KS1 Management of Norwegian Spent Nuclear Fuel

Atkins UK Quality Assessment

Oslo Economics

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Executive Summary

Around 16.5 tonnes of Spent Nuclear Fuel (SNF) is currently in storage in Norway, following the shutdown of three Norwegian research reactors [1]. The nuclear materials, stored at the Kjeller and Halden sites, contain irradiated fuels in the form of metallic uranium (U-Metal), uranium oxide (UO_2) and experimental fuels such as highly enriched uranium (HEU) metal and oxide, thorium oxide (ThO_2) and other chemical forms such as carbide and nitride fuels. The SNFs are currently stored in three storage facilities: two at Kjeller and one at Halden. Inspections conducted by the Institute for Energy Technology (IFE) of the Stavbrønn storage facility at Kjeller revealed that water has ingressed into several storage positions, causing significant safety issues relating to the corrosion of metallic uranium fuel [1]. The other two storage facilities are also operating beyond their planned lifetime [1]. Both nuclear sites are awaiting the removal of all SNF from site, in order to commence with decommissioning activities. Therefore, for these reasons a strategy for the management and disposal of the Norwegian SNF is required. The current site license holders are IFE, with the transferral of responsibility soon to be passed on to the state-owned company Norwegian Nuclear Decommissioning (NND) [2].

At present, no decision has been made for the disposal of Norwegian SNF. The Norwegian government are in the process of developing a management strategy, based around one that provides a full lifecycle solution for the full Norwegian SNF inventory. This assessment on spent fuel, in combination with an assessment on storage, supports the development of such a full-lifecycle strategy. This report has been produced as a Quality Assessment (QA) that identified a list of options for the Norwegian SNF to be taken forward and developed further in the next stage of assessment, KS2.

This report includes an overview on the current situation, the feasible options identified in-line with key drivers and available information, an evaluation of options and key recommendations for further work. Options were evaluated qualitatively using a set of fundamental criteria. The evaluation identified a list of options that should be carried forward to the next stage of assessment, KS2, but does not provide any recommendations as to a preferred single option. The management of the Stavbrønn SNF was also identified as a priority task and was therefore evaluated separately, so that it did not overly influence the evaluation of options for the remaining SNFs that are not deemed as time critical.

The evaluation of options identified the following options to be taken forward:

KS1 Option Number	KS1 Option Name
S2bi	Stavbrønn Studsvik – No Mechanical Treatment
S2bii	Stavbrønn Studsvik – Mechanical Treatment
S2biii	Stavbrønn Studsvik – Oxidation
S2b-a	Stavbrønn Studsvik – Reprocessing
0a	Long-Term Storage at Both Sites
0b	Long-Term Storage at Single Site
0c	Long-Term Storage at Single Site in triple-use casks
1a	Direct Disposal – No Mechanical Treatment
1b	Direct Disposal – Mechanical Treatment
2aii	International Reprocessing – High Level Waste (HLW)
2bii	International Oxidation

These options should be developed further for qualitative assessment in the KS2 stage.

It was concluded that significant knowledge gaps and/or uncertainty exist for many of options which require further research and/or development in order to underpin the options taken forward. Other strategical recommendations are also included in this report, which focus on ensuring sufficient capacity and competency is available in Norway to allow for the successful management of the Norwegian SNF. The development of a more detailed SNF inventory and more robust and mature working relationships between the relevant stakeholders are also key recommendations.

1. Abbreviations and Glossary

1.1. Abbreviations

AGR	Advanced Gas-cooled Reactor
ASN	Autorité de Sûreté Nucléaire
BASE	Bundesamt für die Sicherheit der nuklearen Entsorgung
BAT	Best Available Technique
BWR	Boiling Water Reactor
COEX	Co-extraction
DSA	Norwegian Radiation and Nuclear Safety Authority
EACA	European Association of Competent Authorities
FP	Fission Products
GDF	Geological Disposal Facility
HBWR	Halden Boiling Water Reactor
HE	Highly-Enriched
HETh	Highly-Enriched Thorium
HEU	Highly-Enriched Uranium
HHGW	High-Heat-Generating Waste
HLW	High Level Waste
HOD	Ministry of Health
HSR	Higher Strength Rock
ICV	In-Can Vitrification
IFE	Institute for Energy Technology
ILW	Intermediate Level Waste
IRF	Instant Release Fraction
KLD	Ministry of Environment
KS1	Quality Assurance 1
KS2	Quality Assurance 2
KVU	Preliminary Assessment
LTS	Long-Term Storage
LWR	Light Water Reactor
MA	Minor Actinide
MOX	Mixed Oxide Fuel
MTHM	Metric Tonnes of Heavy Metal
MWd tu^{-1}	Mega Watt Day (per) Tonne Uranium
NCS	Nuclear Cargo Service
NFD	Ministry of Industry and Trade
NRC	Nuclear Regulatory Commission
OPAL	Open Pool Australian Light-water reactor
OPEX	Operational Experience
Orano NPS	Orano Nuclear Packages and Services
PDSR	Package Design Safety Report

PIE	Post-Irradiation Examination
Pu	Plutonium
PuO_2	Plutonium Oxide
PUREX	Plutonium and Uranium Recovery by Extraction
PWR	Pressurised Water Reactor
QA	Quality Assessment
SME	Subject Matter Expert
SNF	Spent Nuclear Fuel
SQEP	Suitably Qualified and Experience Person
THOREX	Thorium Recovery by Extraction
SSM	Swedish Radiation Safety authority
SSSC	Studsvik Small Scale Conversion
t	Tonne
Th	Thorium
ThO_2	Thorium Oxide
TRL	Technology Readiness Level
U	Uranium
U-Al	Uranium Oxide with Aluminium cladding
UD	Ministry of Foreign Affairs
UK	United Kingdom
U-Metal	Uranium Metal
UO_2	Uranium Oxide
USA	United States of America
WAC	Waste Acceptance Criteria

1.2. Glossary

Buffer Storage	Buffer storage is defined as very short-term (1-10 years), or temporary, storage that is primarily constructed to enable on-site operations to be performed. An example of this may be constructing a buffer storage area to store SNF following retrieval before it is re-packaged for transport off-site.
Cropping	Cropping is the cutting of SNF pins into shorter lengths using shearing blades. It is the more technical terms for cutting of SNF.
European Facilities	Within the report, different chemical treatments for SNF are discussed. The term 'European Facilities' is often used in this context, alongside the names of facilities (e.g., Orano). This is due to the fact that for the Stavbrønn SNF, contracts have already been discussed with Orano[1] and Studsvik[2]; no other suppliers will become involved for management of the Stavbrønn SNF due to the shorter time constraints. However, for the management of the remaining Norwegian SNF, which is not so time limited, other suppliers may yet be considered for the contracts; therefore, a broader term is sometimes used that does not specify the supplier.
Interim Storage	Interim storage is a short storage period (up to – 50 years) that is an enabling step before the final geological disposal of SNF. In the context of the management of Norwegian SNF, the interim storage period is in reference to a period of storage in

[1] Orano are a French company that perform industrial scale chemical reprocessing of Spent Nuclear Fuel. Their processing facility is called 'La Hague'.
[2] Studsvik are a Swedish company that perform a variety of chemical and mechanical treatments on Spent Nuclear Fuel. They are a smaller company than Orano and more flexible in their treatment.

	a pre-geological disposal storage facility. Including the time to construct the facility and transfer the SNF, this is estimated to last for around 40/50 years.
Lead Time	The length of time required to put an option in place, design a process, ensure training is available and has been actioned etc. Frequently used as ‘long lead time’, where there will be a significant delay in implementing process/option, which will have a negative effect on a project. Often used when considering TRL’s.
Long-Term Storage	Long-Term Storage (LTS) is where the SNF is stored in a secure and safe facility for periods of time exceeding over 50 years. In some countries, such as the United Kingdom [3], this is anticipated to exceed 100 years. This is a period of storage that would precede transfer to a pre-geological disposal storage facility before the final step involving final disposal of the SNF. During the extended period of long-term storage, options are kept open for the use of any new or existing chemical or mechanical treatments to prepare the SNF for final disposal.
Mechanical Treatment	Mechanical Treatment is defined as a non-chemical treatment of SNF that alters only physical properties of the waste form, such as the removal of cladding, removal of furniture, separation of fuel rods from assemblies or the cropping of SNF. Mechanical treatment excludes any chemical treatment, or other non-mechanical processes such as drying, re-packaging or overpackaging of SNF.
Stavbrønn SNF	The Stavbrønn SNF is the JEEP I SNF. Since it is stored in the Stavbrønn facility, which is an important property in relation to the management of the JEEP I SNF, it is referred to as the Stavbrønn SNF for consistency.
TRL	Technology Readiness Level (TRL) is a measure of technological maturity, based upon a system developed by NASA [4]. Conventionally, the TRL is measured between 1 (lowest) and 9 (highest). However, in this assessment TRLs will be evaluated at a higher level: low (1-3), medium (4-6) and high (7-9).

2. Introduction

2.1. Project Background and Context

Norway became involved with nuclear energy in the 1940s, formalising this with the establishment of the Institute of Atomic Energy; later to become the Institute for Energy Technology (IFE) [5]. The Kjeller facility, which commenced construction in 1947, was the sixth nuclear facility built in the world, and established Norway as a nuclear power state [5]. The facilities built in Norway were purposed to perform research on the use of various fuels and other nuclear materials. The first Norwegian nuclear research reactor, JEEP I, reached criticality in 1951, which was followed by the establishment of another three research facilities: JEEP II, NORA and Halden Boiling Water Reactor (HBWR). All four reactors have now been taken out of service and the Norwegian Government has tasked the relevant regulatory bodies and site licence holders with establishing a suitable decommissioning strategy for the reactors and the safe disposal of Spent Nuclear Fuel (SNF).

The four reactors comprise [6]:

- JEEP I, which operated at Kjeller between 1951 and 1967;
- JEEP II, which operated at Kjeller between 1966 and 2019;
- NORA, which operated at Kjeller between 1961 and 1968; and
- HBWR which operated at Halden between 1959 and 2018.

Each of these facilities irradiated various quantities and types of SNF, which were removed from the reactors during their operation and placed into on-site storage facilities. The details of the approximately 16.5 tonne (t) SNF inventory [7] are given in Section 2.5. The sites now require removal of all SNF to allow decommissioning to occur; a safe, secure, and suitable storage/disposal solution for the SNF is required. The ownership of the nuclear sites and SNF is currently held by IFE but will be soon transferred to the state-owned company Norwegian Nuclear Decommissioning (NND) [2]. The SNF is currently stored within three facilities on the Kjeller and Halden sites; two and one storage facilities respectively. Increasing concerns over the ageing condition of the storage facilities, in combination with a requirement to decommission the sites, have driven changes to the current situation. At present, no long-term management strategy for Norwegian SNF has been developed. This has instigated a review and subsequent requirement for creation of a strategy for all SNF within Norway.

There are five storage facilities that house the SNF that was generated during operations of the reactors, which are:

- Stavbrønn facility (Kjeller), which stores JEEP I SNF;
- JEEP II reactor building (Kjeller), which stores JEEP II SNF;
- Met. Lab-II facility (Kjeller), which stores JEEP II SNF and HBWR SNF that has undergone Post-Irradiation Examination (PIE);
- Fuel pits in the HBWR reactor hall, which store HBWR SNF; and
- Bunker building facility (Halden), which stores HBWR SNF.

Stavbrønn and Met-Lab-II are dry storage facilities, the JEEP II reactor building and HBWR fuel pits are wet storage facilities, and the Bunker Building contains both wet and dry storage systems.

Each of these three storage facilities are in varying conditions, which have been reported by the Bergan committee and more recently in the Phase 1 committee's reports and are summarised in Reference [8]. Out of the three storage facilities, it has been identified that the Stavbrønn facility is of the highest priority, as the storage conditions do not meet the required standards for the safe and secure storage of SNF; water has entered the facility, which poses multiple safety concerns [1]. The Norwegian Radiation and Nuclear Safety Authority (DSA) have expressed that the SNF in this facility needs to be removed and new storage established. The SNF at the Stavbrønn facility must be managed on a much shorter time frame than the rest of the

Norwegian SNF at the other facilities. This is one of the driving factors behind the decommissioning strategy and management of the SNF stored in this facility. Time constraints are also relevant to the other storage facilities (Met. Lab-II and bunker building), which are also both functioning beyond their intended lifetime [1], but not on such a short timescale.

As mentioned above, there is no current developed strategy for the management of the Norwegian SNF; it remains in storage. If no action is to be taken, the Long-Term Storage (LTS) of the SNF, which is in sub-safety standard facilities, will continue to be a case for enforcement of a new strategy. The current situation also does not provide a full-lifecycle solution, as no final disposal of the SNF is considered. Consequently, long term management solutions are required for all the Norwegian SNF inventory, to ensure future safety and environmental regulations are met.

The purpose of this report is to assess all possible options currently available for the management of Norwegian SNF, in order to identify a list of options that can be taken forward to the next stage of assessment. Any change to the current situation will be underpinned by a clear decision-making process, which considers all options available and uses relevant criteria to advise on all aspects of the decision-making process.

2.2. International Context

Globally, the management of SNF and radioactive waste is regulated by national legislation and follows international agreements. The international nuclear community considers management of SNF as part of the nuclear fuel cycle [9]. The SNF is managed either by reprocessing (approximately 30% of all SNF) [9]; repatriated to the country of origin[3]; or held in long-term storage (wet or dry), whilst a suitable solution is agreed or the technologies required are developed. The final stage of management for the material is, in most countries, disposal in a Geological Disposal Facility (GDF). The main objective of any management is to ensure that the fuel cycle is safe, secure, provides resistance to proliferation, is economically efficient and minimises secondary waste production [9]. Reprocessing can allow for the recycling of uranium (U) and plutonium (Pu) from the SNF to form other fuels such as mixed oxide fuel (MOX) for civilian power production.

Some countries opt to apply one approach for the management of all their SNF, such as Finland. Finland, which has four reactors, has approximately 1,700 MTHM (Metric Tonnes of Heavy Metal) of SNF in interim storage [10]. In terms of international Operational Experience (OPEX) for geological disposal of SNF, no country currently has commenced operations in a GDF for SNF. Finland is the only country with a GDF presently under construction [11]; the plans for construction of the American Yucca Mountain GDF have seen significant delays [12].

The management of the SNF can also be a combination of options, such as for Australia, which repatriated over 500 SNF elements originating from the Open Pool Australian Light-water (OPAL) research reactor to the United Kingdom (UK) and United States of America (USA), whilst the remaining 1288 SNF elements were sent to France for reprocessing. The remaining waste product is presently stored in France to be returned to Australia in the near future [13].

The volume of SNF in the Norwegian inventory being considered is small in comparison with that from power stations; for example, the total mass of UK-owned uranium ever produced, or forecast to arise, is estimated to be 200,000 tonnes [14]. Better comparisons can be made with smaller nuclear programmes. Norway must manage a similar volume of SNF, estimated to be 16.5 tonnes by the NND [7], to the research reactors in the UK such as Dounreay, where 11 tonnes of SNF is classified as exotic (oxide fuels/carbide fuels). Dounreay SNF has been packaged and transferred to Sellafield for further management where it will remain in long-term storage until at least 2100 [15].

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[3] If the fuel was transported and used outside of the country of origin, and agreements are in place for the repatriation of the fuel following use.

2.3. Project Scope

Currently, the management of the Norwegian SNF inventory is at the Quality Assurance 1 (KS1) stage, stemming from the translation of “Kvalitetssikring 1”, following the first preliminary assessment (KVU) which carried out an initial review of the problems and the viable options which could be utilised. During the KS1 stage, the different options that are available for the management of the SNF are explored further and evaluated, with the process taking forward a reduced number of more favourable options for a more detailed review and assessment.

This project is part of the development of the SNF strategy for Norway, addressing national and international best practice and where available, OPEX. This new developing strategy must account for the inventory and the specific handling requirements for each of the SNF types. The project culminates in qualitative options assessment (detailed in 5.2), with the identified favourable options being proposed to the NND and Norwegian Government, for further consideration and development in the next stage of assessment, Quality Assurance 2 (KS2).

Therefore, the scope of this QA is:

- To provide a high-level assessment of all potential full-lifecycle management options open to the Norwegian Government for Norwegian SNF.
- To provide review of the transport options to currently considered European treatment facilities, Studsvik (Sweden) and Orano (France), or other European/International suppliers for processing and/or packaging.
- Identify suitable options to be taken forward for further development and evaluation at the next stage of assessment.

2.4. Case for Change

At present, no strategy that provides a full lifecycle, full inventory solution for the management of the Norwegian SNF exists. Therefore, a change to the current situation must be made by the development of a plan that satisfies these two criteria. Reasons that a change to the current situation is required include:

- Inspections of the JEEP I SNF in the Stavbrønn facility in the 1980’s showed evidence of corrosion to some fuel assemblies. Later inspections at Kjeller also showed evidence of the storage tubes and storage containers due to the ingress of moisture to the dry storage; no further corrosion of fuel assemblies was documented. There is an urgent requirement to remove the SNF from its current storage and relocate it to a passively safe state that accounts for chemical and radiological conditions such as SNF degradation, at an alternative national or international location [16]. Inspection of the SNF must also be conducted to determine the radiological inventory. The other storage facilities are also past their intended lifetime but have not yet shown any signs of degradation. Therefore, whilst they are likely to require continued monitoring and inspection, they do not require an urgent retrieval of the SNF stored within.
- The full SNF inventory requires a strategy developing in order to achieve safe full lifecycle management of the SNF, as none exists at present. The strategy must address the issues associated with other ageing storage facilities and enabling the decommissioning of the nuclear sites by removing all SNF from both sites.
- Geological disposal is considered as the only total solution; at present this is not part of the baseline defined in this report but is identified as the ultimate end-point. All other processes or treatments are interim states that allow for better / more stable product or enhanced safety, and aid in the development of the final disposal of the materials. New options that provide a full-lifecycle solution must be identified.
- A strategy needs to be identified in order to allow for the development of the required infrastructure, domestic and international capacity and competency and (required) inter-governmental agreements. Currently, Norway does not have suitable facilities or the domestic technical ability to process the SNF

in-country. To develop any domestic infrastructure would require a long lead time and will result in large costs.

