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KVU – Handling of Norwegian Spent Fuel and other Radioactive Waste

Options for treatment of spent metallic uranium fuel, Task 2

Sture Nordlinder

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Abstract

This report is one of the technical reports in the KVU process regarding a possible new interim storage facility for spent nuclear fuel and other radioactive waste. This report analysis the possible options for handling and treatment of unstable nuclear fuels. Unstable fuel is defined as spent nuclear fuel requiring a conditioning treatment before it is suitable for final storage in a geological repository. The unstable fuel consist of spent metallic uranium and/or spent fuel with aluminium cladding.

Different options to treat the unstable fuel are discussed and advantages and disadvantages are presented for each option. The viable options are then further analysed. The analysis shows that the most advantageous method is reprocessing based on criteria of cost, technology and safety/risk.

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1 Introduction

This report is one of the technical reports in the KVU process regarding a new interim storage facility for spent nuclear fuel and other radioactive waste.

The technical issues important for the storage under consideration are treated within separate tasks. The technical tasks within this KVU are:

Task 1	Overview of existing waste
Task 2	Treatment of unstable fuel (this report)
Task 3	Storage concept
Task 4	Safety and security
Task 5	Environmental protection
Task 6	Operation of the storage

This report only considers unstable nuclear fuels (Task 2) which consist of metallic uranium and/or fuel with aluminium cladding. The unstable fuel must be conditioned before final storage since metallic uranium fuel and aluminium cladding may degrade during storage by corrosion processes. The gases generated as a result of corrosion can jeopardise the integrity of the barriers resulting in leakage and transport of radioactive nuclides to the environment.

The main option for the unstable fuel is either to continue to store the fuel in its present form with necessary packing and precautions or reprocess or condition the fuel to a form suitable for final disposal.

The strategy for treatment of unstable fuel has been evaluated in two previous Norwegian public inquires NOU 2001:30 and 2011:2 /D047 and D048/. The later investigation recommended re-processing of the unstable fuel.

1.1 Purpose

The objective of this task in the KVU-process is to present possible strategies for handling and treatment of the unstable fuel originating from the nuclear facilities in Norway. The assessment of current options will provide recommendations on possible technical solutions to be further evaluated in the KVU process. The strategies assessed and recommended must result in a final strategy that follows the restrictions of the Norwegian legislation (Act no 28 of May 1972 concerning Nuclear Energy Activities and Act on Radiation Protection and Use of Radiation, No. 36 of 12 May 2000).

The methods chosen for conditioning of the unstable fuel and the resulting physical/chemical form of the material after conditioning will have a significant effect on the design of the interim storage for spent fuel and long lived waste.

1.2 Methods

The two Norwegian public inquires NOU 2001:30 and 2011:2 /D047 and D048/ and one investigation /D057/ have assessed different options for treatment of the unstable fuel. The focus for this task has been to collect and review information referring to international practices in management of unstable spent fuel including the available treatment options.

This study will highlight possible strategies/technologies used internationally for unstable fuel. Activities to collect all the available information will be the main focus which are necessary for the KVU process.

The assessment deals with the interim storage and final disposal safety of different options for unstable spent fuel. Advantages and disadvantages will be discussed for each strategy.

The outcome of this assessment will be described thoroughly in terms of advantages and disadvantages of the most promising options, and a ranking of those options from economic, technical and radiation protection points of view.

1.3 Scope, delimitations and assumptions

The spent nuclear fuel in Norway consists of several types, including fuel from experiments and tests. A significant part of this fuel is considered to be unstable. The criteria for this definition, as per NOU 2011:2 /D048/, are that the fuel consist of metallic uranium and/or has aluminium cladding. This report deals mainly with the 11.3 tonnes of metallic uranium fuel and the 1.5 tonnes of uranium oxide fuel with aluminium cladding.

There are also spent nuclear fuels in the form of uranium dioxide with Zircaloy or stainless steel cladding. Those fuels are not treated within this assessment as those types can be stored or disposed of by mature technology and without any major risks for degradation.

2 Background

2.1 Present situation in Norway

The spent nuclear fuels are from three heavy water research reactors in Norway. The JEEP I reactor was in operation at Kjeller from 1951 to 1967, JEEP II, also located at Kjeller, has been in operation since 1966. The Halden Boiling Heavy Water Reactor (HBWR) located in Halden, has been in operation since 1959. JEEP II and HBWR are still in use. A fourth reactor, NORA, was in operation at Kjeller from 1961 to 1968. The fuel from this reactor, which was identical to that used in JEEP I, was returned to USA, and thus is not discussed further in this report. Table 2.1 lists the reactors in Norway.

Table 2.1
Norwegian nuclear reactors, operation period and fuel type /D048/.

Reactor	Operation period	Fuel type	Cladding	Amount of fuel (Tonne)
JEEP I	1951–1967	Metallic	Aluminum	3
NORA	1961−1968	Metallic	Aluminum	Fuel returned to USA
JEEP II	1966–present	Oxide	Aluminum	2
HBWR	1959–1960	Metallic	Aluminum	7
HBWR	1960−present	Oxide	Zircaloy	3

Some spent fuel from JEEP I was used in a pilot reprocessing plant at the Kjeller site, which was in operation from 1961 to 1968, and later decommissioned. The second core loading of the HBWR was reprocessed in Belgium in 1969. The recovered uranium and plutonium was sold for civilian use, and the waste was disposed of in Belgium. With these exceptions, all Norwegian spent fuel is stored at Kjeller and Halden.

2.1.1 Description of fuel

In total Norway has some 17 tonnes of spent fuel, of which six tonnes are stored at Kjeller and 10 tonnes in Halden. Approximately 12 tonnes of the fuel has aluminum cladding, of which 10 tonnes is metallic uranium fuel and the remainder is oxide fuel (UO_2).
Table 2.2 lists the amounts of nuclear fuel in Norway.

Table 2.2
Amount of nuclear fuel in Norway of 1 January 2009 /D048/

	In Kjeller (tonne)	**In Halden (tonne)**	**Total (tonne)**
Enriched uranium	1.98	3.44	5.42
Natural uranium	4.33	6.94	11 221
Total	**5.42**	**11.25**	**16.69**

Table 2.3
Details of the stored fuel from the different reactors reported by Technical Committee /D049/.

