerable cost to move it to the pit because of the massive volume. Not only must all the tailings be pumped to the pit – in order to keep the material suspended – all the water in Taseq will also have to be pumped to the pit.
> 3. Re-slurrying of the tailings will result in the release of salts trapped in the pores of the consolidated solids. This will release further contaminants such as uranium, Fluoride and Phosphate into the tailings water, which then will have to be contained in the pit.
> 4. It will not be practically possible to provide separation of the two tailings fractions if deposited in the pit. This will prevent future recovery of residues such as Zirconium, Thorium and Gallium and heavy Rare Earth metals, which could be economically recovered with future technologies and/or higher product prices.’

If the tailings could be transported to a refinery in the future for reprocessing, see reason 4, why would it be impossible to transport the tailings back to the mining pit, right after closure of the mine?

As pointed out in Chapter 3, the argument to keep the tailings retrievable for reprocessing in the fulture is based on a fallacy. From the Second Law of thermodynamics follows that the extraction of metals from a depleted mixture such as the tailings, would require much more energy, chemicals and equipment per kg product than from the original, much richer mixture, the freshly ground ore. The recovery efficiency declines exponentially with decreasing concentration of the desirable species. This observation alone would imply very high recovery cost of minerals from the tailings. Moreover, the cost of the transport of the tailings to a future refinery, ‘practically not possible’ according to GME, would add enormous production cost to the products. Argument 4 comes not across as thrustworthy.

Summarised, the arguments put forward by GME/Orbicon do not sound very solid and the conclusion might be that there is just one dominant reason for refusing the isolation of the tailings in the mining pit as decribed above: the cost.

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 likely is an euphemism for ‘abandoned’. As far as known no uranium

mining and processing site in the world has ever been rehabilitated in a way compliant with acceptable environmental and health standards.
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 disasters at Chernobyl and Fukushima, cannot be attributed to radioactivity but have mental causes.
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.

5 Health hazards

Mining and milling

In the mining and milling processes the ore minerals containing the desired metals are brought into solution (leaching). In the case of Kvanefjeld the ore minerals contain rare earth elements (REEs) *and* the radioactive elements: uranium and thorium plus their radioactive decay daughters.
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 many 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, as is discussed in Chapter 5. Such events actually did occur at some uranium mines in the past. In case of a mine at Kvanefjeld a dam burst would have disastrous consequences, because the mill tailings would be located uphill and close to inhabitated areas and because of their massive volumes. Hundreds of millions of cubic meters of toxic and radioactive mud would rush down the Narsaq valley into the coastal sea. In view of the devastation by the mud flood from the Samarco mine (Chapter 3), one might imagine the consequenses of a mud flood ten times as massive.

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, and so its radioactive decay products.
The mining operations will generate large amounts of dust. A Risø study [Risø 1990] estimates some 1000 tonnes 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.

Health effects of REEs

Although this report focuses on the radioactive contents of the ores at Kvanefjeld, 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."

Exposure to radioactive materials

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 highy penetrating. Alpha and most beta radiation 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 periods are long: often the radiogenetic diseases become observable only after years or even decades. A point is that most of these diseases can be induced also by non-nuclear causes. So in most cases it is hardly possible to attribute a particular case 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 et al. 2010], [Paulitz 2012].
The relationship between adverse health effects and exposure to radioactivity can statistically be proved by epidemiological investigations, involving large numbers of people during a long period. 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 basis of knowledge on health effects of radioactivity

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. Little is known on the combined action of a number of different kinds of radionuclides together in the body. Empirical evidence proves young children and women to be more sensitive to radiation 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.

Limitations of models

As every scientist knows models are simplified descriptions of phenomena and mechanisms in reality. The outcome of calculations based on a model are determined by the the input of data and the assumptions on which the model is based. If empirical evidence deviates from predictions based on a model, the model is not correct and the evidence should not be discarded as 'outlier' or 'unreliable'.