- In order for the nuclear sites to be decommissioned, the SNF must be removed from site. As the current baseline does not include the removal of SNF from current on-site storage, a new strategy must be identified.

2.5. Norwegian SNF Inventory

The Norwegian SNF inventory contains a number of different SNF types, which have varying properties including chemical compositions, cladding material, maximum enrichment and burn-up. Maintaining accurate information on the properties and condition of inventory has been the responsibility of the site licence holders, IFE [16].

A project decision was made to group fuels within the total Norwegian SNF inventory into Fuel Groups (FGs), according to their current chemical and physical properties; notably fuel type and maximum enrichment. For groups that have differing values for a single property, such as burn-up, the maximum value for any SNF in that group has been stated as a bounding case. Using these principal factors, the following FGs were created:

- FG1: JEEP I, HBWR 1st
- FG2: JEEP II, HBWR 2nd – 4th, HBWR 5th
- FG3: HBWR Booster
- FG4: HBWR Experimental

Information on these fuel groups is provided in Table 2-1 and also represented graphically in

It is acknowledged that within FG2, the JEEP II and HBWR driver fuels differ in their cladding material; Zircaloy and Aluminium respectively. However, in terms of the effect this had when considering the suitability of the different disposal options, such as reprocessing or chemical treatment, the difference in cladding was not seen as a discriminatory factor. For example, the difference in cladding does not make one fuel significantly more suitable than the other for reprocessing; not to the extent that an alternative chemical treatment would be preferable for only one of the fuel types. Therefore, the fuels were grouped together despite this chemical difference. Prior to chemical treatment de-cladding may be required to address the cladding properties.

Figure 2-1. The pie chart highlights that the experimental SNF (FG4) is only a relatively small amount of the total Norwegian SNF.

Table 2-1 – Grouping and Information of Norwegian SNF [7] [17]

Fuel Group	**1**	**2**	**3**	**4**
Fuel(s)	JEEP I, HBWR 1st	JEEP II, HBWR 2nd – 4th, HBWR 5th	HBWR Booster	HBWR Experimental
Fuel Type(s)	Uranium Metal	Uranium Oxide (UO_2)	Uranium Oxide	Uranium Oxide, MOX, Thorium Oxide (ThO_2)
Fuel Cladding(s)	Aluminium	Aluminium, Zircaloy	Zircaloy	Aluminium, Zircaloy
Total Mass (kg)	10,000	5,100	1000[4]	400[4]
Approximate Volume[5] (m^3)	< 0.60	< 0.50	< 0.10	< 0.05

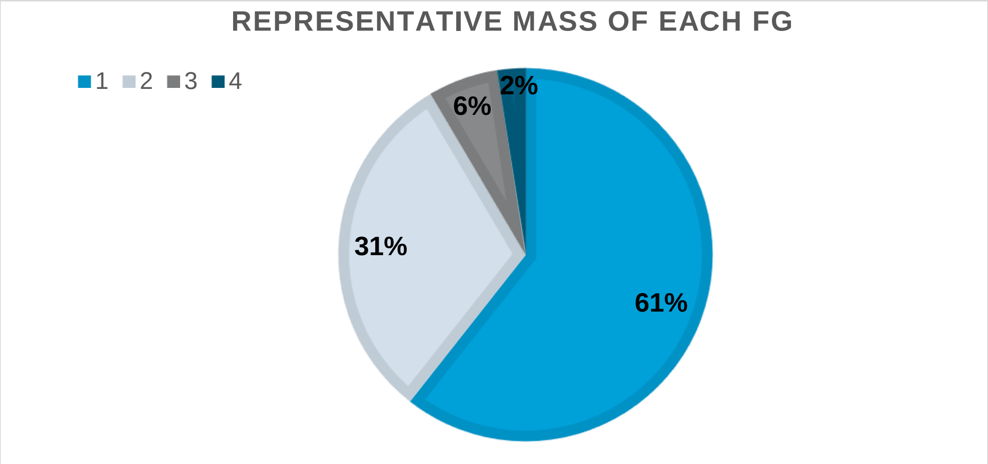
[4] The combined mass of FG3 and FG4 is 1,400 kg. The weight of each group is unknown and has been estimated based on discussions with NND [7]. The formula volume = mass / density has been used.

[5] Total volume has been very approximately calculated taking the densities of UO_2 as 10,960 kg m^{-3} [50] and U-Metal as 19,050kg m^{-3} [51].

Fuel Group	1	2	3	4
Maximum Enrichment	0.72%	10%	20%	90%
Maximum Burn-Up (MWd/kg_U)	≤ 1	≤ 79.4	≤ 79.4	≤ 102.1
Maximum Estimated Decay Heat Power (W/t_U)	25.5	2024.7	2603.6	2603.6
Maximum Rod Dimensions [Length (m), Diameter (mm)]	2.8, 40	≈ 1.8, 15	≤ 1.1, 9.5	≤ 1.1, 14.3
Maximum Assembly Dimensions [Length (m), Diameter (mm)]	2.8, 70	3.66, 90	1.2, ≤ 70	1.2, ≤ 70
Rods or Assemblies	Both	Both	Both	Both
Storage	Dry	Dry, Wet	Dry, Wet	Dry, Wet

It is acknowledged that within FG2, the JEEP II and HBWR driver fuels differ in their cladding material; Zircaloy and Aluminium respectively. However, in terms of the effect this had when considering the suitability of the different disposal options, such as reprocessing or chemical treatment, the difference in cladding was not seen as a discriminatory factor. For example, the difference in cladding does not make one fuel significantly more suitable than the other for reprocessing; not to the extent that an alternative chemical treatment would be preferable for only one of the fuel types. Therefore, the fuels were grouped together despite this chemical difference. Prior to chemical treatment de-cladding may be required to address the cladding properties.

Figure 2-1 - Pie Chart Representing the Percentage Mass of each FG



2.6. Methodology

In order to provide an in-depth and non-biased assessment, a list of options was developed in a systematic and logical manner. All options and subsequent evaluations were underpinned with robust information where available; knowledge gaps were identified for certain options and assumptions were developed. Options were developed for all outcomes without consideration to the advantages and disadvantages of any given option. Once developed, the options were then evaluated using a set of fundamental criteria, from which options to be taken forwards were identified.

The approach taken to perform the development and subsequent evaluation of options can be broken down into the following stages:

- **Information Gathering** (Section 3) – The assessment by collating relevant information to support the assessment, ranging from information included in previous KVU's and reports to international regulations and conference papers. It is important that the decisions made during the assessment can be evidenced and supported by information collected. Information was also gathered on the possible technologies identified.
- **Development of Possible Technologies** (Section 3) – Identification of all possible technological solutions that could be considered for the full-lifecycle and full-inventory management of the Norwegian SNF inventory.
- **Assessment of Norwegian SNF Inventory** (Section 2.5) – By comparing chemical form, maximum enrichment and the suitability of certain fuel types with the identified technologies, it was possible to categorise and consolidate the fuel into Fuel Groups. This made subsequent assessment of options easier and more logical. It was also identified that the Stavbrønn SNF should be identified as a priority waste stream.
- **Stakeholder Engagement** – Numerous meetings with key stakeholders provided a more detailed understanding of the drivers, issues and perspectives of such parties to aid them in their assessment.
- **Process Flow Diagram** (Section 4.2, Appendix B) – A Process Flow Diagram (PFD) of all possible technological solutions and sub-options was developed in order to be able to explore the different possible full options that were available). An individual PFD was also produced for the management of the priority Stavbrønn SNF.
- **Assessment and Evaluation of Options** (Section 5) – Once a list of options had been developed, the different options were evaluated against a set of common criteria. The outcome of the assessment was that each option was given an evaluation term, in-line with previous credible options assessments undertaken on SNF by a UK Regulatory Body [3]. The options evaluated to be credible or contingent are to be taken forward to the next stage of assessment.
- **Recommendations** (Section 8) – Recommendations are given for the options taken forward following their evaluation. Risks and opportunities are also identified.

3. Supporting Work

3.1. Baseline Assumptions, Constraints and Exclusions

A number of assumptions, constraints and exclusions were developed by Atkins UK based upon available information, stakeholder engagement and SME opinion. These are all deemed relevant to both the development and evaluation of options, and are displayed in Table 3-1,Table 3-2 and Table 3-3 below. Supporting details of these assumptions, constraints and exclusions are given throughout this Section 3.

These assumptions, constraints and exclusions have not been endorsed by any stakeholders or involved parties and have been developed independently by Atkins UK.

Table 3-1 - Atkins UK Assumptions

Number	Assumption	Justification
1	The duration of storage before geological disposal for options involving 'Long-Term Storage' is approximated to be 100 years.	Time considered for construction of a supporting infrastructure for geological disposal and international OPEX on long-term storage durations [18].
2	The duration of storage before disposal for options involving 'Direct Disposal' is approximated to be 40 years.	Time considered for construction of a supporting infrastructure for geological disposal GDF [18] and study of suitable disposal containers.
3	Any SNF treated at any European facilities is to be returned to Norway by 2040.	To meet the Studsvik requirements [19]. Orano to return materials after reprocessing is completed [20].
4	No fissile materials (such as U and Pu) that are extracted from SNF using reprocessing technology at an international facility will be returned to Norway.	Requirement for security issues high due to potential for misappropriation of fissile materials. Current Norwegian political stance on such issue unclear pending publication of new report.
5	The Highly-Enriched Uranium (HEU) will not be repatriated to the country of origin.	No such agreement has been reached with country of origin at present and is not expected to be in the future.
6	Suitable transport, storage and disposal casks are, or will, be available for use with all the SNF inventory.	Current supply chain availability already available for storage and transport containers. In SME opinion, it is expected that suitable disposal containers will be available within 40 years.
7	Geological Disposal of all SNF will occur in Norway.	Legislative requirement set by the government [21]. Disposal in other international GDFs not considered[6].
8	Geological Disposal of oxide fuel is a safer[7], easier to implement and therefore preferable fuel type for geological disposal.	More OPEX exists or intention to dispose of SNF in oxide form [22]. Supported by some international research [23]. Will only be determined on further inspection of full inventory.
9	If any fissile material extracted during reprocessing remains in Norwegian ownership, it will be disposed of in a Norwegian GDF.	No other uses for fissile material in Norway.

[6] This is not precluded by law, but no arrangements or plans to do so are currently in place.
[7] Oxide fuel is more chemically stable [34].

Number	Assumption	Justification
10	If the Stavbrønn SNF is reprocessed (at La Hague), the commercial case to reprocess the remaining SNF is significantly improved. However, this does not guarantee that the remaining SNF will be reprocessed.	From a commercial perspective, once part of the inventory is reprocessed it is preferable to reprocess the remaining SNF as well. Further evaluation of options, including technical case, would still be required before decision is made for the remaining SNF.

Table 3-2 - Atkins UK Constraints

Number	Constraint	Justification
1	Stavbrønn SNF must be removed from its current storage facility (Stavbrønn facility) prior to 2024.	Integrity of current storage has been compromised and SNF requires urgent removal due to safety concerns [1].
2	All current SNF storage facilities require upgrading in the next 10-20 years to meet requirements of safe storage.	All current facilities are operating beyond their original intended lifetime [1].
3	The only complete solution (or option) for management of SNF is final geological disposal.	SME opinion and international OPEX (UK policy) [18] [22] [24].
4	At least 5% of experimental inventory i.e. thorium oxide is not currently suitable for chemical reprocessing at Orano.	Understanding of process used in identified facilities [25]. It is possible that suitable facilities for the non-compliant SNF will exist in the future at Orano and therefore will able to provide a full inventory solution.
5	Any mechanical treatment for direct disposal will occur in Norway.	From discussions with Norwegian regulators (DSA), it was stated that the transportation of SNF to a European facility in order for mechanical treatment alone (no chemical treatment) did not improve the wasteform enough to justify the international transportation. Therefore, SNF will only be acceptable for transfer to European facilities for a combination of treatments, where mechanical treatment may be included alongside other treatment options e.g. chemical treatment[8].

Table 3-3 - Atkins UK Exclusions

Number	Exclusions	Justification
1	The assessment of buffer storage, its requirement, size and location are not considered within this report.	It is acknowledged that buffer storage may be a required process in some options. However, in keeping with the level of detail provided in the evaluation of such options, buffer storage is not included in any assessments. Other KS1 assessments are addressing the needs for storage for the

[8] With the exception of the Stavbrønn SNF.

Number	Exclusions	Justification
		Norwegian decommissioning programme, which should consider SNF.
2	The assessment of the interfaces of the management of SNF with the wider Norwegian decommissioning strategy are not considered within this report.	To be developed in a further stage of the KS2 assessment/alternative assessments; not in the scope of this KS1 assessment.
3	The management of the SNF from the NORA reactor is not considered within this report.	All NORA SNF has been repatriated to the country of origin[9] and is therefore not considered as part of the SNF inventory in this assessment [16].
4	Consideration of the influence the geology of the future Norwegian GDF will have on the long-term behaviour of the disposed SNF.	The assessment for the Norwegian GDF is not within the scope of this report. There is also insufficient information on the direct disposal of Norwegian SNF to consider further details relating to interactions with GDF geology.

3.2. Storage

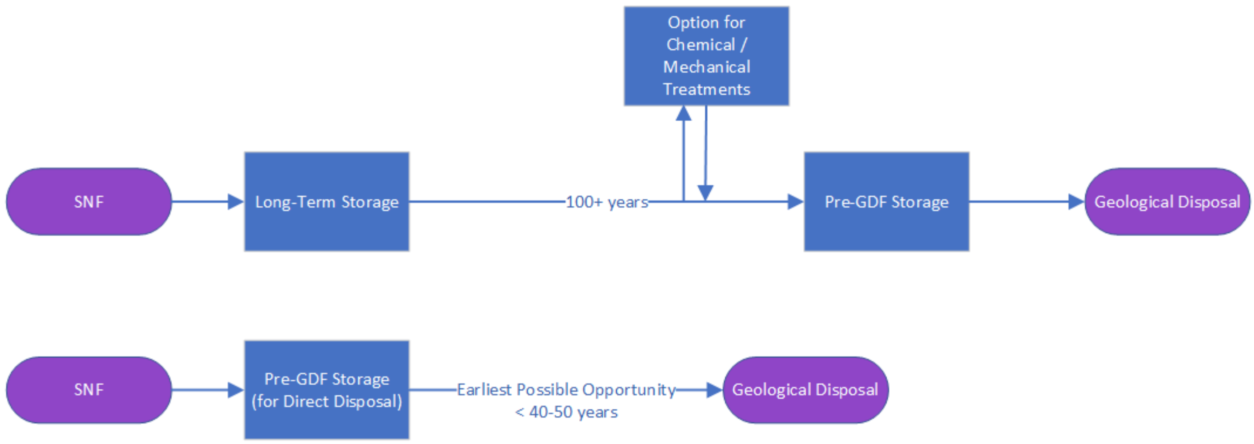
During the description and evaluation of options, references are made to different types of storage. The two types of storage that are included in the description and evaluation of options are interim storage (also referred to as pre-GDF storage) and long-term storage. Buffer storage is excluded from this QA (Table 3-3).

Definitions of interim storage and long-term storage can be found in Section 1.2. The key difference is that interim storage is for shorter periods of time, in a period directly before disposal to a GDF; LTS is a much longer period (can be over double the time of interim storage) and will still require interim storage before disposal to a GDF. It is worth noting that the Pre-GDF Storage, in the LTS scenario, may be at the same geographical location, i.e. the same storage facility. However, it is included to highlight that the purpose and function of the facility will change when the fuel is being prepared for final disposal in a GDF. The fuel may require further inspection and re-packaging for the purpose of disposal (to meet the established waste acceptance criteria (WAC) of the GDF), which is not the function of a LTS facility. In certain cases, a new facility may be constructed to allow for such operations to occur. Until the WAC of the GDF have been established there will be some risk in designating the LTS as the pre-GDF storage.

Also, additional processes can occur during the LTS scenario, whereas they will not during the interim storage period. A visual comparison on the difference in timelines between interim and long-term storage, in the context of the management of the Norwegian SNF inventory, is provided below in Figure 3-1.

[9] The NORA fuel was leased from the USA [57].

Figure 3-1 – Visual Comparison of Interim (Pre-GDF) and Long-Term Storage



3.3. Transport

The principles on safety of transport of any radioactive materials, including SNF, has been developed by the International Atomic Energy Agency (IAEA). The Regulation for the Safe Transport of Radioactive Material [26] and the associated Advisory Material [27] sets the recommended regulatory standard for international transport activities by all modes on land, water or in the air, and applies to numerous countries worldwide.

Radioactive material being transported need to be packaged adequately to provide the necessary protection against the hazardous properties of the materials under routine[10], normal[11] and accident conditions of transport. Specifically, for SNF[12] the key factors include:

- Containment of the radioactivity within the package;
- Control of external radiation level;
- Prevention of a criticality incident; and
- Security to prevent misappropriation of the package content.

Shipment of SNF in Type B packages at scale has been carried out safely since the early 1960s. Competent authority approval is required for Type B packages[13,14,15] based on assessment of documentary evidence of compliance of IAEA regulations, in the form of a Package Design Safety Report (PDSR).

Recognising that transport of radioactive materials is a global process that can involve several countries in the same shipment, the European Association of Competent Authorities (EACA) has been working collaborative on the practicalities of regulatory oversight, resulting in a more effective basis to harmonise interpretation of transport regulatory requirements.

There are a large number of Type B packages designs in existence. In line with the scope identified in Section 2.3, the following Type B packages have been considered:

- Studsvik NCS 45 Type B(U)F package; and
- Orano TN 17/2 Type B(U)F and TN LC Type B(U)F packages.

[10] Routine conditions of transport means that the conveyance is incident free.
[11] Normal conditions of transport means that minor mishaps could occur during the conveyance; the test for demonstrating the ability to withstand normal conditions of transport are defined in SSR-6.
[12] The terms SNF and fuel will be used interchangeably in this section, as both apply in the context of transport.
[13] Type B(U) package designation refers to the package design is unilaterally approved by the country of origin of the design authority.
[14] Type B(M) package designation refers to the package design is approved by the competent authority of each country through or into which the package is to be transport.
[15] Type B(U)F and Type B(M)F denotes that the package is designed for fissile material.