	HBWR	**JEEP I**	**JEEP I Seed**	**JEEP I Void**	**JEEP II**
Fuel material	Metallic uranium	Metallic uranium	UO_2	Metallic uranium	UO_2
Cladding material	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium
Total mass U, tons	6.7	3.1	75 kg	37 kg	2.0
Number of fuel rods	308	176	60	7	1050
Fuel rod diameter, cm	2.54	2.54	1.27	2.54	1.28
Fuel length, cm	237.5	190 (active fuel stack)	96.5 (active fuel stack)	190	90
Initial enrichment, %	Natural uranium	Natural uranium	1.7	Natural uranium	3.5
Irradiation period	1000 hours (1959 – 1962)	1951 - 1967	1951 – 1967	1951 - 1967	1966 to present
Burn-up, MWd/t U	12	1 – 1000 (mostly 200 – 400)	570-1000	NA	Average 15 000

In Kjeller the metallic fuel from the JEEP 1 reactor is stored in a separate building. The storage consists of a concrete foundation containing holes or wells that are about three meters deep and lined by steel tubes. In each hole one fuel element is stored where each element consists of two rods. The elements are placed in steel containers. Initially the fuel was stored in aluminium containers in a wet storage facility. The fuel was transferred to the present day storage facility. In 1982 the fuel was repackaged and put in the stainless steel containers.

The metallic fuels from the HBWR reactor are stored at Halden in horizontal tubes in a construction of concrete. The fuel is placed in containers of aluminium which are water tight. The cladding of the HBWR fuel was anodized, which formed a protective oxide layer on the surface of the cladding. The cladding of JEEP 1 fuels was not anodized.

In 2011 and 2012 some elements of the fuel were examined. The examination was performed for 5 elements of metallic fuel from the HBWR reactor and one element from the JEEP 1 reactor /D146/.

The conclusion from the examination of the selected fuel is that for the HBWR fuel there is no sign of damage or corrosion of the fuel. For the JEEP 1 fuel blisters and cracks were observed. In this latter case, the examined fuel rod was sectioned through one of the blisters and corrosion products between the cladding and the fuel pellets were identified. Since such damage had already been documented at the time when the fuel was transferred to the dry storage, it was assumed that the damage occurred during reactor operation or the initial period of wet storage.

The better condition of the HBWR fuel can probably be attributed to the anodization of the cladding. A program for control of the stored fuel has been suggested by IFE/D147/.

Currently there is no metallic fuel in the reactors at Kjeller and Halden. The fuel in Halden is oxide fuel with zircaloy cladding, the amount of fuel in the core is about 460 kg and 80 kg is exchanged yearly on average. The core at Kjeller contains about 220 kg of fuel and 45 kg is exchanged on average per year. The fuel in JEEP II is in oxide form with aluminium cladding.

2.2 Risks and Safety

Assessment and demonstration of safety for radioactive waste management and development and operation of facilities has to be undertaken before operations begin; a so called “safety case” must be made. The safety case should be approved by the responsible authorities in advance. The safety case should be prepared by the operator /D252/.

The safety principles to be applied during all radioactive waste management and development and operation of facilities are established in the IAEA Fundamental Safety Principles /D250/ and are:

Principle 1: The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks.

Principle 2: An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.

Principle 3: Effective leadership and management for safety must be established and sustained in organizations concerned with, and facilities and activities that give rise to, radiation risks.

Principle 4: Facilities and activities that give rise to radiation risks must yield an overall benefit (justification).

Principle 5: Protection must be optimized to provide the highest level of safety that can reasonably be achieved (optimization).

Principle 6: Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm (limitation of risks to individuals).

Principle 7: People and the environment, present and future, must be protected against radiation risks.

Principle 8: All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.

Principle 9: Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.

Principle 10: Protective actions to reduce existing or unregulated radiation risks must be justified and optimized.

The principles form the technical basis for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, IAEA INF 1997 /D153/.

The main component of the safety case is a safety assessment and involves assessment of a number of aspects, including the radiological impact on humans and the environment. Other important aspects within a safety assessment are site and engineering aspects, operational safety, non-radiological impacts and the management system.

For the spent metallic uranium the following main risks have been identified and should be included in a safety case:

- Corrosion of metallic uranium.
- Radiation exposure of personnel.
- Release of radioactive nuclides to the environment and radiation doses to the public.
- Proliferation risk reduction.
- Physical protection.

2.2.1 Corrosion of metallic uranium

The chemical reactions when uranium metal is exposed to water give rise to the corrosion products uranium oxide (UO_2) and uranium hydride (UH_3). The main corrosion reactions are /D265/:

$$U + 2\ H_2O \rightarrow UO_2 + 2\ H_2$$
$$2\ U + 3\ H_2 \rightarrow 2\ UH_3$$
$$7\ U + 6\ H_2O \rightarrow 3\ UO_2 + 4\ UH_3$$

Uranium hydride reacts with water or oxygen:

$$UH_3 + 2H_2O \rightarrow UO_2 + 7/2H_2$$
$$UH_3 + O_2 \rightarrow UO_2 + 3/2H_2$$

The last two are important from a safety point of view, because of the pyrophoric nature of uranium hydride, which makes it important to limit the supply of oxygen in gaseous form. The risk is due to the rapid exothermic reaction of the uranium hydride oxidation. The rate of the reaction depends on the quantity of the hydride present, the concentration of the hydride within the corrosion products, the accessibility of oxidant, (principally air) and heat transfer. It is difficult to quantify the rate of the reaction. Observations have shown that handling of corroded fuel in hot-cells will increase from a slow to a rapid exothermic reaction within a couple of minutes.

It is necessary to minimize the amount of water and moister, which can come into contact with metallic uranium in order to avoid formation of uranium hydride and hydrogen. The reactions between uranium hydride and water or air (oxygen) and between hydrogen and air can threaten the integrity of the different barriers encapsulating the fuel.

This show that long time storage of metallic fuel must consider storage in inert atmosphere and program for monitoring or inspection must be developed and performed.

2.2.2 Exposure of personnel

The exposure of personnel to radiation from the spent fuel and other radioactive material has to be minimised.

There are three options for reducing the doses from radiation sources: limit the time of exposure; increase the distance from the source; and provide shielding. Distance and shielding are the common methods to minimize the dose to worker.

For radiation workers the dose limits are recommended by the International Commission on Radiological Protections (ICRP) which are published in its annals (http://new.icrp.org). Most important in radiation protection is the ALARA-principle which says that that any activity with risk for radiation exposure should be optimised so that the resulting doses are As Low As Reasonably Achievable.

Inhalation or ingestion of radionuclides will give rise to internal radiation doses. This exposure can be more critical than external exposure as the exposure continues from the nuclides remaining in the body after inhalation or ingestion. If there is a risk for radioactive or aerosols, which can then be inhaled, necessary protective action has to be taken, such as providing respiratory protection.

2.2.3 Releases to the environment

The main fraction of the radioactive nuclides will be generated within the fuel during operation. However, the cladding material, cooling water and construction materials in the reactor will be activated by neutron radiation during operation. Different components will also be contaminated on the surface during operation from nuclides released and then deposited.

In a storage a storage facility radioactive nuclides in the spent fuel are sealed within several barriers with the purpose of avoiding radionuclide releases. The first barrier is the fuel itself as the nuclides will be retained to some extent within the matrix of the uranium. The next barrier is the cladding of the fuel, and then the storage container and a final barrier is the building. Depending on the physical and chemical characteristics of the nuclides the degree of migration through the barriers differ, for example noble gases can more easily be released than nuclides that occur in solid particulate form.