Regulations concerning allowed contamination of air, water, soil, food and drinking water are recommended by the IAEA, but each country is free to set its own regulations. Generally they are not coupled to quantified standards, and in practice they prove to be easily adaptable to economic needs or other interests.

Orbicon in the EIA draft report does not make clear which figures of concentration of species in the waters of rivers, groundwater and coastal sea are based on measurements and experiments, and which are based on model calculations, for instance of the dispersion of dust from the mining activities, from waste rock dump and from the tailings in case they dry up.

We found no quantitatively defined standards related to allowed concentrations in water and dust, including PM2.5, of a number of species that could be dispersed from the processed ore, such as:
U + decay products, Th + decay products, REEs, Zn, As, Hg, Cd, Zr, Nb, Ga, Gd, Tb, Nb, Pb, F, NO_2, SO_2, O_3.

6 Costs, liabilities, guarantees

With respect to responsibilities and liabilities some questions need to be answered.

Which independent institute (see also the previous chapter) would be responsible for inspections and quality checks of the construction and maintenance of the mine facilities, including the tailings storage facilities in Taseq?
And for monitoring in the post-closure phase?

Which quality regulations would be applied?
Are those regulations based on quantitatively defined standards?

Who is liable for the damages as a result of the mining operations, during all phases: construction phase, operation phase and closure phase, including dam failures?
Which guarantees can GMEL and its associates give?
Would the funds set aside by the mining company (companies) for severe accidents be sufficient to cover the costs?
What if not so? Who pays the bill?

Who is liable for the damages as a result of the mining operations in the post-closure phase, including dam failures?
Who would own the mining area after the definitive closure of the mine?
What if serious shortcomings of construction and maintenance come to light in the post-closure phase?
Who pays the bill?

If GMEL, or a possible buyer of its mining rights, would intent to reprocess the tailings in Taseq, would the company apply for a new mining license?

The EIA draft report concerns a mine at the Kvanefjeld with an operational lifetime of 37 years, during which 111 million tonnes of ore would be mined and processed. This mass is 16.5% of the ore resources identified at the Kvanefjeld and 11% of the total resources at the Ilimmaasaq complex. The listed amounts of resources in the report include those of Zone 2 (Sørensen) and Zone 3 (see Table 1 in Chapter 1), suggesting that these resources would also be mined.
In its preliminary reports, published before the EIA, GME mentions an operating lifespan of the mine of 60 years.
In the White Paper of October 2015 GMe states that the life of the Kvanefjed mine Project is expected to go beyond 100 years.
What are the long-term intentions of GME?

ANNEX A

Outlook of uranium and thorium as energy sources

Energy costs energy

Generation of useful energy from a raw energy source, for example fossil fuels, uranium, hydro, wind or solar radiation, requires a technical system to convert the raw energy into useful energy, such as electricity. Construction, operation, maintenance and waste management of any energy system consumes materials and useful energy.
The nuclear energy system consists of industrial processes to prepare nuclear fuel from uranium ore, the nuclear power plant itself and a sequence of industrial processes to manage the radioactive and non-radioactive wastes from the nuclear system. All these processes consume energy and materials, the production of which also consumes useful energy.
The net energy production of the nuclear energy system, like any electricity generating system, is the gross energy production delivered to the grid minus the energy consumed by the system, measured from cradle to grave. By means of a thermodynamic assessment the energy consumed by the system can be reliably estimated.

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 EROEI is a convenient quantity for comparing different energy systems, for example nuclear power and solar power.

Mining energy

The mining of 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; the current world average grade is 400-1000 g U/ton rock. 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, consumes 2-3 times as much energy as from soft ores at same grade [Storm 2012a & 2012b].

Uranium recovery factor
From the fundamental laws of nature follows that any separation of a mixture of different chemical species is less complete as the concentration of the desired species in the mixture is lower and the mixture contains more different species.
The uranium content of the ores at Kvanefjeld 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 might be high, the more so because the uranium-containing minerals at Kvanefjeld are difficult to bring into solution. Because uranium

would be a byproduct at Kvanefjeld, only a part of the input of energy and chemicals of the mine could be attributed to the production of uranium.