Figure 3-2 - NCS 45 Package Inside the 22-Foot Container [28]

The NCS45 is a Type B(U)F package widely used for transportation of full-length Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR) fuel. The package is designed by Daher Nuclear Technologies GmbH, approved by Bundesamt für die Sicherheit der nuklearen Entsorgung (BASE) in Germany and the Swedish Radiation Safety authority (SSM), and fabricated in Germany by Nuclear Cargo Service (NCS).

This package has previously been used at Halden for a ‘cold trial’ to test the methods for handling and charging the fuel rod containers and showed that the NCS 45 is a viable package for transport between Halden and Studsvik. No change to the facility is envisaged; however, a mobile crane will be required to lift the NCS 45 package.

The package is also judged to be suitable for transport between Kjeller and Studsvik. Some upgrades on the Stavbrønn building will be required to facilitate cask loading.

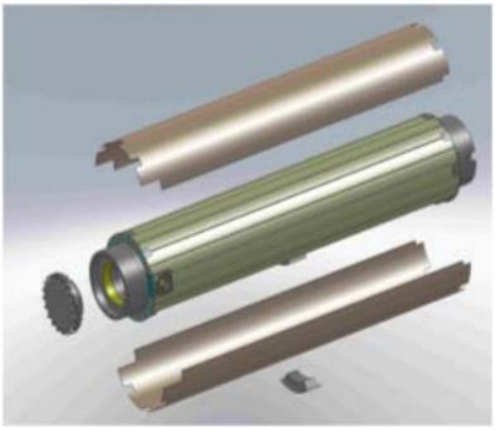
It is understood that loading of the SNF in their current fuel rod containers can be via a hot cell and from there transferred into the transport package, or loaded directly using a loading machine, both in a horizontal configuration. Currently loading machines are not available at either Halden or Kjeller and these will have to be designed and fabricated, installed and commissioned, alongside the containment facility to the required modern safety standards in line with national legislation.

Transportation of failed SNF is possible, with limitations and restriction measures such as the number of fuel rod containers per package. In general, Studsvik does not place requirements for hot cell examinations prior to transport. This is because SNF is routinely transferred from nuclear power plants to Studsvik for hot cell PIE, where a conservative knowledge of the content is sufficient to ensure that the content is within the content specification of the package.

The relatively small capacity of the NCS 45 (22.5t maximum package mass) means that a large number of transports will have to be carried out to complete the entire SNF programme. However, this also means the fuel inventory and fuel loading (mass) will be limited and as such will reduce the likelihood of criticality considerations.

The design of internal components to accommodate metallic fuel has been completed. The content of the latest iteration of the certification includes metallic uranium fuel (natural enrichment) to accommodate JEEP I and HBWR 1st charge fuel [19] [29]. At the time of submission, there was insufficient information available on the experimental fuel for them to be included in the permitted content of this latest iteration. However, these could be transported under similar conditions as the JEEP I and HBWR 1st charge, providing that the maximum burnup does not exceed 1000 MWd tu^{-1} (Mega Watt Day (per) Tonne Uranium) see Table 2-1.

Figure 3-3 – NCS 45 Package Inside a 22-Foot Container [28]



A submission has been made by Daher to the DSA for validation in January 2021 and is currently awaiting approval.

The Orano TN 17/2 is a Type B(M)F package used in France for transportation of PWR and BWR fuel assemblies. The package is designed Orano Nuclear Packages and Services (Orano NPS), approved by Autorité de Sûreté Nucléaire (ASN) in France for Version C and SSM for Version A/B. It has also been licenced for use in Sweden.

The Orano TN LC is a Type B(U)F package used in the US for transportation of BWR, PWR and research/isotope reactor[16] fuel assemblies, approved by ANS in France and Nuclear Regulatory Commission (NRC) in the US.

The TN 17/2 package, which has a maximum laden mass of 80t, is not suitable for use at Halden due to various spatial constraints [20]. Preliminary analysis indicates that the TN LC package could be used at Halden as it is smaller (5017mm length) and lighter (maximum laden mass of 24.5t) [30]. However, the TN LC package is not licensed for receipt at the Orano La Hague facility and therefore a direct transfer from Halden to La Hague is not currently possible. Orano's proposal is that Halden SNF will be transported to Kjeller with the TN LC package, and then transferred to the TN 17/2 package at Kjeller before onward transportation to La Hague [20].

The high-capacity TN 17/2 package means that overall fewer transports are required compared to using the Studsvik NCS 45 packages (the TN 17/2 has approximately 3x the capacity of NCS 45). Further detailed inventory assessment will be required, especially for the experimental and highly enriched SNFs in order to manage criticality considerations. Preliminary data indicates that the TN 17/2 package can be accommodated and used to transport SNF at Kjeller.

The requirements imposed by the use of Orano transport containers requires a "facility"[17] to inspect the compatible container prior to transport; existing facilities at Kjeller and Halen are unlikely to be adequate [20]. Further to this, there are additional requirements for metallic U fuel.

Both casks are designed to be loaded and unloaded vertically. A mobile crane, housed in a suitable containment structure will be required for:

- Loading of HBWR SNF in an Orano defined container into the TN LC package;

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[16] Including Material Testing Reactors (MTRs), Training, research, Isotopes, General Atomics (TRIGA) reactors, Chalk River Laboratories National Research Universal (NRU) reactor and National Research Experimental (NRX) reactor in Canada.

[17] The exact requirements of such a facility have not yet been defined.

- Transfer of the HBWR SNF in an Orano defined container from the TN LC package into the TN 17/2 package; and
- Loading of JEEP SNF in an Orano defined container into the TN 17/2 package.

Although the current content specifications for the TN 17/2 or the TN LC packages do not cover all Norwegian SNF, preliminary investigations suggest that both casks could be licensed for use in Norway for all the spent fuel considered in KS1. Design and fabrication of internal equipment for the packages, update of the PDSR and approval of the packages in Norway and France will have to be carried out prior to commencement of transportation.

3.4. Mechanical Treatment

Mechanical treatment is an identified treatment in some of the options developed in this report. A definition of mechanical treatment is given in Section 1.2.

The reasons that mechanical treatment may be performed upon SNF are:

1. To improve the safety of the waste form for the transportation, storage or disposal of SNF.
2. To improve the packing efficiency for the transportation, storage or disposal of SNF.

From information gathered and SME evaluation, it has been determined that it is unlikely that mechanical treatment of the Norwegian SNF inventory will significantly increase the safety of the SNF in any transport, storage or disposal containers [23] [31]. In the opinion of Atkins UK SMEs, the mechanical treatment of the Norwegian SNF inventory would not improve the safety of any resulting waste form, from either a chemical or criticality perspective. However, it has been indicated from discussions with the NND that the removal of graphite components from the Stavbrønn SNF may improve the safety of the wasteform. The deposition of irradiated graphite may have associated difficulties in disposal, thus making the mechanical removal of such component of the wasteform preferable for safety of disposal.

In a report investigating the treatment and disposal of irradiated graphite (and other carbonaceous waste), findings indicated that graphite waste can be safely disposed in a wide range of disposal systems [32]. It is recommended that in order to develop a safety case for any individual disposal of graphite containing wastes, site-specific studies are required. In order to perform domestic mechanical treatment of SNF, dedicated handling facilities would require construction and suitably trained operators would be needed. The construction, operation and decommissioning of such a facility would also create additional secondary waste streams. Therefore, it is concluded that whilst mechanical treatment in order to remove graphite may improve the robustness of a wasteform and thus the ease and safety of its disposal, it does not provide a significant enough improvement in the overall safety of the wasteform to justify the construction of domestic mechanical treatment facilities.

Previously studies do not show that any of the SNF will need to undergo mechanical treatment in order to be placed in available transport [19], storage or disposal casks [31]; in particular, the compatibility for disposal in the KBS-3 disposal casks. However, it is uncertain whether any of the inventory is severely deformed or heavily oxidised to the extent that it may not fit within the desired container. In such cases, mechanical treatment would be unavoidable. Further assessment into the physical characteristics of the SNF is required.

Mechanical treatment will improve the packaging efficiency of placing SNF in any transport, storage or disposal casks. By cropping the SNF and removing any furniture or cladding, more SNF can be packaged per cask, thus reducing the overall number of casks required. Studsvik have indicated that the number of required shipments to the treatment facility could be reduced if mechanical treatment of the SNF prior/during packaging is undertaken [19]. The same applies for when the SNF is being prepared to be placed into a disposal package.

Mechanical treatment could take place at international facility, rather than in a domestic facility. This could happen as a stand-alone process, to enable packaging for disposal, or in preparation for a chemical treatment.

However, mechanical treatment at an international facility would require multiple handing of the SNF, a transport container suitable for SNF that has not been mechanically treated for transport to the facility, in order for the SNF to then be returned in a different container; this is a sub optimal process and does provide significant improvement to the wasteform. This is captured in Constraint 5.

3.5. Chemical Treatments

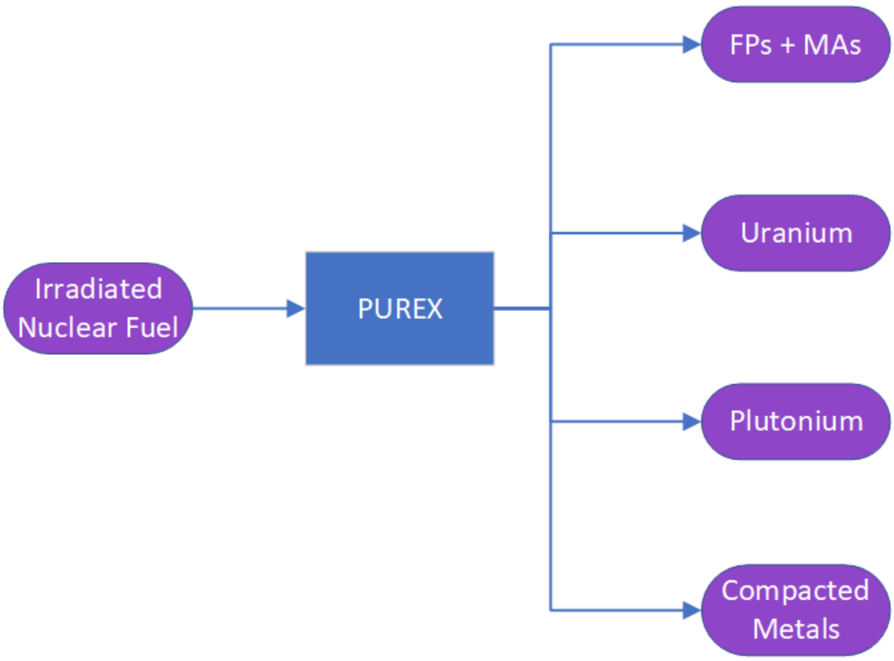
Three main chemical treatments were identified to have potential suitability with the Norwegian SNF. These include chemical reprocessing, chemical oxidation and In-Can Vitrification (Dem'N'Melt/GeoMelt™). A brief description of each of the treatments is given below, in relation to the Norwegian SNF.

3.5.1. Reprocessing

The chemical reprocessing technology considered for use on the Norwegian SNF is plutonium and uranium Recovery by Extraction (PUREX), which is likely to be performed at La Hague, Orano. The principle of reprocessing of fuels has been to separate fuel from cladding material and extract the fission products / actinides and therefore recover the uranium and plutonium for potential reuse.

Out of the Norwegian SNF inventory (Section 2.5), Orano has given both written and verbal confirmation that the majority of the SNF is suitable for the PUREX process. Additional OPEX confirms that PUREX is suitable for fuel types that include UO_2, MOX, uranium oxide clad with aluminium (U-Al) and uranium metal (U-Metal) [25]; this accounts for the majority of the Norwegian SNF inventory. The SNF that has been confirmed by Orano not to be suitable for use in the chemical reprocessing process is approximately 5% of the experimental inventory (FG4), including Thorium oxide and 'other' SNF not yet specified by Orano. Therefore, reprocessing alone is not a full inventory solution in the context of the Norwegian SNF inventory; this is captured in Constraint 4.

Figure 3-4 – Waste and material flow diagram for PUREX reprocessing technology [25]



Orano has extensive experience in performing chemical reprocessing of a range of fuel types, including fuels from research reactors and consequently the process has the highest TRL[18]. PUREX is also an internationally

[18] The technology is in routine, large scale operation.

established process performed at industrial scale by a range of countries with large nuclear programmes including France, Japan, UK (formerly), Russia and India [25] [33].

As a result of chemical reprocessing, different chemical elements within the SNF are separated. These can be categorised into fissile material and waste material. The fissile material is often seen as a resource rather than a waste product, as the fissile content can be re-used in fuel or for other non-commercial uses such as defence. However, in some cases the material is still geologically disposed as waste[19] [18]. The fissile materials extracted in the PUREX process are often converted into an oxide form, to give UO_2 and plutonium oxide (PuO_2). The ownership of this fissile material extracted from SNF can either remain with the current owner or can be transferred to the reprocessing facility. Such material carries significant safety measures to be implemented for safe storage due to the potential for misappropriation of fissile material. In the scenario that Norwegian SNF is reprocessed, it is assumed that the ownership of the material will be transferred to the reprocessing organisation; therefore, no fissile material will return to Norway (Assumption 4).

The other products from the process are regarded as waste. These waste products include compacted fuel element debris (from fuel cladding and end-pieces), which are compacted, fission products (FP)[20] and minor actinides (MA)[21] which are vitrified into a stable, homogenous and durable glass matrix with a long-term predictable behaviour; Intermediate Level Waste (ILW) and HLW respectively [25]. These waste products are encased in a standard universal canister, which is compatible with disposal systems.

Such waste products must be returned to Norway by French law. Article L542-2 of the Environmental Code states that "the disposal in France of radioactive waste from abroad… is forbidden.". Therefore, storage of foreign nuclear waste in France is forbidden. This also means that any SNF unsuitable for reprocessing cannot be transported to Orano i.e. thorium oxide. Additionally, in-line with the EXPER system implement ed in 2008, Equivalent mass and activity must be returned to the foreign customer, excluding:

- valuable materials (i.e. recycled uranium and plutonium);
- effluents; and
- waste originating from the facilities.

Therefore, only waste products suitable for reprocessing can be exported to France and only those wastes suitable for geological disposal will be returned to Norway.

3.5.2. Oxidation

The geological disposal of SNF in oxide form is a common option for life-time management of commercial Advanced Gas-cooled Reactor (AGR) SNFs and disposal has been considered a viable option for the management of part of the UK uranium oxide inventory [22]. The planned disposal of SNF in oxide form is more common internationally [22], in part due to the chemical differences between oxide and metallic fuel; disposal of metallic fuel has more potential safety issues [23] (Assumption 8).

International evidence suggests that it is beneficial to convert metallic fuels to an oxide fuel for disposal, as oxide fuels are less prone to chemical breakdown [34]; this is described in more detail in Section 3.6. Oxide fuels are also less chemically reactive. For example, oxide fuels do not form uranium hydride upon reaction with water, which is a pyrophoric compound. For fuels that are already in an oxide form, further oxidation is not required. It should be noted that oxidation will increase the volume of waste requiring subsequent down-stream management and will ultimately affect disposability.

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[19] The UK's Pu stockpile may still be disposed as waste
[20] Fission products are generated through the fission of fissile elements such as uranium. Examples of FP include iodine, xenon and caesium.
[21] Minor actinides are created through neutron absorption in uranium, also known as trans-uranic elements. Examples include plutonium, neptunium and americium.

Oxidation of metallic fuels has been explored by a European facility, for use on the metallic fuels within Norwegian SNF inventory. The process, called Studsvik Small Scale Conversion (SSSC) process, converts irradiated metallic uranium to uranium oxide pellets, with chemical properties comparable to irradiated Light Water Reactor (LWR) UO_2 fuels [35]. The process has been tested on a sample of aluminium clad irradiated uranium metal from the JEEP I reactor, on degraded irradiated R1 reactor fuel and on high-burnup LWR UO_2 fuel, from which the results showed that the oxidised metallic fuel was stabilized to a degree suitable for storage and final disposal. For more details on the SSSC process, please refer to Reference [35]. Studsvik have also indicated that they are able to blend the different fuels (excluding thorium) to form a more homogeneous wasteform [19]. This will create a blend with a low average enrichment (significantly lower than the highly enriched fuels if left unblended).

Following completion of the oxidation process, the fuel is then packaged into the containers of the client's choice. It is also expected that mechanical treatment will be performed on some fuel, in order to remove furniture or graphite components of the fuel to allow for improved packaging efficiency.

Since part of the Norwegian SNF inventory is already in oxide form, this SNF will not undergo the oxidation process. The oxide fuel, in the context of the Studsvik treatments, can be categorised as the following:

- Uranium oxide fuel:
  - This will be mechanically treated (if required) and then repackaged into casks of the client's choice. Acknowledging requirement of constraint 5 in Table 3-2.
  - There is the potential (if required) for the higher enriched oxide fuels (FG2 & FG3) can be 'down-blended'[22] using the oxidised metallic fuel (FG1) as an additive to obtain a more radiologically homogenous oxidised waste form, in this case the material is no longer regarded as HEU and therefore suitable for long-term storage and disposal if chemical stability criteria can be demonstrated.
- Thorium oxide fuel:
  - As the thorium oxide is in a chemically stable form, the thorium containing material will be mechanically treated (if required) and packaged into containers as the clients specification and await repatriation. Acknowledging requirement of constraint 5 in Table 3-2.

Studsvik's current licence is only valid for small quantities (20 kg/year) for research and development work, the licence does not allow for the treatment of the volumes/mass required to treat the Norwegian fuel [36]. The current licence does however permit the storage of SNF as part of the process for planned hot-cell work. Therefore, once treatment of the SNF is conducted the wasteforms must be returned to Norway for any further storage required before geological disposal. Discussions with the Swedish government regarding disposal of Norwegian SNF in the Swedish GDF have not occurred.

The nuclear materials returned to Norway that will require geological disposal are therefore:

- A homogenous blend of uranium oxide fuel; and
- A stabilised metallic thorium wasteform.

3.5.3. In-Can Vitrification

In-Can Vitrification (ICV) is an alternative chemical treatment that is based upon a vitrification process, which involves containing radioactive waste within glass. There are two main developing ICV technologies: GeoMelt™ of Veolia Nuclear and Dem'N'Melt of a partnership between CEA, Orano, ECM and ANDRA [37] [38]. Given that Orano are a supplier in consideration for providing reprocessing services, it is the Orano Dem'N'Melt technology that is under assessment in the context of the potential treatment of Norwegian SNF.