The purpose of the safety analyses is to prove that any conceivable incident or accident will not compromise the overall barrier system so that no unacceptable release will occur resulting in radiation doses to the public.

2.2.4 Proliferation

Most countries participate in international initiatives designed to limit the proliferation of nuclear weapons. IAEA undertakes regular inspections of civil nuclear facilities and audits the movement of nuclear materials through them. The international safeguards system has been in operation since 1970. Among others it includes export control, inspection at operators holding fissionable material with review of documentation and also physical observation of the material. The inspections are both preregistered and unannounced.

2.2.5 Physical protection

To protect the nuclear material from theft and sabotage the operator together with the security police analyses the threat for the facility. Based on this proper physical protection is established for the facility. The threat should regularly be assessed and updated. The physical protection of nuclear material is regulated in the Norwegian regulation FOR-1984-11-02-1809.

2.3 International experience

According to the IAEA research reactor database (http://nuclus.iaea.org/CIR/CIR/RRDB.html#, 2014) there are 246 research reactors presently in operation, 90 of which have thermal powers of more than 1 MW. In total 338 have been decommissioned and an additional 143 have been shut down. Of those which have been shut down or decommissioned 155 had thermal powers of more than 1 MW.

The fuels for research reactors are, according to international practice, divided into High Enriched Uranium fuel (HEU) or Low Enriched Uranium fuel (LEU). LEU fuel has an enrichment of U-235 lower than 20 % while HEU has enrichment above 20 %.

According to IAEA database there are 24 272 fuel assemblies in research reactor cores presently worldwide, and 60 887 fuel assemblies in storage. Of those stored assemblies 20 665 are HEU and 40 222 LEU.

Most of the research reactors worldwide have received the fuel either from the USA or former Soviet Union. This fuel was in many cases metallic and has to be returned to the country of origin in accordance with conditions for using the fuel. The majority, almost 60 %, of the stored reactor fuels used in research reactors are from the Russian

Federation or USA. These fuels will be taken care of by the supplier within the relevant program: Russian suppliers via the Russian Research Reactor Fuel Return program; and suppliers in the USA via the USA Foreign Research Reactor Spent fuel acceptance program. The fuel in Norway does not come from the USA or the Russian Federation (or former Soviet Union). Therefore it is not possible to return it to those countries within the fuel return programs.

According to IAEA /D260/ there are three definitive solutions for the reactor operator: return of the fuel to the country of origin, send for reprocessing, or final disposal. If none of these options is available, then the only alternative left is the interim storage of the spent fuel. Interim storage is not a final solution and the final solution must be found or be identified and developed in the meantime. There is no final repository in operation world-wide, however, final repositories are in the application process in Finland and Sweden.

2.3.1 Shared facilities for spent fuel

Several multinational projects on collaboration within the nuclear fuel cycle are ongoing and cover the possibility for sharing facilities for disposal of spent fuel and nuclear waste /D262/. There is a change in the global attitude concerning such collaboration. Previously it was a generally held opinion that each nation should take care of its own radioactive waste. Countries which only have small amounts of long-lived wastes from nuclear applications in research, medicine and industry could have difficulties developing and implementing repository facilities. The implementation of multinational or regional repository facilities would have potential advantages for safety, nuclear security, non-proliferation, environmental impact and economics. However, the IAEA document /D262/ states that international cooperation should never be an argument to postpone a decision on a repository facility or to establish a wait-and-see approach.

Several studies are ongoing, with differing scopes and depths and are presented in the reference. Some are merely theoretical concepts while others are more specific projects that could lead to development of shared facilities. However, such a shared facility for disposal of spent fuel and high level waste is not a viable option within the foreseeable future.

The development of a regional or a multinational repository may be a solution /D269/. According to the definition of IAEA a regional repository is between countries belonging to the same geographical region, while otherwise, it is called multinational repository.

A regional or multinational repository will require significant political negotiations to resolve the complex array of agreement needed before it can be implemented. Issues such as compensation, property, responsibility for maintenance, etc. would need to be clearly defined. Laws will also likely need to change since many national jurisdictions forbid receiving radioactive material that is considered “waste”.

2.3.2 Export or swap

According to the Joint convention on the safety of spent fuel management and on the safety of radioactive waste management /D153/ the waste should be disposed of in the country where it was generated. However, the convention also states that during certain circumstances, especially where waste is generated by joint projects, waste could be stored or deposited in a state other than the one in which it was generated. Such an option needs agreement between all involved parties and should be of benefit for all. The convention also states that any state has the right to ban the import of foreign spent fuel or radioactive waste into the country.

The Joint convention does not specifically say anything about swapping waste between countries. However, through agreements among involved parties, waste swapping is possible if it benefits all the involved parties.

Export of spent fuel from research reactors is made within the USA’s program or Russian program presented above. Reprocessing at a foreign facility could be seen as the export/swap of spent nuclear fuel but is normally treated as a specific option.

2.3.3 Reprocessing

The metallic fuel with aluminium cladding from the Swedish research reactor R1 (similar to the Norwegian unstable fuel) was transported to Sellafield, UK in 2007 for reprocessing /D251/. Reprocessing was found to be the most effective method for the fuel as the Swedish system for final deposition of nuclear fuel does not accept metallic fuel. The amount of fuel was 4.8 tonnes of natural uranium. The reactor was located in Stockholm and was in operation between 1954 and 1970. At shut down, the fuel was transported to Studsvik for storage. There was comprehensive preparation and planning to perform the transport and reprocessing, including agreement between the national authorities, safety analyses, a licensing procedure and preparation and packing of the fuel in transport casks. The project was successfully performed.

Reprocessing is performed routinely in Europe, Russia and Japan. Reprocessing is a proven technology for dealing with standard types of fuel as well as for metallic fuels /D262/. In reprocessing plants fissile materials and wastes are handled, processed, treated and stored. Safety features based on the defence-in-depth concept are implemented both in the design of the facility and in its operation. Management of the design process ensures that the structures, systems and components important for ensuring safety have the appropriate technical characteristics, specifications, and material properties, which are compliant with their safety functions /D259/.

2.3.4 Storage

Storage of spent fuel from research reactors is employed worldwide, both wet and dry storage being used /D260/ and discussed /D256/. For long-term storage dry storage is preferred because the operational costs are considerably higher for wet interim storage. Wet storage requires systems for water purification and a corrosion surveillance program has to be implemented. The risk of corrosion damage of the fuel is considerable when wet storage is employed. However, wet storage is commonly used for spent research reactor fuel.

Dry interim storage has been the choice in many countries. It is relatively low cost option that keeps treatment strategies open, and permits a decision on final disposal to be delayed. The main purpose of dry storage is to keep the spent fuel safe and secure while allowing it to be retrieved for alternative management approaches in future (e.g. storage elsewhere, reprocessing or final disposal). The main challenge of an interim store for spent fuel is the necessity to avoid significant fuel degradation during storage which could result in releases of radioactive nuclides.