Thermodynamic boundaries of uranium-for-energy resources; the energy cliff

Thermodynamics sets the boundaries for the resources that fit the conditions of uranium-for-energy resources. Thermodynamics is the science of energy conversions; it is at the basis of physics, chemistry and biology.

The energy content of natural uranium that is in any sense extractable is limited: the nuclear power stations that would form the backbone of future nuclear capacity could not fission more than 0.5-0.6% of the nuclei in natural uranium.
The thermodynamic boundaries of the uranium-for-energy resources are determined by the energy required to extract uranium from the resources as found in nature. Analysis of the physical and chemical processes needed to recover uranium from the earth's crust and all the processes needed to release the potential energy in uranium and convert it to useful energy proves that the amount of energy consumed per kg recovered natural uranium rises exponentially with declining ore grades. Below a grade of 200-100 ppm (0.2-0.1 grams U per kg rock) no net energy can be generated by the nuclear system as a whole from a uranium resource, this relationship is called the *energy cliff*. From this conclusion it follows that only uranium resources at grades higher than 200 ppm (0.2 g U/kg rock) are actually energy sources.

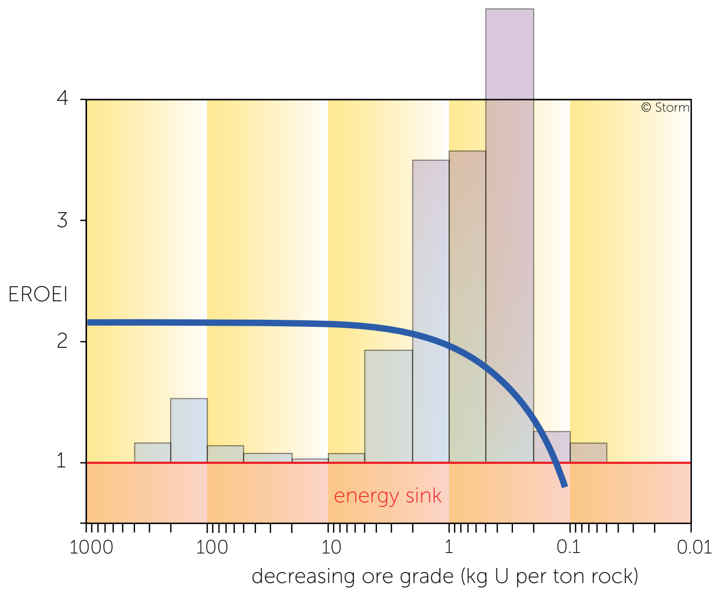

Figure 11

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. At uranium ore grades below 1% U (10 kg uranium per tonne rock) the EROEI of nuclear power starts declining at an increasing rate and becomes zero at grades between 200 and 100 ppm (200-100 gramU/ton rock). The bar diagram in the background represents the grade distribution of the world known uranium resources. The energy cliff does not depend on the operational lifetime of a nuclear power plant. Source: [Storm 2012a].

The ore grades of the known uranium resources which are by definition economically recoverable vary widely: from about 200 down to 0.1 gram uranium per kg rock. A part of the resources classified by the IAEA

as ‘recoverable’ falls beyond the thermodynamic boundaries of uranium-for-energy resources.
The uranium content of the ores at the Ilimmaasaq complex, at an average grade of about 210 gram U per ton rock, is at or near the energy cliff.

CO_2 emission of nuclear power, the CO_2 trap

Nuclear CO_2 emission originates from burning fossil fuels in all processes and factories needed to extract uranium from the ground, prepare nuclear fuel from the recovered uranium, construct the nuclear power plant and to safely manage the radioactive wastes. The fission process in the nuclear reactor is the only process of the nuclear system that has (virtually) no CO_2 emission. In addition CO_2 is generated by chemical reactions during the production of necessary materials and chemicals, for example cement (concrete) and steel. A generic NPP contains some 150 000 tonnes of steel and 850 000 tonnes of concrete, in addition to several thousands of tonnes of other materials. The sum of all materials consumed by an NPP during its operational lifetime is about 76 grams per kilowatt.hour delivered to the grid, excluding the mass of rock displaced for mining and final sequestration of the radioactive wastes.