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[22] The fuels are mixed together to form one wasteform with an enrichment roughly averaged across the individual fuels in proportion to relative volumes.

Dem'N'Melt has been used to treat solid and liquid wastes (including sludges), after being originally developed for use on Defence waste vitrification [37]. Dem'N'Melt, in addition to operation in established facilities, is able to provide direct (in-situ) on-site processing solutions[23]. The use of such technology has been considered at numerous sites in France and other countries, such as Germany, Belgium and Japan [37]. The technology is also proposed to be used for treatment for mobile waste generated from water treatments operations at the Fukushima Daiichi site [37].

Orano stated that they believe Dem'N'Melt is suitable for use on SNF (pending further investigation), including the Norwegian SNFs unsuitable for PUREX reprocessing, such as thorium oxide (Section 3.5.1) [20]. However, there currently does not exist any OPEX using such technologies on SNF. Therefore, the technology is assessed to have a low TRL at present (approximately 1-2).

Pending further research, these alternative methods are proposed to aid the management of the nuclear material found in FG4. Primarily the HEU and MOX enrichment could be down-blended using depleted uranium and other materials as an additive, generating a vitrified low enriched uranium homogenised product suitable for storage and geological disposal if chemical stability requirements can be demonstrated.

3.6. Geological Disposal

As previously mentioned, all enabling stages of managing SNF, such as mechanical and chemical treatment, will ultimately require the final geological disposal of all materials to be considered full lifecycle.

A geological disposal facility uses multiple barriers provide isolation of the radioactive waste and slowing and minimising the release of radioactivity. GDFs utilise natural geology in combination with multiple engineered barriers to create a safe multibarrier system [39]. Once placed underground, the waste will remain there permanently. It is important to note that the presence of groundwater in geological stored conditions is expected. A diagram of a GDF disposal concept for High-Heat-Generating Waste (HHGW) in Higher Strength Rock (HSR) is shown in Figure 3-5.

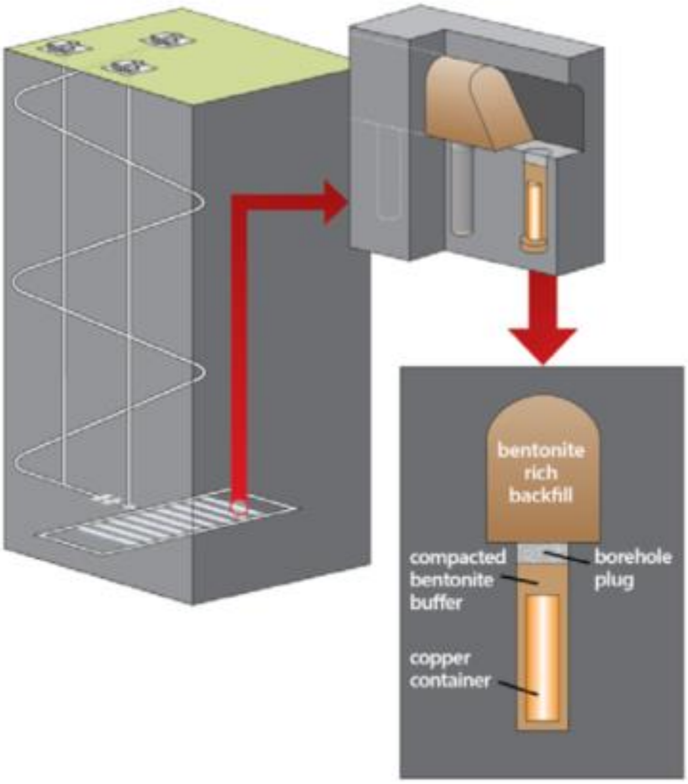
When assessing the feasibility of any SNF for disposal, key safety concerns such as heat output, criticality prevention, corrosion and gas generation must be considered. Due to chemical differences, safety considerations are not the same for all fuel types and they each present different challenges for disposal [34]. It should be noted that these oxides have been produced for use in commercial facilities and as such the quality assurance and purity of the products are expected to be higher than that of the SSSC process (Section 3.5.2) which has been developed to aid disposability and long-term management rather than utilisation in commercial reactors. In considering the likely release of activity in the full multibarrier disposal system, there is negligible difference between the performance of the high QA fuel, which subsequently has undergone temperature and pressure regimes found within the operational reactor and the oxides which are repackaged within a new container that has not been subjected to such an operating history.

Feasibility studies have been undertaken regarding the disposability of both uranium oxide and uranium metal fuels; AGR and Magnox fuels in the UK respectively [34]. Other fuels, such as MOX fuels have also been investigated for disposal.

Studies have shown that the disposal of metallic uranium fuels may be more challenging than the disposal of uranium oxide fuels [34] [40]. Oxide fuels are predicted to be more stable under geological disposal conditions and pose fewer safety concerns in relation to contact with groundwater.

[23] Whether Dem'N'Melt, if selected as a treatment option, will be performed in Norway or at a suppliers (Orano) facilities has not yet been decided.

Figure 3-5 - RWM GDF Disposal Concept for HHGW in HSR [23]



Metallic uranium fuels have higher rates of Instant Release Fraction (IRF) of radionuclides on loss of containment and higher chemical susceptibility for corrosion and radiolysis of residual water. The latter two processes will lead to the generation of gases, which could result in container over-pressurisation. Also, this may lead to the formation of uranium hydride, which is a pyrophoric substance that ignites upon contact with air. Highly enriched fuels, such as those originating from research reactors, are also bound by their fissile content (criticality prevention); this is recognised as a key challenge for disposal. In many research papers on the geological disposal of SNF, highly enriched research reactor fuels are omitted due to the challenges presented for their disposal [23] [34].

Therefore, the feasibility of disposing of metallic uranium or highly enriched fuels is evidenced to be more problematic than for oxide fuels. Current research has not given definitive answers on such topics. In addition, there is not yet any OPEX for the disposal of any SNF[24]. It should be noted that the option to down-blend HEU using depleted uranium and / or natural uranium (FG1) would negate the issues associated with disposition of HEU. Further research, and the first GDFs becoming operational, will be required in order to provide a better underpinning behind the assessment of direct disposal options for the Norwegian SNF inventory. Until such time, it has been assumed that the direct disposal of all Norwegian SNF will be feasible at the time that

[24] No current plans to do so are known to exist.

geological disposal becomes available in Norway (30-40 years at the minimum); this is captured in Assumption 2 and Assumption 6.

4. Technical Case

4.1. Description of Options

During the initial development of options, it was identified that the management of the Stavbrønn SNF should be acknowledged to be a separate Phase of the overall management of the SNF within this project. This is due to the detection of water inside the storage facility the SNF is currently held within; described in more detail in Section 2.1.

The management of the Stavbrønn SNF was denoted as 'Phase 1', with any option numbers preceded with an S (for Stavbrønn), and the management of the remaining SNF (JEEP II, HBWR) denoted as 'Phase 2'. The two Phases are related; the management of the Stavbrønn SNF in Phase 1 has a direct connection with the downstream management of the remaining SNF in Phase 2 in many of the options developed. This has been demonstrated in both the PFD (Appendix B) and in this section.

The table below provides a brief description of all options considered. A more detailed description of the options can be found in Appendix A.

Table 4-1 - Description of Options

Option Number	Option Name	Description
S0	Stavbrønn Baseline	Stavbrønn SNF remains in Stavbrønn facility in existing containers. No change to the current situation.
S1	Stavbrønn Direct Disposal	At the earliest opportunity, SNF is transported to (centralised) pre-GDF storage, or to upgraded and expanded JEEP II or Halden storage facility. The SNF is then directly disposed to a Norwegian GDF; no chemical treatments are performed.
S2a	Stavbrønn Orano - Reprocessing	At the earliest possible opportunity, SNF is transported to Orano's La Hague facility in France for reprocessing. Once reprocessing is complete, HLW is returned to Norway. Ownership of fissile material is transferred to Orano. HLW stored in (centralised) pre-GDF storage. Final disposal in Norwegian GDF.
S2bi	Stavbrønn Studsvik - No Mechanical Treatment	At the earliest possible opportunity, SNF is transported to Studsvik for inspection. The SNF is then re-packaged into suitable storage or disposal containers. Once new storage facilities are available in Norway, it will be transported to Norway.
S2bii	Stavbrønn Studsvik - Mechanical Treatment	At the earliest possible opportunity, SNF is transported to Studsvik for inspection. The SNF is mechanically treated and re-packed into suitable storage or disposal containers. Once new storage facilities are available in Norway, it will be transported to Norway.
S2biii	Stavbrønn Studsvik - Oxidation	At the earliest possible opportunity, SNF is transported to Studsvik for inspection. The SNF then undergoes the Studsvik oxidation process, alongside the remaining Norwegian SNF inventory[25]. The SNF is returned to Norway for disposal in a Norwegian GDF.
S2b-a	Stavbrønn Studsvik – Reprocessing	At the earliest possible opportunity, SNF is transported to Studsvik for inspection. The SNF will be mechanically treated and prepared so that it is suitable for reprocessing at Orano's La Hague facility in France. The SNF will be shipped from Studsvik to a reprocessing facility. Once reprocessing is complete, HLW is returned to Norway as a vitrified

[25] The fuels in the remaining inventory that are already in oxide form will only undergo mechanical treatment and down-blending with the other oxide fuels.

Option Number	Option Name	Description
		wasteform. Ownership of fissile material is transferred to Orano. HLW stored in (centralised) pre-GDF storage. Final disposal in Norwegian GDF.
0	Baseline	Baseline Option – Includes the Stavbrønn Baseline SNF (S0). Long-Term Storage of all SNF by upgrading the existing storage facilities at both original locations (Kjeller and Halden). SNF is kept in existing containers.
0a	Long-Term Storage at both sites	Long-Term Storage of all SNF by upgrading the existing storage facilities at both original locations (Kjeller and Halden). After optional mechanical treatment, the SNF is re-packaged in new sole-use containers (storage). After local long-term storage (100+ years), SNF is re-packaged in transport and/or disposal casks. Transfer to centralised pre-GDF storage. Final disposal in Norwegian geological disposal facility.
0b	Long-Term Storage at co-located site	Long-Term Storage of all SNF by upgrading the existing storage facilities at one of the sites (Kjeller and Halden) or at a new centralised facility. After optional mechanical treatment, the SNF is re-packaged in new dual-use containers (transport and storage) and co-located at either of the existing sites. After long-term co-located storage (100+ years), SNF is re-packaged in transport and/or disposal casks and transferred to centralised pre-GDF storage (if different). Final disposal in Norwegian geological disposal facility.
0c	Long-Term Storage at co-located site in triple-use casks	Long-Term Storage of all SNF by upgrading the existing storage facilities at one of the sites (Kjeller and Halden) or at a new centralised facility. After optional mechanical treatment, the SNF is re-packaged in new triple-use containers[26] (storage, transport, and disposal) and co-located at either of the existing sites. After long-term co-located storage (100+ years), SNF is transferred to centralised pre-GDF storage (if different). Final disposal in Norwegian geological disposal facility.
1a	Direct Disposal – No Mechanical Treatment	SNF is re-packaged into new dual-use casks (transport and disposal) – no mechanical treatment occurs. At the earliest opportunity (20-30 years), SNF is transported to (centralised) pre-GDF storage. Final disposal in Norwegian GDF; no chemical or mechanical treatments are performed.
1b	Direct Disposal – Mechanical Treatment	SNF is re-packaged into new dual-use casks (transport and disposal). Mechanical treatment occurs. At the earliest opportunity (20-30 years), SNF is transported to (centralised) pre-GDF storage. Final disposal in Norwegian GDF.
2a	Domestic Reprocessing	SNF is re-packaged into sole-use casks (transport) and transported to new domestic reprocessing facilities once completed. Reprocessing of SNF in new Norwegian facilities. All products (fissile material and HLW) stored in (centralised) pre-GDF storage (if different). Final disposal in Norwegian GDF.
2ai	International Reprocessing – No Waste	At the earliest possible opportunity, SNF is transported to Orano's La Hague facility in France for reprocessing. Once reprocessing is complete, no materials (U, Pu and the HLW) return to Norway[27].

[26] Should these exist at the time of re-packaging; they do not exist at present.
[27] This is in violation of French law regarding foreign waste (Section 3.5.1)

Option Number	Option Name	Description
2aii	International Reprocessing – HLW	At the earliest possible opportunity, SNF is transported to Orano's La Hague facility in France for reprocessing. Once reprocessing is complete, HLW is returned to Norway in universal canisters. Ownership of fissile material is transferred to Orano. HLW stored in (centralised) pre-GDF storage. Final disposal in Norwegian GDF.
2aiii	International Reprocessing – U, Pu and HLW	At the earliest possible opportunity, SNF is transported to Orano's La Hague facility in France for reprocessing. Once reprocessing is complete, all materials (U, Pu and HLW) are returned to Norway in universal canisters. All materials (U, Pu and HLW) are stored in (centralised) pre-GDF storage. Final disposal in Norwegian GDF.
2b	Domestic Oxidation	SNF is re-packaged into sole-use casks (transport) and transported to new domestic oxidation facilities once completed. Oxidation of suitable SNFs in new Norwegian facilities. SNFs already in oxide form are treated mechanically in new Norwegian facilities. All SNF (now all in oxide form) stored in (centralised) pre-GDF storage (if different). Final disposal in Norwegian GDF.
2bi	International Oxidation – No Waste	At the earliest possible opportunity, SNF is transported to Studsvik's facility in Sweden for oxidation and mechanical treatment. All SNFs not in oxide form undergo Studsvik's oxidation process. SNFs already in oxide form are mechanically treated. All SNFs re-packaged in desired storage/disposal containers. Once process is complete, no materials are returned to Norway[28].
2bii	International Oxidation	At the earliest possible opportunity, SNF is transported to Studsvik's facility in Sweden for oxidation and mechanical treatment. All SNFs not in oxide form undergo Studsvik's oxidation process. SNFs already in oxide form are mechanically treated. All SNFs re-packaged in desired storage/disposal containers. Once process is complete, all SNF (now all in oxide form) is returned to Norway. All SNFs (now all in oxide form) are stored in (centralised) pre-GDF storage. Final disposal in Norwegian GDF.
2c	Domestic In-Can Vitrification	SNF is re-packaged into sole-use casks (transport) and transported to new domestic In-Can Vitrification (utilising Dem'N'Melt or GeoMelt technology) facilities once completed. In-Can Vitrification of suitable SNFs in new Norwegian facilities following any required mechanical treatment. All SNF (as a vitreous wasteform) stored in (centralised) pre-GDF storage (if different). Final disposal in Norwegian GDF.
2ci	International In-Can Vitrification – No Waste	At the earliest possible opportunity, SNF is transported to a facility equipped with In-Can Vitrification technology; this is likely to be at Orano's La Hague facility in France. Once in-Can Vitrification is complete, no materials are returned to Norway.
2cii	International In-Can Vitrification	At the earliest possible opportunity, SNF is transported to a facility equipped with In-Can Vitrification technology; this is likely to be at Orano's La Hague facility in France. Once in-Can Vitrification is complete, SNF (now encapsulated in glass in canisters) is returned to Norway. SNF (now encapsulated in glass in canisters) stored in (centralised) pre-GDF storage. Final disposal in Norwegian GDF.

[28] This is in violation of Swedish law regarding foreign waste (Section 3.5.2)

4.1.1. Mitigations in Options

For several options, the proposed technological solution may not be able to provide a full inventory solution. This is due to some SNF being incompatible with the proposed technology, or that insufficient information is available to guarantee that the full inventory is compatible. In such options, a mitigation is put into place to deal with the excluded SNF. This mitigation will include the use of a different technological solutions and may be implemented at differing stages during the proposed timeline for the option. Such mitigations are covered in the detailed description of the options (Appendix A). An example of the mitigations for non-compliant SNF is presented in Appendix C.

This method of defining the options avoids the requirement for having a very large amounts of options that include all possible sub-combinations of technologies, whilst still allowing the majority of sub-options to exist within the options through the mitigations.

4.2. Process Flow Diagram

A Process flow diagram, shown in Figure 9-2, was developed to identify the options for the management of the Norwegian SNF inventory. As mentioned in Section 4.1, the management of the SNF was defined as Phase 1 and Phase 2 with regards to the management of the Stavbrønn SNF. Figure 9-2 represents pictorially how the SNF inventory is segregated before it is able to undergo any of the many options considered in the diagram.

The diagram is useful in identifying the key decisions at various stages of the lifetime management of the SNF. The primary decision, after segregation of the SNF, is regarding the selected technology, which leads into further sub-options. The diagram also shows how the management of the Stavbrønn SNF can be linked downstream to the Phase 2 SNF management.

In the Phase 1 section of the diagram, it can be seen that four of the five possible options have been marked with the red cross symbol and that they do not join on to the Phase 2 process. This is due to initial evaluation of the Phase 1 options, where it was assessed that none of the marked options were feasible; the reasoning for which is covered in Section 0. This is also represented pictorially in Figure 9-1, which shows the Phase 1 options and additional supporting information to justify the screening out of certain options.

5. Evaluation of Options

At this KS1 stage in the process, it is necessary to identify which options will be taken forward for further assessment and development in the next stage (KS2), and which options should not be considered further.

The assessment is only at the KS1 stage due to the absence of detailed and validated information on certain important elements available. Therefore, in order for this QA to reflect this, the evaluation of options performed was a qualitative process; no numerical scoring or weighting was given to any of the evaluation criteria.

5.1. Evaluation Criteria

In order to identify the options to be taken forward, a set of evaluation criteria was developed. The criteria were developed in such a way that they:

- Aligned with the principles and goals of the project;
- Accounted for the views of the Norwegian Government[29];
- Included key safety considerations;
- Reflected the level of information available, i.e. were high-level; and
- Considered other factors deemed important by Subject Matter Expert (SME) evaluation.

These criteria were defined as the 'fundamental criteria' and are listed in Table 5-1 below. The sub-criteria have been included to give insight into some of the factors that were considered within the main criterion.