Two types of dry storage systems can be are used: sealed system where the spent fuel assemblies in fully-sealed containers and non-sealed system where the spent fuel is stored in non-sealed containers or holders open to the environment of the storage building.

Non-sealed dry storage is similar to wet storage in the sense that active systems are required. A non-sealed dry store requires a ventilation system to be operated continuously and control of the humidity in the storage building. This implies operational costs for a long time.

The sealed dry storage option has lower operational costs than wet and non-sealed dry storage, but the initial investment is higher. A high-technology infra-structure is needed to handle, dry and seal the spent fuel. It may include the necessity of building a hot-cell, or the development of some equipment with sufficient shielding, where the fuel can be properly dried and encapsulated. Once the fuel is properly dried and put in a canister, the probability of corrosion decreases considerably. No additional action is required, unless there is some evidence requiring a mitigating action, like for example, canister pressurization /D260/.

2.4 Future nuclear fuel cycles

In connection with the future development of nuclear reactors and the associated fuel cycle, a number of treatment options for spent fuel are under development and/or being demonstrated at a pilot scale.

The advantage in some of the new reprocessing concepts is that those can avoid separation of pure plutonium /D262/. Furthermore, an important issue in new reprocessing concepts is to recover all actinides and long-lived fission products which will reduce the radio-toxicity of the waste products. However, there are no facilities planned for processing metallic fuel which would become available in the foreseeable future. On the contrary, it is more likely that the new facilities which accepts metallic uranium fuel will be fewer or even non-existent in the future.

3 Conclusions and recommendations

The review of possible options (see chapter 4) resulted in four methods which were further analyzed. The options for the unstable fuel are to:

- Continue with the present stores
- Build a new store with improved conditions that reduce the risk for corrosion of the cladding and fuel
- Reprocess
- Conditioning

Interim storage of spent fuel is part of the management strategy for the overwhelming majority of research reactor facilities /D360/. Interim storage is used where the waste generators cannot return the spent fuel under the terms of the fuel return programs operated by Russia and USA. The Norwegian fuel is not qualified for either of these programs. Interim storage will require that a final disposal option is subsequently decided.

Storage is a possible option for the spent fuel in Norway, however for long-term storage repacking and a new storage facility is recommended. Storage in the present facilities will require regular control of the conditions of fuel and cladding. With repacking, conditions can be obtained, which allow long time storage.

Reprocessing or conditioning of the fuel abroad will be a possible solution for Norway. Domestic reprocessing requires development of new facilities and/ or technologies. The option of reprocessing fuel abroad implies that the main fractions of spent fuel (uranium and plutonium) will be reused in new nuclear fuel and only a small fraction of the radionuclides in the spent fuel will require final disposal. For the conditioning option all conditioned fuel will need final disposal as well as the decommissioning of the facility used for conditioning.

The ranking of the four selected options shows that reprocessing or long-term storage in a new facility are equally advantageous. However, within the ranking final disposal was not included. The criteria used for the ranking was costs, technological maturity and a lumped criteria corresponding to safety and risk.

4 Analysis

The first step in the KVU process is to list all possible options for treatment of used unstable nuclear fuel which internationally have been used or are viable. Those are considered in Section 4.1 “Overview of opportunities”. Options that have been proposed in the past elsewhere, but which are considered to be clearly impracticable and / or unsafe, such as sending the waste into space, were not considered. For each option the advantages and disadvantages are listed. In Section 4.2 the selected possible methods are analyzed and finally the ranking of the options is given in Section 4.3.

4.1 Overview of opportunities

This section refers to the results of the opportunity study within the KVU-process regarding the treatment of the unstable fuel (metallic fuel and/or fuel with aluminium cladding). All possible options are discussed and a first evaluation is performed based on the experience and competence of the authors. Some of the options are more or less feasible due to technical difficulties. The following main categories of options are valid:

- Storage
- Exchange or export
- Reprocessing
- Conditioning

Within each of these main categories there is more than one option. Each option is described in the following subsections.

The main problem with metallic uranium and aluminium is corrosion. One of the corrosion products which can be obtained if water is present, is uranium hydride which is very reactive with oxygen. The corrosion will also generate hydrogen and in sufficient concentration and in the presence of oxygen this will be explosive. The generation of gas may also jeopardize the integrity of barriers between the waste and environment due to the pressure increase that will occur. Therefore it is very important to avoid the risk of significant corrosion within a store or repository, so that safety far into the future can be ensured.

Any conditioning of the unstable spent fuel should be performed with the purpose of stabilizing the fuel to produce a form suitable for emplacement in a final repository without any further treatment. This implies that the metallic fuel and aluminium has to be conditioned to a physically and chemically stable form with controlled characteristics.

4.1.1 Storage in present facilities

This alternative implies continuation with the present storage as it is (wait and see). The capacities of the stores at Kjeller and Halden will allow for operation of the reactors up to 2032 and 2025, respectively /D048/. If the operation of the reactors should continue for a longer period some type of additional storage for the spent fuel will be needed.

The present storage facilities could probably not be in use for an additional 100 years. There is a risk that the metallic fuel could be corroded in the present store. If such corrosion is allowed to continue without any mitigation action it could jeopardize the integrity of the store and result in releases of radioactive substances to the environment.

A program for regular inspection and control of the fuel has to be developed. Recent investigation of some fuel rods /D146/ did not identify any new signs of corrosion. However, only a very limited number of rods were investigated and a more comprehensive investigation needs to be performed to verify that the condition of the fuel is sufficiently good for further storage, such plane for inspection and monitoring is prepared by IFE /D147/.

Disadvantages:

- Safety cannot be guaranteed for a period of 50 to 100 years of storage.
- The unstable fuel must be conditioned in the future.
- Responsibility for a final solution is transferred to future generations.
- There is uncertainty about future costs.
- Suitable facilities for conditioning/reprocessing may not be available in future.
- Regular surveillance and inspection of the fuel will be necessary.

Advantages:

- The initial cost is relatively low.
- The decay of radionuclides will decrease the dose-rate over time and simplify the handling of the fuel in future (will only be of marginal importance as the short lived nuclides have already mostly decayed).

4.1.2 Storage in a new facility

Long-term interim storage of the unstable fuel is thoroughly discussed in the report from the Technical committee /D049/ (section 8.1.2.). The conclusion by the technical committee is that this method is inconsistent with the ethical recommendations by the OECD/NEA /D267/. The public inquiry /D048/ recommended reprocessing for the unstable fuel. Long-term storage of the metallic fuel was, furthermore, not recommended by the Technical committee. The OECD/NEA stress the importance of defining the time period for which a store should be in operation /D256/.

Nevertheless, the specification of this task in the mandate given for the KVU clearly states that this option should be assessed.