By means of the same thermodynamic analysis that revealed the energy cliff, see above, the sum of the CO_2 emissions of all processes constituting the nuclear energy system could be estimated at roughly 90-150 gram CO_2 per kilowatt.hour. This figure is based on the assumption that all electric inputs of the nuclear process chain are provided by the nuclear power plant itself, to avoid discussions of the local fuel mix of electricity generation. The emission figure will rise with time, as will be explained below.

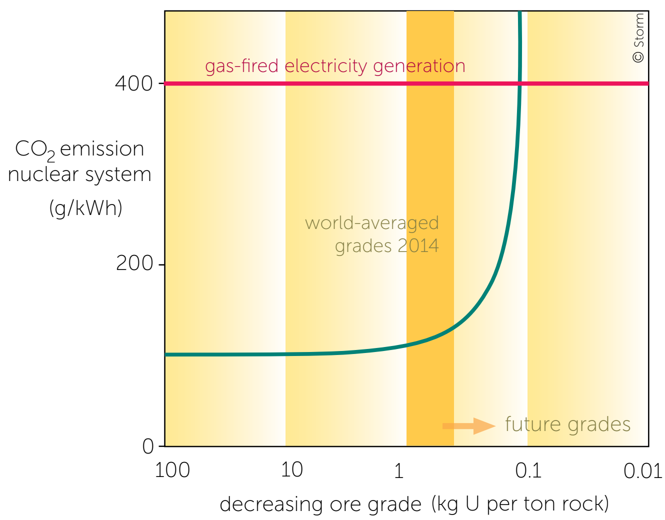

Figure 12
CO2 trap. CO2 emission of the nuclear energy system as function of the uranium ore grade. At present the world-averaged ore grade is 0.1-0.04% U (1000-400 grams U per ton rock). The average ore grade is declining because the richest ores are mined first and no new rich ore resources are found. Source: [Storm 2012a].

The energy consumption and consequently the CO_2 emission of the recovery of uranium from the earth’s crust strongly depend on the ore grade, and several other physical and chemical factors that are not discussed here. In practice the most easily recoverable and richest resources are exploited first, a common practice in mining, because these offer the highest return on investment. As a result of this practice the remaining resources have lower grades and uranium recovery becomes more energy-intensive and more CO_2 intensive. Consequently the specific CO_2 emission of nuclear power will rise with time; when the average ore grade approaches 100 ppm, the specific CO_2 emission of the nuclear energy system will surpass that of fossil-fuelled electricity generation. This phenomenon is called the *CO_2 trap*.

Coal equivalence
At a grade of about 200 ppm U, 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 published ore grades of Kvanefjeld are near this limit: in one of its recent publications GME mentions an average grade of 218 ppm U.

Prospects of new advanced nuclear technology

The nuclear industry promises the application within a few decades of advanced nuclear systems that would enable mankind to use nuclear power for hundreds to thousands of years. This promise, dating from the 1950s, concerns two main classes of closed-cycle reactor systems: uranium-based systems and thorium-based systems:
– uranium-plutonium recycle in conventional reactors, generally light-water reactors (LWRs)
– fast reactors, that are uranium-plutonium breeder reactors
– thorium reactors.

Reprocessing
A crucial component common to these advanced reactor systems is the reprocessing of spent fuel, that is the sequence of physical and chemical processes required to separate spent nuclear fuel into a number of fractions: unused uranium, newly formed plutonium, actinides, fission products and other fractions. The reprocessed uranium and plutonium would be used to fabricate new nuclear fuel to be placed into reactors. In case of a thorium-based system the spent fuel would be separated into unused thorium-232, newly formed uranium-233, fission products and other fractions.
Reprocessing is a complicated, highly polluting, and very energy-intensive process. Decommissioning and dismantling of a reprocessing plant after it has to be closed down requires massive investments of materials, energy and financial resources and likely will take more than a century of dedicated effort.