Table 5-1 - Fundamental Criterion Table

Number	Criterion	Sub-Criteria
1	Safety & Environment	• Radiological safety (which refers to dose received) and conventional which relates to non-radiological safety, considered for both workers; the public; future generations; and non-human biota • Risk and hazard reduction • Full-lifecycle security considerations • Robustness of the waste form/waste package • Minimisation of handling/processing • Minimisation of number of waste forms • Secondary impacts outside of the country • Environmental impact of new build including resources and energy use[30], noise, visual impact, dust etc. • Transport • Chemical hazard/toxicity • Environmental discharges (national and international) • Generation of secondary wastes
2	Full inventory Full Lifecycle	• Solution for all the SNF inventory • Solution covers the full lifecycle (including final disposal)

[29] As understood by Atkins UK from interactions with Oslo Economics and Norwegian Ministries. These views have not been endorsed by the Norwegian Government.
[30] This includes carbon emissions and non-rad waste arisings.

Number	Criterion	Sub-Criteria
3	Engineering Considerations	• Technology Readiness Level (TRL) • Reversibility – can the solution be reversed if more suitable future treatments/disposal options become available • Future technologies • Re-purposing/re-use of facilities and equipment
4	National and International Considerations	• Meets national legislation/regulations/agreements • Coherent nuclear strategy • International best practice – including IAEA recommendations, other Nuclear agreements • Requirements of international non-proliferation • International conventions/treaties • Trans frontier shipment
5	Capacity and Competency	• Supply chain capability • Suitably Qualified and Experienced Persons (SQEP) to manage the solution
6	Ease of Implementation	• Schedule • Knowledge transfer • Existing infrastructure and resources

The fundamental criteria are aspects of an option that would have significant impacts on the feasibility of completion of the option. These can be seen as 'make or break' when assessing if an option should be taken forward or not.

A qualitative assessment of all the options was performed using the fundamental assessment criteria, in order to assign each option an evaluation term. The evaluation term determined whether an option was taken forward or not too the KS2 assessment stage. If an option was regarded to sufficiently satisfy the fundamental criteria, judged qualitatively, the option was given one of the two terms for options to be taken forward; contingent or viable. For any options which did not meet the fundamental criteria, these were considered dormant or rejected.

This was a qualitative process which used SME judgement, international best practices and OPEX during the evaluation. Only options which were seen as non-conformant to international and/or national regulations were rejected. An explanation of the evaluation terms, which have been based upon preferred options assessment conducted by UK nuclear regulatory bodies [3], is included in Table 5-2 below.

Table 5-2 - Evaluation Terms and Definitions

Evaluation Terms	Definition
Viable	An option which could be delivered to meet the key drivers and objectives as defined.
Contingent	An option which warrants further development in the case that the viable options turn out to be undeliverable.
Dormant	An option which represents a potential option, but at present do not require any further development.
Rejected	An option which will not be developed further.

5.2. Evaluation of Options

A summary table of the options evaluation is provided below. For a more detailed breakdown of the evaluation of options, please refer to Appendix D.

Table 5-3 - Evaluation of Options Summary

KS1 Option Number	KS1 Option Name	Option Evaluation
S0	Stavbrønn Baseline	**Rejected**
S1	Stavbrønn Direct Disposal	**Rejected**
S2a	Stavbrønn Orano – Reprocessing	**Dormant**
S2bi	Stavbrønn Studsvik – No Mechanical Treatment	**Contingent**
S2bii	Stavbrønn Studsvik – Mechanical Treatment	**Viable**
S2biii	Stavbrønn Studsvik - Oxidation	**Viable**
S2b-a	Stavbrønn Studsvik – Reprocessing	**Viable**
0	Baseline	**Dormant**
0a	Long-Term Storage at both sites	**Contingent**
0b	Long-Term Storage at co-located site	**Viable**
0c	Long-Term Storage at co-located site in triple-use casks	**Viable**
1a	Direct Disposal – No Mechanical Treatment	**Viable**
1b	Direct Disposal –Mechanical Treatment	**Viable**
2a	Domestic Reprocessing	**Dormant**
2ai	International Reprocessing – No Waste	**Rejected**
2aii	International Reprocessing – HLW	**Viable**
2aiii	International Reprocessing – U, Pu and HLW	**Dormant**
2b	Domestic Oxidation	**Dormant**
2bi	International Oxidation – No Waste	**Rejected**
2bii	International Oxidation	**Viable**
2c	Domestic In-Can Vitrification	**Dormant**
2ci	International In-Can Vitrification – No Waste	**Rejected**
2cii	International In-Can Vitrification	**Dormant**

6. Options Taken Forward

The evaluation of options produced a shortened list of options that are recommended to be taken forward. These options should be developed further in the KS2 assessment. More detailed and verified information will be required to underpin these options and in order to produce a quantitative assessment for final option selection.

Options that were evaluated as dormant should not be developed further at present; however, they may be a potential consideration in the future or if circumstances change significantly. Rejected options should not be considered any further and should be excluded entirely from future assessments.

Table 6-1 - Summary of Options Taken Forward

Concept Number	Concept Name	Concept Evaluation
	Phase 1	
S2bi	Stavbrønn Studsvik – No Mechanical Treatment	Contingent
S2bii	Stavbrønn Studsvik – Mechanical Treatment	Viable
S2biii	Stavbrønn Studsvik – Oxidation	Viable
S2b-a	Stavbrønn Studsvik – Reprocessing	Viable
	Phase 2	
0a	Long-Term Storage at Both Sites	Contingent
0b	Long-Term Storage at Single Site	Viable
0c	Long-Term Storage at Single Site in triple-use casks	Viable
1a	Direct Disposal – No Mechanical Treatment	Viable
1b	Direct Disposal – Mechanical Treatment	Viable
2aii	International Reprocessing – HLW	Viable
2bii	International Oxidation	Viable

7. Conclusion

Many of the options that were developed and evaluated in this QA do not have sufficient underpinning information and significant knowledge gaps are present. As a result of the evaluation, a list of options was produced that are recommended to be taken forward further in the next stage of assessment, KS2. A number of options were excluded from this list and as such should be not developed further at present.

The key conclusions from this options assessment are:

- Stavbrønn SNF must be given priority management. Options that do not address the ageing storage facility should not be considered further. Options involving Studsvik removing and transporting the Stavbrønn SNF were identified as options to be taken forward in the management of Stavbrønn SNF; this largely due to the ability to relocate the SNF in the shortest timescale.
- Significant knowledge gaps are present that need resolving in order to underpin options. This includes the level of detail available on the SNF inventory that may cause issues in the development of contracts with international treatment facilities. These knowledge gaps must be resolved if a more detailed evaluation of options is to occur in the next phase of assessment, in addition to giving potential suppliers confidence in the information available on the SNF.
- It may be challenging to identify an option that is able to provide a full-inventory solution through the use of only one technology (i.e. solely reprocessing). This is due to the challenging chemical properties associated with parts of the experimental inventory. Mitigations may have to be made for the management of this SNF.
- Current information on the treatment of the Norwegian SNF at Studsvik indicates that this may be the option most likely to provide a full-inventory solution. There remains uncertainty around the quality (leachability) of the wasteform produced in the oxide treatment, as well as the treatment of the thorium fuel. However, it offers many benefits such as minimisation of final wasteforms for disposal and was evaluated as a viable option.
- The use of Orano’s reprocessing technology prohibits a full inventory solution from being achieved. It is possible that if this treatment is combined with the use of ICV technology on the non-compliant (thorium) fuel, then a full inventory solution may be achievable. However, no OPEX is available for the use of such technology on SNF and this may still require alternative mitigations to be considered.
- Feasibility of direct disposal[31] of the full inventory (FG1 and FG4) requires further investigation; there does not exist at present sufficient information to say definitively whether all the fuel types within the Norwegian inventory can be geologically disposed without any chemical treatment. Consideration to the interaction between the GDF’s geology and the SNF is also yet to be consider (Exclusion 4). Further research into the geological disposal of Norwegian SNF is required.
- Options that involve the construction and operation of domestic treatment facilities are not evaluated to be preferable. Such options should not be developed further and should only be re-considered if significant changes to the situation at present (e.g. closure of international treatment facilities) occur.
- A small number of options that considered the scenario in which, after international chemical treatment, no material requiring storage and/or disposal returns to Norway, were rejected. Therefore, Norway will be required to have the necessary infrastructure to enable geological disposal of nuclear materials; geological disposal is unavoidable.
- Regardless of the option selected in the next phase of assessment, there are common aspects of all options that have been identified. This includes supporting infrastructure such as pre-GDF storage and GDF, as well as domestic knowledge/capacity and storage and/or disposal casks.
- The experimental fuel (FG4) is a small quantity ($\lesssim 0.05\ m^3$)[32]; the options undertaken for this fuel, which may include mitigations within options, should be proportional to the quantity, i.e. the construction (and decommissioning/deconstruction) of a domestic ICV plant just for the treatment of the experimental fuel is not proportional to the quantity of fuel.

[31] This refers only to technical feasibility in regards to chemical and physical considerations for disposal.
[32] Volume of FG4 has been very approximately calculated taking the densities of UO_2 as 10,960 kg m^{-3} [50].

8. Recommendations

8.1. Further Work

Based upon the conclusions of this KS1 assessment, the suggestions for further work are divided into strategic and project-based recommendations.

8.1.1. Strategy Recommendations

Table 8-1 - Strategy Recommendation Table

Number	**Recommendation**	**Proposed Responsible Entity**
1	Complete a full inventory of SNF as soon as possible to provide verifiable data to underpin detailed assessment of options. This will allow for confidence to be given to potential suppliers, and for easier assessment of disposal safety cases.	IFE[33], NND.
2	Develop a shared set of key assumptions and assumption/decision hierarchy for the full lifecycle management of Norwegian SNF. This should be agreed by all relevant parties (NND, IFE, DSA etc.).	IFE, NND, DSA
3	Address knowledge gaps in current list of options to be taken forward prior to KS2 assessment. In order to provide a reliable and valid KS2 assessment all options must be suitably underpinned by information.	IFE, NND
4	Continuing establishing strong working relationships between the site licence holders and relevant regulatory bodies. Strong, well communicated relationships will ensure for more efficient progression with the development of the options.	IFE, NND, DSA, relevant Ministries
5	Development of Decommissioning Nuclear Strategy for Norway identifying responsibilities and accountabilities amongst the stakeholders.	IFE, NND
6	Improve documentation of why treatment abroad is necessary for parts of the Norwegian SNF inventory, based on lack of capacity, competence, and facilities in Norway at present, and risks associated with alternative domestic solutions.	IFE, NND
7	Develop further the options for direct disposal. This includes investigating the availability and accessibility of all package types and their suitability for SNF storage and disposal, in particular for metallic uranium and highly-enriched experimental fuels.	IFE, NND
8	Ensure the management of SNF is incorporated into the wider programme for radioactive waste management and final storage option development to ensure co-ordination and optimal solutions in a full inventory, life cycle perspective.	IFE, NND
9	Ensure suitable capacity and competence is available to process safety applications efficiently; this may involve increasing domestic capacity and competence or employing the use of consultants.	IFE, NND, DSA
10	Actively pursue opportunities for learning from other countries' radiation authorities, with current experience of applications for SNF management, decommissioning and treatment and export of SNF.	DSA, relevant Ministries

[33] Wherever IFE is listed, this is only until transferal of responsibility for their sites and SNF to NND.

Number	Recommendation	Proposed Responsible Entity
11	Continue work to coordinate the actions of the ministries involved; Ministry of Industry (NFD), Ministry of Health (HOD), Ministry of Environment (KLD) and Ministry of Foreign Affairs (UD).	NND, DSA, relevant Ministries

8.1.2. Project Recommendations

Table 8-2 - Project Recommendation Table

Number	Recommendation	Proposed Responsible Entity
1	Continue to develop options for Stavbrønn SNF to be transferred to Studsvik for any of the given viable and contingent Phase 1 options. Agreements should be reached as soon as possible to ensure timely evacuation of the SNF in compromised storage.	IFE, NND
2	Prioritise the establishment of new storage facilities/site for SNF, likely to be cask-based, which ensures flexibility in terms of the stored wasteforms. Ensure integration with wider waste management strategy requirements.	IFE, NND
3	Continuation of development of plans for final repository, conceptual understanding of relevant geological environments that a repository might be built in Norway and supporting infrastructure. This should be progressed in close coordination with both the management of SNF and the wider programme for radioactive waste management.	NND, DSA, relevant Ministries
4	Continue to develop the options for chemical treatment solutions at Orano and Studsvik, in coordination with the suppliers. Underpinning the full inventory and full lifecycle elements of such options is essential; or a more detailed exploration of possible mitigations to ensure that the full inventory is covered.	IFE, NND, relevant Ministries
5	Develop further guidance on how to interpret relevant regulation, and what to document in which way in applications, addressing understanding, adherence, and expectations of all parties.	DSA

8.2. Risks

- The Stavbrønn SNF will deteriorate further unless an option is agreed on within the next 1-2 years, leading to possible contamination release and further degradation to the SNF.
- Storage facilities at Met. Lab-II and Halden Bunker Building are operating beyond their intended lifetime and will allow water ingress due to their worsening condition. This creates similar safety concerns as for the Stavbrønn facility.
- Orano, or other potential suppliers of chemical treatments, are unable to sign contracts for reprocessing of SNF due to inadequate full inventory information. The supplier does not have confidence in the information provided in order to ensure that the SNF can be treated.
- SNF is returned to Norway (if treated internationally) before suitable storage facilities are available to accept it.
- After further study, direct disposal is not feasible given the current selection of disposal casks and condition and chemical properties of the SNF inventory.
- Lead time issues with domestic treatment facilities prevent safe handling of SNF leading to contamination release/ increase risk of dose rate due to delay in waste handling.

8.3. Opportunities

- Establish working relationship with any given European supplier for the management of the Stavbrønn SNF, making the Phase 2 management of the remaining SNF more efficient.
- New commercial opportunities with facilities such as Hot Cell which would allow for other decommissioning operations to benefit.
- New chemical treatment technologies become available that offer preferable options for management of Norwegian SNF.
- New disposal casks, or new studies into the disposal of certain SNFs, offer simpler direct disposal options.
- If co-ordination with wider waste management strategy is fully explored, significant savings of both cost and resources can be made[34].

[34] If new facilities are designed to be multipurpose and integrate with both the management of the SNF and wider decommissioning plan.

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Appendix A. Detailed Description of Options

The table below provides a detailed description of all the options that can be identified from the full inventory PFD. It includes information on how the options will be performed, any mitigations that may be required, and other notable factors.

KS1 Option Number	KS1 Option Name	Detailed Description
Phase 1 - Stavbrønn SNF (denoted by S)		
S0	Stavbrønn Baseline	Stavbrønn SNF remains in Stavbrønn facility in existing containers. No changes are made to the situation at present.
S1	Stavbrønn Direct Disposal	At the earliest opportunity, SNF is removed from the Stavbrønn storage facility. It will then be packaged into suitable transport containers for transportation (and possibly storage and/or disposal) to (centralised) pre-GDF storage, or to upgraded and expanded JEEP II or Halden storage facility. After a period of storage in the pre-GDF facility, the SNF would be packaged into suitable disposal containers (if it is not already in them) just before the GDF is operational. Final disposal in Norwegian geological disposal facility.
S2a	Stavbrønn Orano - Reprocessing	At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will packaged into Orano transport inner-casks, which would then require a number of measurements to be taken upon them. In order for these measurements to be taken, it may be required that additional facilities (or additions to existing facilities) are made; this adds uncertainty to the timescale of when transportation can be completed. Once these are performed, the inner-casks are placed in transport casks, and the SNF is transported to La Hague. At La Hague, the SNF will reprocessed using PUREX technology. The waste products (fission products + minor actinides, and also compacted metal waste) would be returned to Norway; assumed that the uranium and plutonium content remains at Orano. These HLW products will still require final disposal in a geological facility, and therefore also Pre-GDF storage. Waste products will be returned in universal canisters suitable for disposal, no facilities will be required to re-package or mechanically treat the HLW.
S2bi	Stavbrønn Studsvik - No Mechanical Treatment	At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will be placed into Studsvik transport casks; unlike the Orano option, no measurements will be required. No required change to the facilities, and thus fewer possible time delays. The SNF is transported to Studsvik, for inspection. After new storage in Norway (whether this is pre-GDF or long-term storage) is completed, the SNF will be placed into suitable transport and storage/disposal containers and will return to Norway. The SNF will then be disposed in the GDF when in operation; provided that it has been shown that the disposal of such SNFs is feasible.
S2bii	Stavbrønn Studsvik - Mechanical Treatment	At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will be placed into Studsvik transport casks; no measurements will be required. The SNF is then transported to Studsvik, whereby it is inspected. Following this, mechanical treatment can be performed. This may include: removal of cladding, removal of furniture, separation of SNF rods from assemblies or the cropping of SNF. After new storage in Norway (whether this is pre-GDF or long-term storage) is completed, the SNF will be placed into suitable transport and storage/disposal containers and will return to Norway. The SNF will then be disposed in the GDF when in operation; provided that it has been shown that the disposal of such SNFs is feasible.
S2biii	Stavbrønn Studsvik - Oxidation	At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will be placed into Studsvik transport casks; no measurements will be required. No required change to the facilities, and fewer possible time delays. The SNF is transported to Studsvik, it is inspected. During the Phase 2, it is decided that all the SNF will be treated at Studsvik. Alongside the remaining inventory, this Stavbrønn SNF is oxidised. After new storage in Norway (whether this is pre-GDF or long-term storage) is completed, the SNF will be placed into suitable transport and storage/disposal containers and will return to Norway. The SNF will then be disposed in the GDF when in operation; provided that it has been shown that the disposal of such SNFs is feasible.
S2b-a	Stavbrønn Studsvik – Reprocessing	At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will be placed into Studsvik transport casks; no measurements will be required. No required change to the facilities, and fewer possible time delays. The SNF is transported to Studsvik, it is inspected. During the Phase 2, the SNF will be reprocessed at La Hague. Studsvik would then discuss with Orano what preparations need to be made to the SNF to make it suitable for reprocessing. In certain scenarios, it may be possible that the remaining SNF is also shipped to Studsvik for preparation. The Stavbrønn SNF is prepared mechanically by Studsvik (most likely removal of Al cladding), packed into suitable transport containers and sent to La Hague. At La Hague, the SNF is reprocessed using PUREX technology. The waste products (fission products + minor actinides, and also compacted metal waste) are returned to Norway; assumed that fissile content remains at Orano. These HLW products will still require final disposal in a geological facility, and therefore also Pre-GDF storage. However, these products will come in universal canisters which are suitable for disposal, and so no facilities will be required to re-package or mechanically treat the HLW.