Before the metallic and aluminium clad fuel can be deposited in a repository it must be conditioned as otherwise this type of fuel will not be accepted for final disposal (in fact the safety of the repository has to be proven). Therefore, if the fuel is stored in metallic or aluminium-clad form initially, reprocessing or conditioning will be necessary in a later stage. The reason to delay the conditioning could be to allow new and better methods to be developed in the meantime. The OECD/NEA and IAEA endorse an active participation in the development of such new methods /D267/. However, it is not satisfactory just to wait and see what other operators will come up with.

Today there are only a few facilities which can reprocess the metallic fuel (discussed further below). In different parts of the world there is development of new concepts for nuclear power plants with new type of fuels and fuel cycles. However, it cannot be assumed that those new processes will be better suited for treatment of the Norwegian metallic fuel than the processes that are presently available.

Long-time storage of the unstable fuel is feasible but requires attainment of preferable conditions. The main options for storage of spent fuel are wet or dry storage. Wet storage should be excluded, as this is normally used for used fuel with high decay power and/or where the water is suitable for shielding. The present fuel has low decay power and the storage in water will only complicate the necessity to avoid corrosion.

For spent research reactor fuel, the IAEA recommend dry storage /D260/. For dry storage two main options are used internationally: storage canisters; or vaults with controlled ventilation. The selection of canister should consider the requirements for transportation of the spent fuel to a facility for conditioning, ideally to avoid repacking the fuel in other transport casks.

The key issue for safe storage for extended periods of time is mitigation of corrosion by controlling the environmental conditions around the fuel. This can be achieved by ensuring dry conditions within the storage packaging, involving drying the fuel and ensuring that the packages contain a dry and inert atmosphere

Before canisters are sealed, fuels need to be dried to remove as much of the free and chemisorbed water as possible. The most common method is vacuum drying. Heating the fuel is also used. This latter method has been assessed for storage and degradation of metallic fuel /D260/. Long-term storage is feasible for at least 50 years, however, before final disposal the unstable fuel must be conditioned to a stable form. Therefore, storage of unstable fuel will only delay the necessary treatment. Commercial alternatives for reprocessing metallic fuel are available today. However, it is uncertain whether these alternatives will continue to be available over the time frame of 100 years. There is no evidence that any new options or facilities suitable for processing metallic fuel would become available in the foreseeable future.

Disadvantages:

- The unstable fuel must be conditioned in the future.
- It is uncertain whether facilities for reprocessing will continue to exist in the future.
- This option transfers the problem to future generations.
- There is uncertainty about future costs.

Advantages:

- The degradation of the fuel during storage can be avoided with suitable encapsulation.
- Sufficient physical protection can be provided.
- Periodic inspections can be employed to verify integrity.
- New methods for conditioning may be developed during the period of storage and prior to final disposal.

4.1.3 Disposal of metallic fuel in a final repository

Direct disposal of metallic and aluminium clad fuel is not considered as a viable option as the risk for corrosion of metallic uranium and aluminium may threaten the integrity of the barriers in a repository. According to international guidance disposal of metallic uranium and aluminium should be avoided in repositories as it will be difficult to prove the long time safety of the repository.

Disadvantages:

- Long-time safety of the repository cannot be guaranteed.
- Risk of release of radioactive nuclides from the final repository resulting in doses to future generations.
- Not internationally accepted

Advantages:

- None, as it is not acceptable

This method is not feasible and will not be considered further in the evaluation process.

4.1.4 Export within the GTRP program

The Technical Committee /D049/ had correspondence with the US department of Energy regarding the possibility of including the metallic fuel within the Global Threat Reduction Program (GTRP). Only a small fraction of the spent fuel has its origin in the USA and could be accepted in the program. The majority of the used fuel did not fulfil the criteria, for example the origin of the uranium and its low enrichment made the fuel ineligible for acceptance under the program. The Technical Committee recommended further diplomatic contacts to evaluate further the possibility of including the spent fuel in the GTRP. The public inquiry, NOU 2011:2 /D048/ did not address this issue.

This procedure will not be further analysed in the evaluation process as the spent nuclear fuel does not fulfil the criteria for acceptance within the GTRP.

Probably this option would be the most preferable solution if the spent fuel could be accepted within the GTRP program. This possibility requires further negotiations between responsible authorities. Unless previous negotiations reached a final conclusion it is recommended to establish contacts between responsible parties for the further investigation of this possibility.

Disadvantages:

- The possibility for the spent fuel to be accepted for the GTRP is low.
- The total cost is uncertain.

Advantages:

- A repository for this spent fuel will not be needed.
- Handling of the spent fuel is relatively simple and straightforward.
- No reprocessing or conditioning would be needed before export.

4.1.5 Exchange or export of fuel

The Technical Committee /D049/ concluded that the exchange of fuel was not in accordance with recommendations by the OECD/NEA. This option was not further assessed by the Technical Committee. There is no identified case of spent fuel being exchanged during the last few decades.

The Joint convention on safety of spent fuel management and on the safety of radioactive waste management /D153/ state that radioactive waste should be disposed of in the state in which it is generated. However, it is recognized that radioactive waste and spent fuel can be sent to facilities in other countries, especially if the waste has its origin in joint projects. However, any state has the right to prohibit the import of spent fuel or radioactive waste.

The implementation of this option requires significant political efforts to resolve the complex agreements. The KVU will not further investigate this option, as there is so far no obvious partner for such exchange or export.

Disadvantages:

- The possibility of finding an acceptable exchange partner is low.
- The total cost is uncertain.

Advantages:

- The unstable fuel could be replaced with conventional uranium dioxide fuel with Zircaloy cladding. Thus, no special treatment of the unstable fuel will be required.

4.1.6 Commercial reprocessing

The public inquiry, NOU 2011:2 /D048/ recommended this option. Nuclear fuel reprocessing is performed routinely in Europe, Russia and Japan. Commercial reprocessing services for the Norwegian spent fuel have been discussed with operators in France and Russia. In France the operator is AREVA NC while in Russia the relevant company is the Sosny Research Company. India, Japan and the UK also have facilities for reprocessing /D355/.

Reprocessing is a proven technology for dealing with standard types of fuel as well as for metallic fuels /D260 & D262/. In reprocessing plants fissile materials and waste are treated and processed using chemicals which can be toxic, corrosive or combustible. Safety features based on the defense-in-depth concept are implemented both in the design of the facility and in its operation. Management of the design process ensures that the structures, systems and components important to safety have the appropriate technical characteristics, specifications, and material properties which are compliant with their safety functions /D262/.

The principal radiological safety objective at reprocessing facilities is the protection of operators, members of the general public and the environment from the potentially deleterious effects of radiation. This objective requires shielding of intense sources of radiation, preventing the spread of radioactive contamination and strictly limiting the release of radioactive materials. All fuel cycle facilities apply the concept of multiple-component protection to maintain safety and a system of successive physical barriers are used to prevent the spread into the environment of ionizing radiation, nuclear materials and radioactive substances. In addition systems of technical and organizational arrangements are employed to protect operators, the general public and the environment. The IAEA general safety guide GSG-3 /D252/ gives recommendations regarding process and responsibilities of operator and license organizations regarding safety case and safety assessment for management of radioactive waste.