U-Pu recycle in LWRs
Uranium-plutonium recycling in conventional reactors (LWRs), relates to the use of plutonium as fissile material in nuclear fuel instead of uranium-235, as in enriched uranium; plutonium-containing fuel is usually called MOX: Mixed OXide fuel. If all spent fuel discharged from the current global nuclear fleet (all conventional reactors except one) were to be reprocessed and the plutonium obtained were to be used in conventional reactors, the global uranium demand would decrease by some 18%.
Thermodynamic analysis of U-Pu recycle in LWRs proves that the energy balance of the system is negative, meaning that the system is actually an energy sink instead of an energy source. The main cause of this is the required energy input of reprocessing and of the decommissioning and dismantling of the reprocessing plant at the end of its service life.

Fast reactors: uranium-plutonium breeders
The term ‘fast reactor’ usually refers to the breeder system, a closed-cycle system that would generate (breed) more fissile nuclei from uranium than consumed in the fission process by converting non-fissile

uranium-238 nuclei into fissile plutonium nuclei.
The envisioned breeders would be able to extract 50-100 times more energy from a kilogram of natural uranium than the current conventional reactors, that cannot fission more than about 0.6% of the nuclei in natural uranium.
A breeder (FBR) is not just a reactor but a cyclic system consisting of a fast-neutron nuclear reactor plus a reprocessing plant plus a fuel fabrication plant. Each of the three components of the cycle would have to operate flawlessly and finely tuned to the two other without any interruption. If one component fails in any respect, the whole system fails and breeding is out of question. Operation of the cyclic system is further complicated by the high radioactivity of the materials to be processed, increasing with each following cycle. Four decades of intensive research in several countries and investments of some $100bn, have proven that the breeding cycle is technically unfeasible.
The failure to realize the U-Pu breeder concept can be traced back to fundamental laws of nature, especially the Second Law of thermodynamics. From the Second Law follows, among other consequences, that separation processes of mixtures of different substances never go to completion and consequently perfect materials are not possible. Critical in the breeder cycle are the availability of perfect materials and constructions, and the ability to separate spent fuel completely in 100% pure fractions, as soon as possible after unloading from the reactor,

Thorium reactors

Thorium is a radioactive metal, more abundant in the Earth's crust than uranium. The concept of the thorium reactor is based on the conversion by neutron capture of non-fissile thorium-232 into uranium-233, which is as fissile as plutonium-239. Application of thorium-based systems would make nuclear power independent of the uranium supply, according to the promises of the nuclear industry.

The fundamental obstacles that render the U-Pu breeder technically unfeasible apply even more to the thorium breeder. Another drawback of the thorium cycle is that a thorium reactor cannot sustain a fission process in combination with breeding uranium-233 from thorium-232, but always would need an external accelerator-driven neutron source, or the addition of extra fissile material, such as plutonium or uranium-235 from conventional reactors.

Thermodynamic barrier to U-Pu and Th-U breeders

Examination of the breeder concepts, U-Pu as well as Th-U, proves that these concepts are based on inherently infeasible assumptions. *Conditio sine qua non* for these closed-cycle nuclear generating systems is the availability of:

- perfect materials with perfectly predictable properties across decades
- fail-safe and fool-proof technical systems with perfectly predictable properties across decades
- perfect separation of strongly radioactive, complex mixtures of dozens of different chemical species into 100% pure fractions.

None of these conditions is possible, as a consequence of the Second Law of thermodynamics, and for that reason materialization of the U-Pu and Th-U breeder concepts is inherently unfeasible.
From this observation it follows that nuclear power in the future would have to rely solely on once-through reactor technology based on natural uranium. As a consequence the size of the uranium-for-energy resources will be a restricting factor for the expansion of civil nuclear power.

ANNEX B

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.

Politicians should be aware of the promotional and political aspects and of 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].

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 viewpoints on that issue.

Reliance on radiological 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.

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