KS1 Option Number	KS1 Option Name	Description
Phase 2 – After Initial Management of Stavbrønn SNF. At this point in time, the Stavbrønn SNF has undergone one of the above S options. It can be assumed that whatever is decided, it will re-join the remaining inventory for the option decided in the second Phase. Phase 1 options merging with the Phase 2 options are indicated on the full inventory process flow diagram (Figure 9-2).		
0	Baseline	Baseline Option – for both Phases. This baseline option also includes the Stavbrønn Baseline SNF (S0) – meaning that the Stavbrønn SNF will not be moved from its current storage or storage containers. This option is Long-Term Storage by upgrading the existing storage facilities at both original locations (Kjeller and Halden) and keeping in existing containers. However, it must be noted that the upgrading of such facilities is not expected to be feasible within the required timeframe for the Stavbrønn SNF. In this option, there is no 'end goal' of final disposal. This is simply keeping the SNF where it is but improving the facilities so that they still comply with the required legal safety standards. It is the option that involves the least change (and also financial cost) from the situation at present.
0a	Long-Term Storage at both sites	Long-Term Storage of all SNFs. In this option, the Stavbrønn SNF could have taken any of the possible Phase 1 options. Should this option be chosen for Phase 2, the Stavbrønn SNF would return to Norway (after any of the S options) and enter into LTS with the remaining Norwegian SNFs. All SNFs are Long-Term Stored in their existing facilities, which will have to be upgraded to meet safety requirements. The period of the storage is intended to be for very long periods of time – may exceed 100 years [22]. The intention is that after a very long storage period, the SNFs will be geologically disposed. However, it is not defined whether there may be additional enabling processes in between the storage period and the final disposal, i.e. it is possible that if a new technology for chemical treatment of the SNFs is available after 100 years, the decision may be made to utilise this. Regardless of whether any additional enabling steps do occur, the SNF will always end up being geologically disposed after the long storage period. In this option, during some stage of the storage period (preferably as soon as possible) the SNF is re-packaged in new **sole-use** containers (storage) following optional mechanical treatment. It is likely that mechanical treatment is something that is better to consider at a later stage in this option's lifetime, i.e. when it is finally being prepared for final disposal. After the long-term storage period, by the time at which the pre-GDF storage facility has been constructed, the SNF is re-packaged in transport and/or disposal casks* and transferred to this pre-GDF storage. The storage at the pre-GDF facility is mainly based upon how long it takes to get an operational GDF. If the SNF is not already in final disposal casks, then it will be re-packaged when the GDF is near operation. Once operational, the SNF will be transported for final disposal in the Norwegian geological disposal facility.
0b	Long-Term Storage at co-located site	Long-Term Storage of all SNFs. The Stavbrønn SNF could have taken any of the possible Phase 1 options. Should this option be chosen for Phase 2, the Stavbrønn SNF would return to Norway (after any of the S options) and enter into LTS with the remaining Norwegian SNFs. In this option, the SNFs are to be co-located on a single site. All SNFs are Long-Term Stored in one co-located facility; this could be Kjeller, Halden, or a new centralised facility. It is likely that upgrading/expanding facilities, and then moving one site to another (or both), will take 10+ years. The period of the storage is intended to be for very long periods of time – may exceed 100 years. The intention is that after a very long storage period, the SNFs will be geologically disposed. However, it is not defined whether there may be additional enabling processes in between the storage period and the final disposal, i.e. it is possible that if a new technology for chemical treatment of the SNFs is available after 100 years, the decision may be made to utilise this. Regardless of whether any additional enabling steps do occur, the SNF will always end up being geologically disposed after the long storage period. In this option, during some stage of the storage period (preferably as soon as possible) the SNF is re-packaged in new **dual-use** containers (transport and storage) following optional mechanical treatment. It is likely that mechanical treatment is something that is better to consider at a later stage in this option's lifetime, i.e. when it is finally being prepared for final disposal. After the long-term storage period, by the time at which the pre-GDF storage facility has been constructed, the SNF does not need to be re-packed, as it is already in transport appropriate casks. It will be transferred to the pre-GDF storage. The storage at the pre-GDF facility is mainly based upon how long it takes to get an operational GDF. Close to the time of final disposal, the SNF will be re-packaged into suitable disposal casks. Once operational, the SNF will be transported for final disposal in the Norwegian geological disposal facility.

0c	Long-Term Storage at co-located site in triple-use casks	Long-Term Storage of all SNFs. The Stavbrønn SNF could have taken any of the possible Phase 1 options. Should this option be chosen for Phase 2, the Stavbrønn SNF would return to Norway (after any of the S options) and enter into LTS with the remaining Norwegian SNFs. The SNFs are to be co-located on a single site. All SNFs are Long-Term Stored in one co-located facility; this could be Kjeller, Halden, or a new centralised facility. It is likely that upgrading/expanding facilities, and then moving one site to another (or both), will take 10+ years. The period of the storage is intended to be for very long periods of time – may exceed 100 years (see UK strategy). The intention is that after a very long storage period, the SNFs will be geologically disposed. However, it is not defined whether there may be additional enabling processes in between the storage period and the final disposal, i.e. it is possible that if a new technology for chemical treatment of the SNFs is available after 100 years, the decision may be made to utilise this. Regardless of whether any additional enabling steps do occur, the SNF will always end up being geologically disposed after the long storage period. In this option, during some stage of the storage period (preferably as soon as possible) the SNF is re-packaged in new **triple-use** containers (transport and storage) following optional mechanical treatment. It is likely that mechanical treatment is something that is better to consider at a later stage in this option's lifetime, i.e. when it is finally being prepared for final disposal. After the long-term storage period, by the time at which the pre-GDF storage facility has been constructed, the SNF does not need to be re-packed (as in 0a), as it is already in transport appropriate casks. It will be transferred to the pre-GDF storage. The storage at the pre-GDF facility is mainly based upon how long it takes to get an operational GDF. Close to the time of final disposal, the SNF does not need to re-packed, as it is already in suitable disposal casks. One operational, the SNF will be transported for final disposal in the Norwegian geological disposal facility.
1a	Direct Disposal – No Mechanical Treatment	In this option, the Stavbrønn SNF could have gone down any of the S options excluding reprocessing (if reprocessing is chosen for the Stavbrønn SNF, the remaining inventory would also be reprocessed). So, for any of the other S options, the SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for direct disposal. Direct disposal of all SNFs. In this option, the point at which the SNF is geologically disposed is much sooner than for any of the LTS options. Direct disposal will move the SNF to pre-GDF storage **as soon as possible**, and then dispose of the SNF in the geological facility **as soon as possible**. The SNF will remain at both sites whilst the sitting of the GDF location is carried out. During this period, the SNF is re-packaged into new **dual-use** containers (transport and disposal[35]), in preparation to be moved to the pre-GDF storage facility. No mechanical treatment occurs during the re-packaging. Once the GDF site has been decided, the pre-GDF storage facility can be built near to the proposed site. The SNF can be moved the pre-GDF storage as soon as it is ready. Then, the GDF must be constructed. At the earliest opportunity, SNF is transported to the final disposal in Norwegian geological disposal facility. It is expected that this option should be 20-40 years in total. It is possible that the direct disposal of some of the SNF, notably metallic uranium SNF known to contain hydride and Highly-Enriched (HE) uranium and thorium fuels, may not be feasible. Should any SNF not be suitable for direct disposal without mechanical treatment, mitigations would include: • SNF remains in the pre-GDF storage facility until more information is available on the disposal of the unsuitable SNF • A 'Russian Doll' approach is evaluated; this would involve using a many layered cask system to create a more secure disposal waste package. This may be suitable for solutions involving small quantities of SNF (i.e. the experimental inventory) • Domestic research into a suitable disposal cask and/or mechanical treatment

[35] Disposal casks are suitable for storage when the period of storage is approximately less than 50 years.

1b	Direct Disposal – Mechanical Treatment	In this option, the Stavbrønn SNF could have gone down any of the S options excluding reprocessing (S2a) (if reprocessing is chosen for the Stavbrønn SNF, the remaining inventory would also be reprocessed). So, for any of the other S options, the SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for direct disposal. Direct disposal is decided upon as the option. Direct disposal will move the SNF to pre-GDF storage **as soon as possible**, and then dispose of the SNF in the geological facility **as soon as possible**. The SNF will remain at both sites whilst the sitting of the GDF location is carried out. During this period, the SNF is re-packaged into new dual-use casks (transport and disposal[36]), in preparation to be moved to the pre-GDF storage facility. In this option mechanical treatment **does** occur during the re-packaging. Mechanical treatment is assumed to occur domestically during direct disposal. Once the GDF site has been decided, the pre-GDF storage facility can be built near to the proposed site. The SNF can be moved the pre-GDF storage as soon as it is ready. Then, the GDF must be constructed. At the earliest opportunity, SNF is transported to the final disposal in Norwegian geological disposal facility. It is expected that this option should be 20-40 years in total. Once the GDF site has been decided, the pre-GDF storage facility can be built near to the proposed site. The SNF can be moved the pre-GDF storage as soon as it is ready. Then, the GDF must be constructed. At the earliest opportunity, SNF is transported to the final disposal in Norwegian geological disposal facility. It is expected that this option should be 20-40 years in total. It is possible that the direct disposal of some of the SNF, notably metallic uranium SNF known to contain hydride and HE uranium and thorium fuels, may not be feasible. Should any SNF not be suitable for direct disposal without mechanical treatment, mitigations would include: • SNF remains in the pre-GDF storage facility until more information is available on the disposal of the unsuitable SNF • A 'Russian Doll' approach is evaluated; this would involve using a many layered cask system to create a more secure disposal waste package. This may be suitable for solutions involving small quantities of SNF (i.e. the experimental inventory). • Domestic research into a suitable disposal cask and/or mechanical treatment
2a	Domestic Reprocessing	In this option, the Stavbrønn SNF could have gone down any of the S options, excluding reprocessing[37] (S2a). The SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for reprocessing. The remaining SNF (in Norway) will remain in storage at both sites (may need to still be upgraded given the predicted timeframe of developing reprocessing facilities) whilst reprocessing facilities are developed in Norway, as well as suitable operators. It is expected to take a significant amount of time (20-40 years) to achieve this. In order to achieve a full inventory solution, Norway will have to develop multiple processes. Since thorium fuel is not suitable for PUREX, Thorium Recovery by Extraction (THOREX) capabilities would be required. Alternatively, a mitigation for the incompatible SNF would have been developed. This would include: • Long-term storage • Use of an alternative chemical treatment at an international facility (e.g. Dem'N'Melt) • Direct Disposal; should OPEX indicate that this is feasible. Once the reprocessing facilities are operational, the SNF inventory can be reprocessed. Once this has been successfully completed, Norway will be left with waste, in the form of compacted metals and minor actinides, and fissile material, U and Pu. All these materials and wastes must be stored in appropriate facilities until final disposal. It is assumed that the fissile material will be disposed of alongside the waste products, when the Norwegian GDF becomes available.
2ai	International Reprocessing – No Waste	Reprocessing of SNF at an International facility. No materials (U, Pu and the HLW) returns to Norway. This has been excluded as it goes against French national law that no waste products are returned to the country of origin.

[36] Disposal casks are suitable for storage when the period of storage is approximately less than 50 years.
[37] If reprocessing is undertaken internationally, it does not make financial or commercial sense to then develop domestic facilities; all the fuel would be reprocessed internationally.

2aii	International Reprocessing – HLW	In this option, the Stavbrønn SNF could have gone down any of the S options; it is obviously most preferable if the Stavbrønn SNF went down option S2a and is already at La Hague. For the other S options, the SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for reprocessing at La Hague or will be sent directly to La Hague (S2b-a). At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will packaged into Orano transport inner-casks, which would then require a number of measurements to be taken upon them. In order for these measurements to be taken, it may be required that additional facilities (or additions to existing facilities) are made; this adds uncertainty to the timescale of when transportation can be completed. Once these are performed, the inner-casks are placed in transport casks, and the SNF is transported to La Hague. At La Hague, the SNF will reprocessed using PUREX technology. The waste products (fission products + minor actinides, and also compacted metal waste) would be returned to Norway; it is assumed that the fissile content remains at Orano. These HLW products will still require final disposal in a geological facility, and therefore also Pre-GDF storage. However, these products will come in universal canisters which are suitable for disposal, and so no facilities will be required to re-package or mechanically treat the HLW. It must be noted the part of the inventory[38] has been identified as incompatible with the Orano process. Mitigations include: • Orano confirm that Dem'N'Melt can be used on this SNF. The SNF goes to La Hague will all the other inventory and is returned and disposed of the same as well. • An alternative supplier is contacted who have the suitable reprocessing technologies for use with the THOREX SNF. • The SNF is directly disposed alongside the reprocessed materials. Due to the small quantity of SNFs, a Russian doll approach (cask inside a cask inside a cask) may be possible. • The SNF is to be chemically and/or mechanically treated by Studsvik, using their process in development for thorium fuels. • The SNF remains in long-term storage until Norway until a suitable option can be found.
2aiii	International Reprocessing – U, Pu and HLW	In this option, the Stavbrønn SNF could have gone down any of the S options. After Phase 1, the Stavbrønn SNF will return to Norway at the appropriate time to join the remaining inventory in preparation for reprocessing at La Hague or will be sent directly to La Hague (S2b-a). At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will packaged into Orano transport inner-casks, which would then require a number of measurements to be taken upon them. In order for these measurements to be taken, it may be required that additional facilities (or additions to existing facilities) are made. Once these are performed, the inner-casks are placed in transport casks, and the SNF is transported to La Hague. At La Hague, the SNF will reprocessed using PUREX technology. The waste products (fission products + minor actinides, and also compacted metal waste) would be returned to Norway. In this option, the extracted uranium and plutonium will also return to Norway. All materials must be stored prior to final geological disposal in Norway. It is assumed that the fissile material will be disposed of – this will also require further study to investigate the feasibility of disposing of very high enrichment UO_2 and PuO_2. The HLW products will also require final disposal in a geological facility, and therefore also Pre-GDF storage. However, these products will come in universal canisters which are suitable for disposal, and so no facilities will be required to re-package or mechanically treat the HLW. It must be noted the part of the inventory[38] has been identified as incompatible with the Orano process. Mitigations include: • Orano confirm that Dem'N'Melt can be used on this SNF. The SNF goes to La Hague will all the other inventory and is returned and disposed of the same as well. • An alternative supplier is contacted who have the suitable reprocessing technologies for use with the THOREX SNF. • The SNF is directly disposed alongside the reprocessed materials. Due to the small quantity of SNFs, a Russian doll approach (cask inside a cask inside a cask) may be possible. • The SNF is to be chemically and/or mechanically treated by Studsvik, using their process in development for thorium fuels. • The SNF remains in long-term storage until Norway until a suitable option can be found.

[38] This includes the thorium fuel and other fuels within FG4

2b	Domestic Oxidation	In this option, the Stavbrønn SNF could have gone down any of the S options apart from reprocessing (options S2a and S2b-a). The Stavbrønn SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for reprocessing. The remaining SNF (in Norway) will remain at both sites (may need to still be upgraded given the predicted timeframe of developing Oxidation facilities) whilst the oxidation facilities are developed. It is expected to take a significant amount of time (20-40 years) to achieve this. In order to achieve a full inventory solution, mechanical treatment capability will also be required. Use of reduction chemical treatment[39] for thorium fuel may also be considered. There may be a mitigation for the thorium fuel if the current stabilisation process under development is not suitable for the Norwegian thorium fuel. Mitigations that may have to be explored are: • The SNF remains in long-term storage until Norway until a suitable option can be found. • The SNF is mechanically treated and packaged separately to the other SNFs (if disposal in this form is feasible). • A totally new technique is developed by Norway (or elsewhere). • Alternative chemical solutions such as Dem'N'Melt may be explored. • An alternative supplier is contacted who have the suitable reprocessing technologies for use with the thorium fuel. The SNF will then be transported to the newly constructed pre-GDF facility. If the SNF is not in disposal canisters, it will require re-packaging before disposal. Once the GDF is operational, the SNF will be disposed.
2bi	International Oxidation – No Waste	Oxidation of suitable SNF at an International facility, mechanical treatment of other SNFs at an international facility. No materials returns to Norway. This has been excluded as it goes against Swedish national law that no waste products are returned to the country of origin.
2bii	International Oxidation	In this option, the Stavbrønn SNF could have gone down any of the S options apart from reprocessing (options S2a and S2b-a). It is preferable that the Stavbrønn SNF has undertaken S2biii, so that the Stavbrønn SNF is still at Studsvik and awaiting oxidation. The remaining Norwegian SNF inventory will be transported to Studsvik in the same manner as the transportation performed by Studsvik in the S2b options. Once at Studsvik, all of the metallic fuel will be treated using the SSSC process (following any required mechanical treatment of all SNFs). The SNF already in oxide form will not require this treatment. The HE-ThO_2 will undergo a reduction/stabilisation process. Once all the SNF is in an oxide form, Studsvik will 'blend' the SNFs together to achieve a homogenous blend of oxide – this means that the overall enrichment will be more uniform and the wasteform will take on one very similar form. There may be a mitigation for the thorium fuel if the current stabilisation process under development is not suitable for the Norwegian thorium fuel. Mitigations that may have to be explored are: • The SNF remains in long-term storage until Norway until a suitable option can be found. • The SNF is mechanically treated and packaged separately to the other SNFs (if disposal in this form is feasible). • A totally new technique is developed by Norway (or elsewhere). • Alternative chemical solutions such as Dem'N'Melt may be explored. • An alternative supplier is contacted who have the suitable reprocessing technologies for use with the thorium fuel. Studsvik then pack the oxide wasteform into suitable transport and storage/disposal canisters. The SNF will then return to Norway to the newly constructed pre-GDF facility. If the SNF is not in disposal canisters, it will require re-packaging before disposal. Once the GDF is operational, the SNF will be disposed.

[39] Currently under development by Studsvik.