There are several methods to separate the uranium and plutonium from the spent fuel matrix. The main purpose of reprocessing is to extract the uranium and plutonium for reuse as fuel in commercial nuclear power plants. The remaining fraction is the fission products for which a storage solution, and ultimately a disposal solution are needed.

The most common method for reprocessing today is to chop the spent nuclear fuel into pieces and dissolve them in nitric acid /D249/. The uranium and plutonium in the spent fuel are extracted from this nitric acid solution using organic solvents. The extraction is accomplished by manipulating the chemical reduction-oxidation states of the plutonium and uranium ions in the solution. This process is the only one that has been operated at a commercial scale and is called the Plutonium-Uranium Redox Extraction (PUREX) process.

The remaining liquid fractions from reprocessing must eventually be solidified. A commonly used method is to mix the liquid fraction with molten glass, which is then hardened, a process known as vitrification. The vitrified waste can then be appropriately packaged and disposed of in a geologic repository.

The reprocessed fissile material, uranium and plutonium, can be used for the fabrication of new fuel elements or sold for other peaceful uses, all in accordance with the safeguard agreement controlled by the IAEA. The waste from the reprocessing can be returned to the owner of the fuel or in some cases it can be taken care of in the country performing the reprocessing. According to French law the waste has to be returned to the country of origin while for reprocessing in Russia it is possible to transfer the waste to the Russian organization performing the reprocessing. It is also worth noting that the amount of waste that would be generated by reprocessing the unstable Norwegian fuel will be very small and could be placed in one barrel (estimated mass 50 kg /D253/).

Before the transport and reprocessing a political agreement between the Norwegian government and the government of the country where the reprocessing should take place would have to be signed.

The most common procedure is that the ownership of the plutonium and uranium is transferred to the organization carrying out the reprocessing. The transfer must of course follow the international safeguard agreement. The vitrified waste can be returned to Norway or final disposal of the vitrified waste can be carried out in the country where the reprocessing is undertaken.

It must be noted that some countries are concerned with the potential disadvantages of the current fuel reprocessing strategies, like the cost of reprocessing, potentially lower proliferation resistance, and releases of radioactive nuclides to the environment.

Spent fuel reprocessing plants have been operating at an industrial scale for several decades. Substantial reductions have been achieved in the radiological discharges from reprocessing plants and are today only small fractions of the peak levels during the 1980s /D262/. The nuclear industry, including the reprocessing facilities, is working on further reducing these emissions through new waste management facilities and process optimization.

Disadvantages:

- Packaging and transport of the material has security and cost implications.

Advantages:

- The method is well proven.
- There would be either no return of waste or a return of only a small quantity of waste in a well-defined and stable form suitable for storage.
- There would be a reduction of risk to future generations.

4.1.7 Conditioning

Conditioning in this context means the transformation of the unstable fuel to a chemical stable form (e.g. metallic uranium to uranium oxide), which then can be deposited in a repository.

The difference from reprocessing is that whereas the purpose of reprocessing is to extract the plutonium and uranium for reuse in the nuclear fuel cycle, conditioning aims to produce a stable form of the spent fuel for storage and disposal. Conditioning can be performed within Norway or abroad. Besides the eventual differences in costs the main reason for conditioning instead of reprocessing are ethical and/or political. If it is essential not to process the metallic fuel abroad it will be necessary to perform the conditioning in Norway. A key reason for conditioning abroad could be a decision that all waste generated should be disposed of in Norway.

Three main options for conditioning were discussed by the technical committee /D049/ PUREX, electrometallurgy and calcination.

A technology based on the PUREX process used in current reprocessing plants can be used for conditioning. In this case the PUREX process is modified to avoid the separation whereby pure plutonium is obtained. The conditioning can then be performed at a reprocessing plant, assuming that it is commercially acceptable for the plant to do so and that the conditioning can be accepted by responsible authorities. This conditioning approach implies that the final product is a mixture of plutonium and uranium in a chemical stable form and that the high level waste produced by conditioning will be transferred back to Norway.

When considering domestic conditioning in Norway the technical committee preferred a process based on the PUREX process, due to the benefits of the wet process and considerable experience of this method in Norway. Chemical processes are often carried out in liquid systems as homogeneous phases are produced which can be better controlled than solid reactants.

The technical committee estimated the costs of treating the fuel in a domestic facility would be at least fifty times higher than the cost of reprocessing at a commercial facility. In addition to the higher costs, the extra radioactive waste which that would be produced as a result of the operation and decommissioning of the domestic facility must be considered.

In a process based on electrometallurgical treatment, spent fuel is melted together with silicon and then electro-refined. The bulk of the aluminium is electrolytically removed for disposal as low level waste, the residual aluminium, actinides and fission products are vitrified. Pure uranium can then be recovered /D266/. The technique was not further considered by the technical committee and they considered that this treatment does not meet the requirements that the fuel management strategy should be technically suitable.

Calcination is dry oxidation of metallic uranium to UO_2. This method was used by Studsvik to treat plutonium before it was transported to the USA within the retrieval program /D268/. For spent fuel with aluminium cladding the rods need to be de-clad, cut into small pieces and then crushed. The sizes of the particles must be in such a range that they can be completely oxidised to uranium oxide powder in a furnace. Used temperatures are between 350 and 500 °C. Since spontaneous ignition can occur at even lower temperatures, it is necessary to control the rate of oxidization by controlling the oxygen concentration in the furnace. The end product will be a UO_2-powder. Powder has a much larger surface area than a high density material and this must be allowed for when designing a final disposal solution so as to ensure safety. Sintering of the powder to a high density product would make it more stable and suitable for final disposal.

A conditioning facility in Norway would produce significant amounts of secondary radioactive waste during operation and decommissioning of such a facility.

It can be stated that no facilities currently exist which can be used to condition metallic uranium fuel or aluminium-clad fuel besides the present reprocessing plants. However, constructing and operating facilities in Norway is fully feasible. If conditioning is considered as an alternative, this would mainly be for ethical and/or political reasons. The conditioning methods based on both the PUREX and calcination processes respectively seem to be most relevant. The conditioning at Studsvik was performed in a glove-box, as the material was not irradiated. For spent fuel such a facility could be built within a hot-cell. Further assessments have to be performed to evaluate optimal solutions from technical, economical and last but not least safety points of view.

The advantages and disadvantages of conditioning in Norway are:

Disadvantages:

- A facility would need to be designed, built, operated and decommissioned for the sole purpose of treating the unstable fuel.
- The volumes of low and intermediate level radioactive waste would increase.
- It is difficult to make a realistic cost estimate, but building a facility would carry a considerable cost.
- Considerable assessment, planning and licensing procedure for a facility would be required.

Advantages:

- The whole process would be controlled by Norwegian authorities.
- There would be no risk of proliferating sensitive materials.
- No export of nuclear fuel and no import of waste would be needed and hence there would be no international transportation of radioactive material.
- The fuel and waste would be taken care of in the country where the waste was generated, thereby leaving no difficult waste as a legacy to future generations.

The advantages and disadvantages of conditioning abroad are:

Disadvantages:

- It may be difficult to find an operator providing the services
- It is difficult to make a realistic cost estimate
- Considerable assessment, planning and licensing procedure for transport and acceptance would be required.

Advantages:

- No export of nuclear fuel or waste.
- Responsible clean-up in the country where the waste was generated.

4.2 Selected options for analysis

The following options for treatment of the unstable were selected for further analyses:

- Storage in present stores (wait and see).
- New storage.
- Reprocessing.
- Conditioning.

The remaining options included in the overview will not be further considered because these options cannot be implemented feasibly. In the following sections the expected end products are presented (Section 4.2.1) and then the cost for each option is assessed (Section 4.2.2).

The analysis considers the period from the present up to 100 years in the future.

4.2.1 End products

The initial amount of spent fuel is presented in Section 2.1 above. The amount of waste for storage and/or disposal will depend on the selected option for treatment.

Storage in present facilities will not give any additional waste. The amounts are as given in Section 2.1.

A **new store** implies repacking of the waste to achieve a better environment for long-term storage for up to 100 years. This will generate operational waste, which can be included in the waste stream to be disposed of at Himdalen or similar new facility. A new storage also make it possible to increase the amount of storage capacity.

The metallic fuel is unsuitable for final disposal and cannot be an acceptable final product. Therefore reprocessing or conditioning of this fuel has to be performed before final disposal. The end products of reprocessing or conditioning are presented below.

Reprocessing implies that the main part of the spent fuel will be used for production of nuclear fuel and only a minor part of the radioactive material within the fuel will become waste that will need to be disposed of. The major part of reprocessing fractions is uranium and a minor fraction is plutonium. These fractions can be reused for nuclear fuel fabrication. The vitrified waste will be between 30 and 50 times less in volume than that of the initial spent fuel. Furthermore, the long-term radiotoxicity of the separated waste will be a factor of 10 lower than that of initial spent fuel /D254/. Reprocessing with the PUREX methods would give 23 tonnes of uranyl nitrate, slightly more than one kg of plutonium and 50 kg of vitrified high level radioactive waste /D253/. According to the technical committee /D049/ the vitrified waste from reprocessing would be less than 0.2 m^3.

Conditioning methods that may be employed commercially have not been identified. Conditioning will increase the amount of waste for final disposal. If conditioning is considered it is essential that the end product is in a form suitable for disposal in a final repository. The transformation of metallic uranium to a stable uranium oxide form will increase the volume and mass. However, this increase will not be of any major importance. In addition secondary waste from the treatment will be generated. If the conditioning is performed in an existing reprocessing facility or hot-cell this waste will consist of special tools and equipment used in the processing. However, if a new facility has to be built this option will generate considerably more radioactive waste as the decommissioning of the facility has to be taken into consideration. However, it will be possible to dispose of this waste in Himdalen or a similar repository.

The PUREX process is being used in all commercial reprocessing plants currently operating /D262/. This method can be used for conditioning but in this case the uranium and plutonium will be returned to Norway in the conditioned fuel.

Other methods, such as calcination, the dry oxidation of metallic uranium to UO_2, will need further analysis and optimization. Potential other options are not further analyzed as of the required data is lacking.

4.2.2 Costs

Fuel for research reactors represent less than 1% of the uranium market and normally the fuel has higher enrichment than is used in power reactors. Research reactors may use fuel that is enriched from about 20 % U-235 upwards, while fuel for commercial power reactors normally has enrichment of less than 5 % U-235. There are significant differences between different research reactors as each reactor has its unique features. Consequently there is no standard type of fuel and hence there is no standard method for the treatment for research reactor fuel which can be applied. The cost estimates given are quite uncertain and the figures below should only be considered as indications of the order of magnitude of the cost.

The cost for treatment and reprocessing is in many studies given as the cost per kilogram of heavy metal (kgHM). However, these costs typically refer to the treatment of spent fuel from power reactors. For power plants there are large volumes and recurrent campaigns. The cost per unit for fuel from research reactors can be expected to be higher as each kind of fuel is present in much smaller volumes than any particular kind of power reactor fuel and in many cases may need special treatment.

The cost and economics of reprocessing versus direct disposal has been evaluated /D249/. The focus is on low-enriched nuclear fuel for power plants. Some generic values on cost are given for reprocessing, storage and direct disposal. The estimated cost of reprocessing of the spent fuel is NOK 6 000 per kgHM (used exchange rate $1 = NOK 6) which then should correspond roughly to MNOK 100 for 16 tonnes. In the same report the cost for disposal of the radioactive waste from reprocessing is NOK/kgHM 1 200. The cost comparison between different fuel cycle analyses is summarized in an OECD/NEA report /D258/. The costs for reprocessing are between NOK/kgHM 6 000 and 24 000 for uranium oxide fuel. These costs are for power plant fuel and for small batches the unit costs can be expected to increase.

The metallic fuel from the first Swedish research reactor (R1) was sent for reprocessing. The total amount of spent fuel was 4.8 tonnes of metallic uranium with aluminium cladding. The first step in the process was to take the fuel from the storage location to the hot-cell and pack it into two transport casks. The cost for this procedure was a little bit more than MSEK 12 /D251/. The cost for transporting the fuel by sea was about MSEK 20 /D263/. The cost for reprocessing was MSEK 40. The contract was signed in 1998 /D261/. In the same report the cost for transportation of the waste back to Sweden was estimated to be MSEK 2. The corresponding cost for the Norwegian fuel will be higher, due to the larger amount of fuel and also the general increase of costs due to inflation.

In an appendix in the report from the technical committee /D049/ the cost for transport and reprocessing of the Norwegian spent fuel is given. The details of different options can be seen in the report but here it is sufficient to give the average magnitude of different costs. The cost for preparation of the fuel for shipment is in the order of MNOK 60 and the cost for shipment is less than MNOK 10. The reprocessing cost will be up to MNOK 350. The total cost for 16 tonnes of fuel, including transport and reprocessing, will then be in the order of NOK/kgHM 25 000. This cost is higher than is typical for nuclear power fuel, as reported in international literature, but this should be expected for this relatively small batch.

Based on this overview the cost for different options can be assessed.

For the continued use of the **present storage** the future annual cost for operation and maintenance can be assumed to be the same as it is today in real terms. There will be additional costs for inspection and examination of the fuel for early detection of eventual degradation and corrosion. This will be necessary to minimize the risk of releasing radionuclides to the environment. It will probably not be possible to use present storage for long-time storage without a thoroughly inspection and monitoring program. Furthermore, final disposal of metallic fuel is not possible and therefore it will be necessary to perform reprocessing or conditioning at some point in the future. Future costs for new storage, reprocessing or conditioning must be considered.