2c	Domestic In-Can Vitrification	In this option, the Stavbrønn SNF could have gone down any of the S options, excluding reprocessing (S2a). The Stavbrønn SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for encapsulation. The remaining SNF (in Norway) will remain at both sites (may need to still be upgraded given the predicted timeframe of developing encapsulation facilities) whilst ICV facilities are developed. It is expected to take a significant amount of time (20-40 years) to achieve this. At the earliest possible opportunity, SNF is retrieved from the current storage. The SNFs will be transported to the domestic plant. Here, the SNFs will be mechanically treated (if required) and then will be encapsulated in canisters using Dem'N'Melt technology. The waste products (nuclear SNF in glass in canisters) would then be transported to Norwegian pre-GDF storage followed by GDF disposal. Not enough information on the use of Dem'N'Melt with SNF is available to give any more details on the packaging and whether SNF will need to be re-packaged, treated further etc. If ICV is not suitable use on certain SNFs, mitigations would include: • The SNF remains in long-term storage until Norway until a suitable option can be found. • Direct disposal of SNF (if feasible)
2ci	International In-Can Vitrification – No Waste	In-Can Vitrification (Dem'N'Melt/GeoMelt) at a European facility (likely at La Hague), no material returns to Norway. This has been excluded as it goes against French national law that no waste products are returned to the country of origin.
2cii	International In-Can Vitrification	In this option, the Stavbrønn SNF could have gone down any of the S options. For the other S options, the SNF will return to Norway at the appropriate time to join the remaining inventory in the preparation for reprocessing at La Hague or will be sent directly to La Hague (S2b-a). At the earliest possible opportunity, SNF is retrieved from the current storage. The SNF will packaged into Orano transport inner-casks, which would then require a number of measurements to be taken upon them. In order for these measurements to be taken, it may be required that additional facilities (or additions to existing facilities) are made. Once these are performed, the inner casks are placed in transport casks, and the SNF is transported to La Hague. At La Hague, the SNFs will be mechanically treated (if not so already) and then will be encapsulated in canisters using Dem'N'Melt technology. The waste products (nuclear SNF in glass in canisters) would be returned to Norway for pre-GDF storage followed by GDF disposal. Not enough information on the use of Dem'N'Melt with SNF is available to give any more details on the packaging and whether SNF will need to be re-packaged, treated further etc.

Appendix B. Process Flow Diagrams

Figure 9-1 - Phase 1 Process Flow Diagram

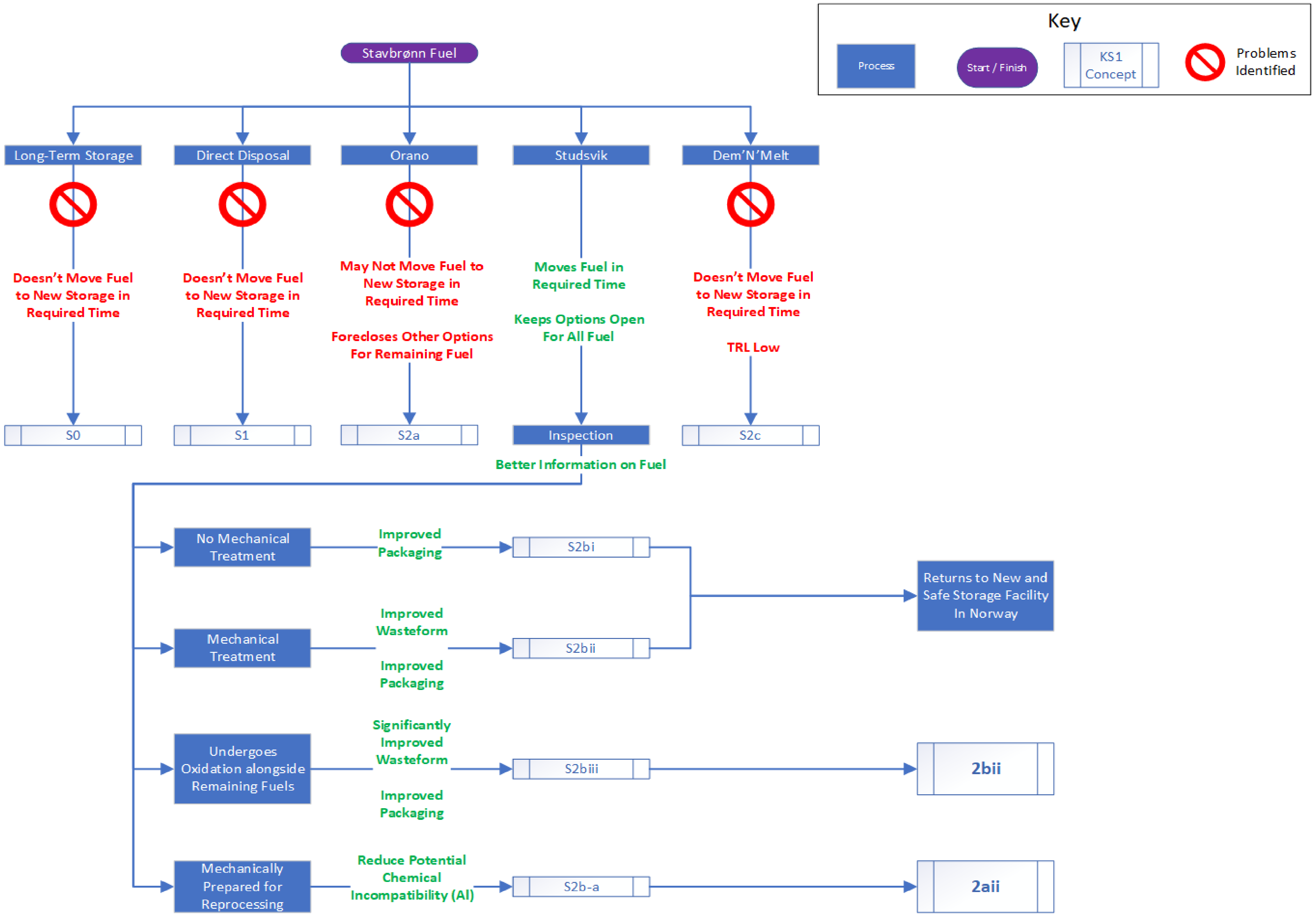

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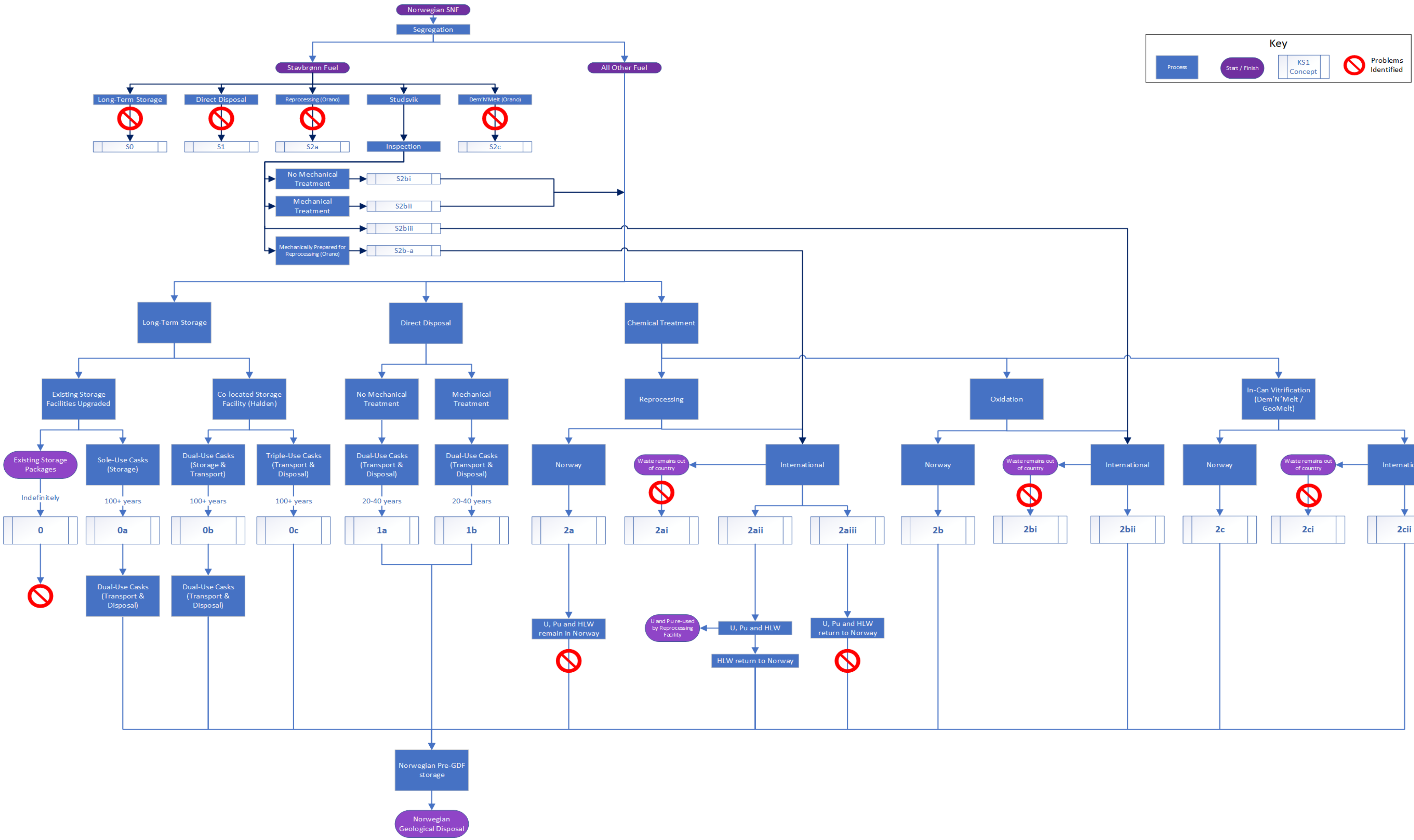
Figure 9-2 - Full Inventory Process Flow Diagram

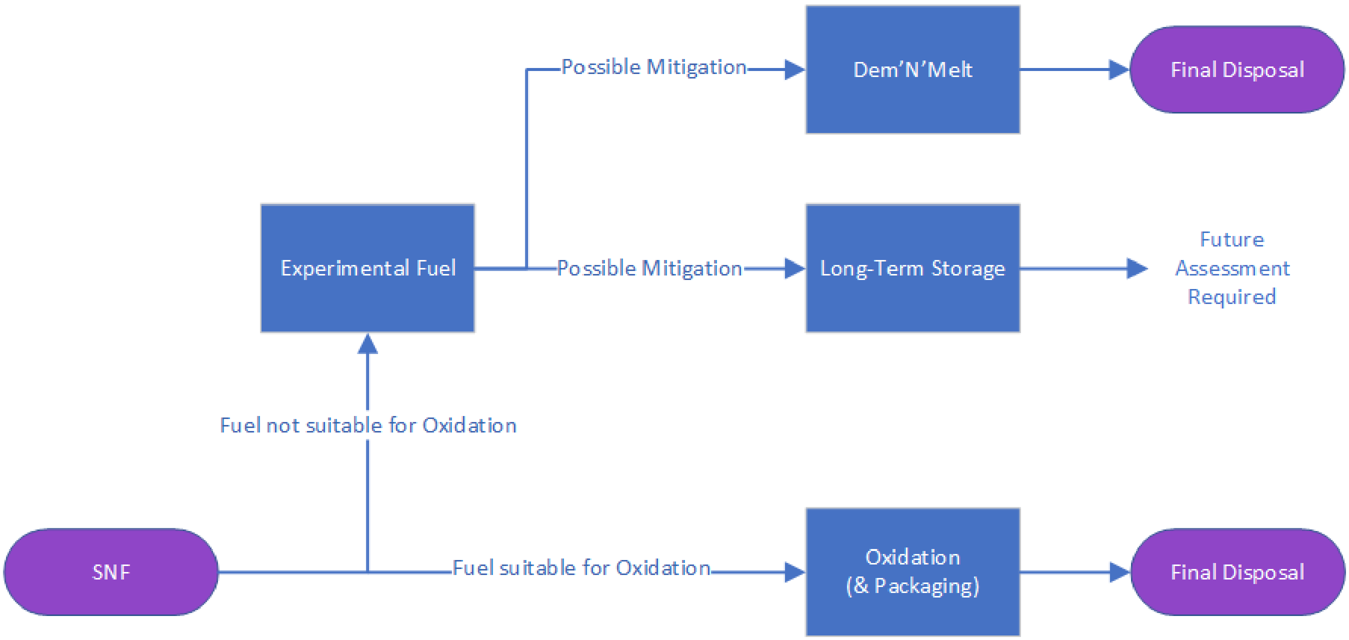


Appendix C. Mitigation Example

The figure below provides further clarification on the mitigations for non-compliant SNF.

1. When considering the technological solution of Oxidation/Stabilisation, current information from suppliers does not provide concrete evidence that all of the experimental inventory (FG4) is suitable for such a process. Therefore, mitigations for this SNF must be put in place. Considering the feasibility of using reprocessing with this SNF is also uncertain, a common mitigation may be to place the problematic SNF into Long-Term Storage pending the development of future research/OPEX that will enable a decision on the solution for the SNF to be made. Alternative technologies may also be considered, such as Dem'N'Melt.

Figure 9-3 - Mitigation Example



Appendix D. Supporting Evaluation Information

D.1. Evaluation of Options Tables

All options were evaluated qualitatively. No weighting was put on the evaluation criteria, and the final evaluation result is not any form of average across the evaluation results of each criteria. It is noted that whilst no weighting is given, safety and environment was seen as the most important evaluation criteria. The reasoning for each evaluation result of each criteria are detailed in bullet points.

Option S0 – Stavbrønn Baseline		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• This option fails to move the SNF out of this storage within the required timeframe. • It does not address significant safety issues relating to the water-ingress in the Stavbrønn storage facility, potential to cause further safety issues from corrosion of SNF. • Does not improve the robustness of the wasteform. • Likely that further degradation to the SNF would occur. • No transport required.	Rejected
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase. • Not a full lifecycle solution as it does not include final disposal.	Rejected
Engineering Considerations	• TRL not relevant for storage. • Keeps future options open.	Contingent
National and International Considerations	• Does not develop a coherent nuclear strategy. • Long-Term Storage is a common international practice for the management of SNF. • The SNF is not in a form resistant to proliferation.	Dormant
Capacity and Competency	• No required domestic capacity. • No required SQEP.	Viable
Ease of Implementation	• No schedule as no change from current situation. • No knowledge transfer, infrastructure or resources required.	Viable
Final Evaluation Result		**Rejected**

Option S1 – Stavbrønn Direct Disposal		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• The construction of a pre-GDF facility is expected to take longer than 3 years. Therefore, this option fails to move the SNF out of this storage within the required timeframe. • It does not address significant safety issues relating to the water-ingress in the Stavbrønn storage facility, potential to cause further safety issues from corrosion of SNF. • Does not improve the robustness of the wasteform. • Transport required to pre-GDF and GDF.	Rejected
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase. • Full lifecycle solution, provided that all of the uranium metallic fuel known to contain uranium hydride can be disposed directly (without chemical treatment); this will require study and investigation.	Contingent
Engineering Considerations	• Direct disposal of metallic fuels has been investigated in part, but there is not yet any international OPEX to support this • TRL of disposal casks for metallic fuel is low. • Does not keep options open – will always undergo direct disposal once at the pre-GDF facility.	Dormant

Option S1 – Stavbrønn Direct Disposal		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
National and International Considerations	• Does develop a coherent nuclear strategy. • Planning for direct disposal is a common international practice for the management of SNF, but not in regard to metallic uranium SNF. • The SNF is not in a form resistant to proliferation.	Contingent
Capacity and Competency	• Requires reasonable domestic capacity for achieving direct disposal of metallic uranium; may require mechanical treatment capacity. • Required SQEP for safety case for direct disposal of metallic fuel.	Dormant
Ease of Implementation	• Some difficulty in upgrading of facilities anticipated. • Will require construction of pre-GDF storage, GDF, and re-packaging with possible mechanical treatment of SNF. • A study is required for the disposal of metallic uranium and mechanical treatment facilities and operators are required.	Dormant
Final Evaluation Result		**Rejected**

Option S2a – Stavbrønn Orano – Reprocessing		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Retrieval and transport (by Orano) of the SNF would be required. There is still significant uncertainty as to whether this is expected to take longer than 3 years. Therefore, it is unclear if this option will fail to move the SNF out of this storage within the required timeframe • It does not address significant safety issues relating to the water-ingress in the Stavbrønn storage facility, potential to cause further safety issues from corrosion of SNF. • After reprocessing, the waste form and waste package returned to Norway (assumed to just be HLW), safety and robustness of the waste form would have improved. Some secondary impacts out of country including generation of secondary wastes during reprocessing. • Requires international transport. • Minimises number of final waste forms for disposal, no re-packaging required.	Dormant
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase. Potential issue with contaminants from Al cladding, but this is the supplier's issue. • Accounts for the full lifecycle if HLW is geologically disposed in Norway; disposal of HLW in universal containers is internationally evidenced. Does not account for the lifecycle of the fissile material should ownership be transferred to reprocessing facility.	Contingent
Engineering Considerations	• High TRL of PUREX reprocessing technology. • High TRL of universal containers. • Does not keep other options open, once SNF is reprocessed no further options are available. • Reprocessing technologies that produce a wasteform more resistant to misappropriation, e.g. co-extraction (COEX), may develop higher TRLs in future [25].	Contingent
National and International Considerations	• Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy. • Returns a product that is in a form resistant to proliferation. Fissile material will remain at the reprocessing facility, so may not be in-line with Norwegian views on the use of the fissile material[40].	Contingent
Capacity and Competency	• As no contracts/permits/inter-governmental agreements are yet in place, would require a very quick turnaround of many applications by Norwegian regulators and license holders to achieve retrieval and transport of SNF in the required timeframe. Concerns over current capacity to do so.	Contingent
Ease of Implementation	• Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Dormant**

Option S2bi – Stavbrønn Studsvik – No Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Retrieval and transport (by Studsvik) of the SNF would be required. The supplier has given confidence that the SNF can be retrieved by 2024. This meets the requirement to move the SNF in the required timeframe.	Contingent

[40] The Norwegian Ministry of Defence's views on this are to be published in an up-coming paper