A new store for the fuel is one option. The advantage is that the storage conditions can be improved compared to those in the present storage, for example by drying the fuel and storing it in an inert gas. A proper new store can be constructed for operation for up to 100 years. A prefeasibility study on dry storage solutions for the spent fuel at IFE estimated the cost for a dry store to be MNOK 500 /D151/ (used exchange rate €1 = NOK 8.25). Even for storage for 100 years, future costs for reprocessing or conditioning have to be considered.

The costs for **reprocessing** are illustrated above and imply that the amount of waste for final disposal in Norway will only be a minor fraction of the spent fuel. This waste will be in the form of vitrified high level waste. The cost for reprocessing can be estimated to about MNOK 350. The cost of storage and disposal of the vitrified fraction will only have a low impact on the overall costs.

The cost for **conditioning** can be compared to those for reprocessing if the PUREX method is used. The conditioning can then be performed in an existing repossessing plant, but the uranium and plutonium will then be returned to Norway (rather than used to fabricate for new fuel which is then used elsewhere). Depending on the legislation in the country where the reprocessing is undertaken the return of all fractions are not possible, especially plutonium. If the uranium and plutonium is returned the purpose should be to dispose of it finally in Norway.

The total cost for other methods cannot be estimated with any accuracy since there is no commercial facility available. Conditioning by calcination which can be performed in any hot-cell facility, may not be feasible at a lower cost than reprocessing. The technical committee /D049/ could not justify a new facility in Norway.

In Table 4.1 the costs for the different options are summarized.

Table 4.1
Summary of costs for different options for up to 100 years assuming a final storage after 100 year.

Option	Present	Additional costs within 100 years	After 100 years
Present storage	Present cost for storage plus additional regular controls	New storage MNOK ~500	Reprocessing or conditioning with final disposal in an underground repository
		Reprocessing MNOK >350 Minor costs for disposal of vitrified waste	Minor amount of waste
		Conditioning MNOK >350 and Cost for storage until final disposal MNOK ~500	Final underground repository
New Storage	~500 MNOK	Cost for operation and maintenance	Reprocessing or conditioning with final disposal in an underground repository
Reprocessing	~350 MNOK	Minor costs for storage of vitrified waste	Minor amount of waste
Conditioning	>350 MNOK	Cost for a new storage until final disposal MNOK ~500	Final underground repository

4.3 Ranking of options

A primary ranking of the possible options has been performed against a few generic criteria and using a ranking scale of four levels.

4.3.1 Criteria

For the ranking of the different options a set of criteria has been used. At this stage of the evaluation process three generic criteria have been assumed sufficient:

- Costs
- Technological maturity
- Safety and risk, including radiation effects and safeguard issues

Costs:
For each option all costs during the first 100 years are included. Costs for a final repository for spent fuel and other long lived nuclides are not included. The detailed costs cannot be obtained, but the estimated order of magnitude costs presented in Table 4.1 are the basis for the cost ranking.

Technological maturity:
Mature technologies are those which are used and for which there is proven experience. Only technology which is used frequently by several operators is classified as a mature technology.

Safety and risk:
This criterion is a merging of many factors that influence risks and safeguards. Safety and risk have to be thoroughly evaluated within the safety case for the selected option. This evaluation will require comprehensive analysis which will not have a negligible cost in any of the options.

All different options can, with proper planning and safety arrangements, be performed with sufficient safety for all personnel involved. There are no obvious differences between the options regarding this issue. The ALARA principle implies that an optimization process has to be performed regardless of the method selected. The same is valid for the radiological environmental impact during normal operation. Modern regulations require that to be acceptable any discharges from activities are as low as possible using available methods. All operations and activities should be properly planned and analyzed in the safety case.

The risk of incidents or accidents resulting in exposure of personnel or releases of radionuclides to the environment increases with the complexity of the handling process. In general more complex handling and increasing numbers of actions will increase probability for incidents and thereby the risk. The safety case should include analysis of possible scenarios including mitigation actions.

4.3.2 Rating

There are four options for treatment considered and for each one the rating of each criteria is set from 1 to 4, where the most preferable, (i.e. lowest cost, most mature technology and lowest risks) is assigned a value of 4. The ranking is based on costs and actions up to 100 years (a final repository is not considered).

4.3.3 Ranking scheme

The ranking is based on a qualitative judgment where the ranking for each option is discussed below.

Table 4.2
Ranking of possible options for treatment of unstable fuel.

Option	Costs	Mature technology	Safety and risk
Storage in present facilities	1	4	1
Storage in new facility	3	4	4
Reprocessing	4	4	3
Conditioning	2	2	2

From this ranking it can be seen that a new storage facility and reprocessing have the same ranking if the criteria are all given the same weight. It should be noted that the new facility will need reprocessing/conditioning at a later date.

Reprocessing where the uranium and plutonium are reused for fuel fabrication are the only alternative which could be finalized within the time frame of 100 years, and then would be the most preferable. Reprocessing scores most favorably on cost because the cost for storage and disposal of the vitrified high level waste produced will be much lower than storage and disposal costs for conditioned spent fuel.

The lowest ranked option on cost grounds is the continuation of present storage reflecting the necessity for a new store, conditioning or reprocessing within 100 years.

Regarding the maturity of technology, both the storage alternatives and reprocessing are well known technologies and are used worldwide. Reprocessing can be undertaken on commercial basis by several suppliers. There are no obvious differences regarding experience of these technologies which should generate differences in the ranking. Therefore all options have been given the same ranking. The ranking of conditioning is not obvious. Conditioning using the PUREX method or calcination should be similarly ranked to reprocessing, while conditioning with another method in a new facility has to be further developed before it can be implemented. However, conditioning is not commercial available as reprocessing.

The final criterion, safety and risk, is based on a general judgment from experience of safety analyses within the nuclear industry. The safety and risk includes both personal risk during operation and potential risk for accidents resulting in releases and doses to the public or receptors. Reprocessing has a lower risk than conditioning outside Norway, mainly due to the additional risks associated with returning the uranium and plutonium to Norway. This implies that the use of uranium and plutonium for nuclear fuel will be handled according to international agreements regarding safeguard and radiation protection.

The relatively low ranking of safety and risk for the present storage is due to the risk that the fuel, cladding and matrix will degrade due to corrosion. The present storage could probably not be in operation for an additional 100 years without any protective actions. Furthermore, reprocessing or conditioning will be necessary in a later phase. This later handling of the fuel will also contribute to the risk ranking.

In a new storage facility it is assumed that a proper environment for the spent metallic will be obtained which will prevent any unacceptable degradation of fuel. Such storage can be in operation for 100 years. During this time frame there will be no major additional handling and therefore risks will be lower than for continued use of the existing store.

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