Option S2bi – Stavbrønn Studsvik – No Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• Minimises further degradation of the wasteform; only up until the point at which it is retrieved. • The safety of the wasteform is not significantly improved, but more information will be available on the condition of the SNF following inspection. • Requires international transport. • The SNF will be re-packaged into better transport and storage/disposal containers, thus improving the waste package. • No generation of secondary wastes from chemical treatment.	
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase. • Only covers part of the lifecycle, will need to be combined with one of the options in Phase 2 to achieve full lifecycle. This option is viewed as an enabling process for the full lifecycle management of the Stavbrønn SNF.	Contingent
Engineering Considerations	• No relevant TRL. • Keeps future options open.	Viable
National and International Considerations	• Still requires development of downstream national strategy. • The SNF is not in a form resistant to proliferation.	Dormant
Capacity and Competency	• Contracts to retrieve SNF already in place with Studsvik, requires approval of cask certifications – not expected to cause any significant issues. • Downstream treatment/processing may be required, necessitating greater domestic capacity. • International supplier has extensive experience transporting and handling similar SNFs [19]. • No domestic SQEP required.	Viable
Ease of Implementation	• At minimum will require retrievals, pre-GDF storage and final disposal; downstream management to achieve full lifecycle management upon return to Norway may require more supporting infrastructure.	Viable
Final Evaluation Result		**Contingent**

Option S2bii – Stavbrønn Studsvik - Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Retrieval and transport (by Studsvik) of the SNF would be required. The supplier has given confidence that the SNF can be retrieved by 2024. This meets the requirement to move the SNF in the required timeframe. • Minimises further degradation of the wasteform; only up until the point at which it is retrieved. • The safety of the wasteform is improved through mechanical treatment; this also improves packaging efficiency. More information will be available on the condition of the SNF following inspection. • Requires international transport. • The SNF will be re-packaged into better transport and storage/disposal containers, thus improving the waste package. • No generation of secondary wastes from chemical treatment; some secondary wastes to be disposed of arising from mechanical treatment (e.g. graphite, cladding etc.).	Viable
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase. • Only covers part of the lifecycle, will need to be combined with one of the options in Phase 2 to achieve full lifecycle. This option is viewed as an enabling process for the full lifecycle management of the Stavbrønn SNF.	Contingent
Engineering Considerations	• No relevant TRL. • Keeps future options open.	Viable
National and International Considerations	• Still requires development of downstream national strategy. • The SNF is not in a form resistant to proliferation.	Dormant
Capacity and Competency	• Contracts to retrieve SNF already in place with Studsvik, requires approval of cask certifications – not expected to cause any significant issues. • Downstream treatment/processing may be required, necessitating greater domestic capacity. • International supplier has extensive experience transporting and handling similar SNFs [19]. • No domestic SQEP required.	Viable

Option S2bii – Stavbrønn Studsvik - Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Ease of Implementation	• At minimum will require retrievals, pre-GDF storage and final disposal; downstream management to achieve full lifecycle management upon return to Norway may require more supporting infrastructure.	Viable
Final Evaluation Result		**Viable**

Option S2biii - Stavbrønn Studsvik - Oxidation		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Retrieval and transport (by Studsvik) of the SNF would be required. The supplier has given confidence that the SNF can be retrieved by 2024. This meets the requirement to move the SNF in the required timeframe. • Minimises further degradation of the wasteform; only up until the point at which it is retrieved. • The safety of the wasteform is significantly improved through chemical treatment; SNF is more chemical stable in oxide form. More information will be available on the condition of the SNF following inspection and treatment. • Requires international transport. • The SNF will be re-packaged into better transport and storage/disposal containers, thus improving the waste package. • Generation of secondary wastes from chemical treatment; some secondary wastes to be disposed of arising from mechanical treatment (e.g. graphite, cladding etc.).	Viable
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase. Also accounts for the remaining SNF; full inventory for entire Norwegian SNF inventory. • Accounts for the full lifecycle if oxide fuel (and remaining SNF) is geologically disposed in Norway.	Viable
Engineering Considerations	• TRL of the Studsvik oxidation process is medium at present; the process has been performed on smaller scales but needs to up-scaled [35]. • Keeps some future options open; forecloses direct disposal but keeps option for reprocessing available if so desired.	Contingent
National and International Considerations	• The SNF will remain is not in a form resistant to proliferation; however, if SNFs are blended then the wasteform will be in a less vulnerable form. • Coherent nuclear strategy. • Planned disposal of oxide fuel is a current SNF strategy for numerous countries.	Dormant
Capacity and Competency	• Contracts to retrieve SNF already in place with Studsvik, requires approval of cask certifications – not expected to cause any significant issues. • Downstream treatment/processing may be required, necessitating greater domestic capacity. • International supplier has extensive experience transporting and handling similar SNFs [19]. • No domestic SQEP required.	Viable
Ease of Implementation	• Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Viable**

Option S2b-a – Stavbrønn Studsvik – Reprocessing		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Retrieval and transport (by Studsvik) of the SNF would be required. The supplier has given confidence that the SNF can be retrieved by 2024. This meets the requirement to move the SNF in the required timeframe. • Minimises further degradation of the wasteform; only up until the point at which it is retrieved. • The safety of the wasteform is not significantly improved in initial transfer to Studsvik, but more information will be available on the condition of the SNF following inspection. • After reprocessing, the waste form and waste package returned to Norway (assumed to just be HLW), safety and robustness of the waste form would have improved. Some secondary impacts out of country including generation of secondary wastes during reprocessing. • Requires multiple international transports. • Minimises number of final waste forms for disposal, no re-packaging required; this is assuming the remaining inventory also undergoes reprocessing.	Viable
Full Inventory Full Lifecycle	• Accounts for all of the Stavbrønn SNF; full inventory for this Phase.	Viable

Option S2b-a – Stavbrønn Studsvik – Reprocessing		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• Accounts for the full lifecycle if HLW is geologically disposed in Norway; disposal of HLW in universal containers is internationally evidenced. Does not account for the lifecycle of the fissile material should ownership be transferred to reprocessing facility.	
Engineering Considerations	• High TRL of PUREX reprocessing technology. • High TRL of universal containers. • Removes issues of Al cladding as can be removed in the pre-treatment at Studsvik. • Does not keep other options open, once SNF is reprocessed no further options are available. Also forecloses options for remaining SNF. • Reprocessing technologies that produce a wasteform more resistant to misappropriation, e.g. COEX, may develop higher TRLs in future [25].	Dormant
National and International Considerations	• Returns a product that is in a form resistant to proliferation. Fissile material will remain at the reprocessing facility, so may not be in-line with Norwegian views on the use of the fissile material[41]. • Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy.	Viable
Capacity and Competency	• Contracts to retrieve SNF already in place with Studsvik, requires approval of cask certifications – not expected to cause any significant issues. • Downstream treatment/processing may be required, necessitating greater domestic capacity. • International supplier has extensive experience transporting and handling similar SNFs [19]. • Other international supplier has extensive experience reprocessing research reactor SNFs [20]. • No domestic SQEP required.	Viable
Ease of Implementation	• Will require construction of pre-GDF storage, GDF. • Will require a tri-governmental agreement, and coordination between Studsvik and Orano on the preparation of SNF for reprocessing.	Contingent
Final Evaluation Result		**Viable**

Option 0 – Baseline		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• This option fails to move the SNF out of the Stavbrønn storage within the required timeframe. • It does not address significant safety issues relating to the water-ingress in the Stavbrønn storage facility, potential to cause further safety issues from corrosion of SNF. • Does not improve the robustness of the wasteforms. Likely that further degradation to the SNF would occur. • The Met. Lab-II and Bunker Building will require upgrading if they are to meet safety standards and prevent any degradation to the waste forms. • No transport required.	Rejected
Full Inventory Full Lifecycle	• Full inventory. • Not a full lifecycle solution as it does not include final disposal.	Rejected
Engineering Considerations	• TRL not relevant for storage. • Keeps future options open.	Contingent
National and International Considerations	• Does not develop a coherent nuclear strategy. • Long-Term Storage is a common international practice for the management of SNF. • The SNF is not in a form resistant to proliferation.	Dormant
Capacity and Competency	• No required domestic capacity beyond upgrading facilities. • No required SQEP.	Viable
Ease of Implementation	• Upgrading of storage facilities must happen. • No knowledge transfer, infrastructure or resources required.	Viable

[41] The Norwegian Ministry of Defence's views on this are to be published in an up-coming paper

Option 0 – Baseline		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Final Evaluation Result		**Dormant**

Option 0a – Long-Term Storage at both sites		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• This option now excludes the management of the Stavbrønn SNF; those safety considerations are not relevant. • Does not improve the robustness of the wasteforms. Likely that further degradation to the SNF would occur. • The Met. Lab-II and Bunker Building will require upgrading if they are to meet safety standards. • Domestic transport required.	Contingent
Full Inventory Full Lifecycle	• Full inventory. • Full lifecycle solution if it includes final disposal. • Does not cover *all* of the lifecycle in detail. It enables the final disposal, but parts of the lifecycle remain undefined.	Contingent
Engineering Considerations	• TRL not relevant for storage. • Direct disposal of metallic fuels has been investigated in part, but there is not yet any international OPEX to support this • TRL of disposal casks for metallic fuel is low. • Keeps options open.	Contingent
National and International Considerations	• Does develop a coherent nuclear strategy; does not outline the strategy in full detail. • Long-Term Storage with the intentional of geological disposal is a common international practice for the management of SNF. • The SNF is not in a form resistant to proliferation.	Contingent
Capacity and Competency	• No required domestic capacity beyond upgrading facilities. • No required SQEP.	Viable
Ease of Implementation	• Upgrading of storage facilities must happen. • Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Contingent**

Option 0b – Long-Term Storage at co-located site		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• This option now excludes the management of the Stavbrønn SNF; those safety considerations are not relevant. • Does not improve the robustness of the wasteforms. Likely that further degradation to the SNF would occur. • One of either the Met. Lab-II and Bunker Building will require upgrading (and expanding to facilitate the co-located inventory) if they are to meet safety standards, or the construction of a new centralised storage facility. • SNF all located in a single storage location; easier to manage in terms of safety and security. • Domestic transport required.	Viable
Full Inventory Full Lifecycle	• Full inventory. • Full lifecycle solution if it includes final disposal. • Does not cover *all* of the lifecycle in detail. It enables the final disposal, but parts of the lifecycle remain undefined.	Contingent
Engineering Considerations	• TRL not relevant for storage. • Direct disposal of metallic fuels has been investigated in part, but there is not yet any international OPEX to support this • TRL of disposal casks for metallic fuel is low. • Keeps options open.	Contingent

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Option 0b – Long-Term Storage at co-located site		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
National and International Considerations	• Does develop a coherent nuclear strategy; does not outline the strategy in full detail. • Long-Term Storage with the intentional of geological disposal is a common international practice for the management of SNF. • The SNF is not in a form resistant to proliferation.	Contingent
Capacity and Competency	• No required domestic capacity beyond upgrading facilities. • No required SQEP.	Viable
Ease of Implementation	• Upgrading of storage facility or construction of centralised facility must happen. • Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Viable**

Option 0b – Long-Term Storage at co-located site in triple-use casks		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• This option now excludes the management of the Stavbrønn SNF; those safety considerations are not relevant. • Does not improve the robustness of the wasteforms. Likely that further degradation to the SNF would occur. • One of either the Met. Lab-II and Bunker Building will require upgrading (and expanding to facilitate the co-located inventory) if they are to meet safety standards, or the construction of a new centralised storage facility. • SNF all located in a single storage location; easier to manage in terms of safety and security. • Waste package greatly improved. • Will only require re-packaging once into the triple-use casks. • Domestic transport required.	Viable
Full Inventory Full Lifecycle	• Full inventory. • Full lifecycle solution if it includes final disposal. • Does not cover *all* of the lifecycle in detail. It enables the final disposal, but parts of the lifecycle remain undefined.	Contingent
Engineering Considerations	• TRL not relevant for storage. • Direct disposal of metallic fuels has been investigated in part, but there is not yet any international OPEX to support this • TRL of disposal casks for metallic fuel is low. • Risks that SNF cannot been disposed in triple-use casks; these also do not yet exist and so have a TRL of low. • Keeps options open.	Contingent
National and International Considerations	• Does develop a coherent nuclear strategy; does not outline the strategy in full detail. • Long-Term Storage with the intentional of geological disposal is a common international practice for the management of SNF. • The SNF is not in a form resistant to proliferation.	Contingent
Capacity and Competency	• No required domestic capacity beyond upgrading facilities. • No required SQEP.	Viable
Ease of Implementation	• Upgrading of storage facility or construction of centralised facility must happen. • Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Viable**

Option 1a – Direct Disposal – No Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Does not improve the robustness of the wasteform.	Viable

Option 1a – Direct Disposal – No Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• One of either the Met. Lab-II and Bunker Building may require upgrading (and expanding to facilitate the co-located inventory) if they are to meet safety standards, or the construction of a new centralised storage facility; this is dependent on the timescale for the construction of the pre-GDF facility. • Disposes of SNF in significantly shorter timeframe when compared to long-term storage; geological disposal is ultimate safety measure. • Domestic transport required.	
Full Inventory Full Lifecycle	• Full inventory and full lifecycle solution; provided that all of the uranium metallic fuel known to contain uranium hydride and HEU/HETh can be disposed directly (without chemical treatment); this will require study and investigation.	Contingent
Engineering Considerations	• Direct disposal of metallic fuels has been investigated in part, but there is not yet any international OPEX to support this. • TRL of disposal casks for metallic fuel is low. • Does not keep options open – will always undergo direct disposal once at the pre-GDF facility. However, foreclosure of options earlier on due to geological disposal is a positive aspect. • Less time to develop disposal studies.	Contingent
National and International Considerations	• Does develop a coherent nuclear strategy. • Planning for direct disposal is a common international practice for the management of SNF, but not in regard to metallic uranium SNF. • The SNF will remain in a form that is not resistant to proliferation; shorter time period in this option.	Viable
Capacity and Competency	• Requires reasonable domestic capacity for achieving direct disposal of metallic uranium; may require mechanical treatment capacity. • Required SQEP for safety case for direct disposal of metallic fuel.	Dormant
Ease of Implementation	• Some difficulty in upgrading of facilities anticipated. • Will require construction of pre-GDF storage, GDF, and re-packaging facilities. • A study is required for the disposal of metallic uranium and safety case is required.	Contingent
Final Evaluation Result		**Viable**

Option 1b – Direct Disposal – Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Does not improve the robustness of the wasteform. • One of either the Met. Lab-II and Bunker Building may require upgrading (and expanding to facilitate the co-located inventory) if they are to meet safety standards, or the construction of a new centralised storage facility; this is dependent on the timescale for the construction of the pre-GDF facility. • Disposes of SNF in significantly shorter timeframe when compared to long-term storage; geological disposal is ultimate safety measure. • Domestic transport required.	Viable
Full Inventory Full Lifecycle	• Full inventory and full lifecycle solution; provided that all of the uranium metallic fuel known to contain uranium hydride and HEU/HETh can be disposed directly (without chemical treatment); this will require study and investigation. • Feasibility of direct disposal increases slightly with the option to mechanically treat the SNF.	Contingent
Engineering Considerations	• Direct disposal of metallic fuels has been investigated in part, but there is not yet any international OPEX to support this. • TRL of disposal casks for metallic fuel is low. • Does not keep options open – will always undergo direct disposal once at the pre-GDF facility. However, foreclosure of options earlier on due to geological disposal is a positive aspect. • Less time to develop disposal studies. • Mechanical treatment will improve packaging efficiency and may also help safety features.	Contingent
National and International Considerations	• Does develop a coherent nuclear strategy. • Planning for direct disposal is a common international practice for the management of SNF, but not in regard to metallic uranium SNF. • The SNF will remain in a form that is not resistant to proliferation; shorter time period in this option.	Viable
Capacity and Competency	• Requires reasonable domestic capacity for achieving direct disposal of metallic uranium; may require mechanical treatment capacity.	Dormant

Option 1b – Direct Disposal – Mechanical Treatment		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• Required SQEP for safety case for direct disposal of metallic fuel.	
Ease of Implementation	• Some difficulty in upgrading of facilities anticipated. • Will require construction of pre-GDF storage, GDF, and re-packaging and mechanical treatment facilities with suitable operators. • A study is required for the disposal of metallic uranium and safety case is required.	Contingent
Final Evaluation Result		**Viable**

Option 2a – Domestic Reprocessing		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Not expected to move the SNF out of current storage; facilities will require upgrading • High risks associated with chemical reprocessing technology • Generation of secondary wastes resulting from chemical treatment. • Does not improve the safety of the wasteform until reprocessing. • Impact of building new reprocessing facility. • Domestic transport required. • Number of handling and treatment processes. • Minimises number of final wasteforms for disposal. • Facility must also be decommissioned in future; secondary waste creation.	Dormant
Full Inventory Full Lifecycle	• Full inventory and full lifecycle; more than one chemical reprocessing or chemical treatment would be required – need THOREX or other chemical treatment to treat thorium fuel. • Potential issues with Al cladding of SNF.	Dormant
Engineering Considerations	• TRL of PUREX high, medium for THOREX. • TRL of chemical reprocessing in Norway is zero. • High TRL of universal containers. • Does not keep other options open, once SNF is reprocessed no further options are available. • Reprocessing technologies that produce a wasteform more resistant to misappropriation, e.g. COEX, may develop higher TRLs in future [25]. • Extreme security measures for the management of fissile material. • Facilities constructed are likely to only have a use for the management of the Norwegian SNF inventory. It's possible that the facilities could be used for other SNF from other countries if desired in future.	Dormant
National and International Considerations	• Results in a product that is in a form that is resistant to proliferation. Will have ownership over fissile material. • Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy.	Contingent
Capacity and Competency	• Very high capability required of supply chain. Would have to rely on using international expertise to achieve such an operation. • Significant training of SQEP required. • Incredibly demanding domestically.	Rejected
Ease of Implementation	• Will require construction of new reprocessing facilities, pre-GDF storage and GDF. • Significant knowledge transfer required. • Significant improvement in all domestic infrastructure and resources required. • Very difficult to implement.	Rejected
Final Evaluation Result		**Dormant**

Option 2ai – International Reprocessing – No Waste		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• The Met. Lab-II and Bunker Building will require upgrading if they are to meet safety standards; dependant on the timeframe in which Orano are able to retrieve the SNF. • Some secondary impacts out of country including generation of secondary wastes during reprocessing. • Requires international transport. • No materials for disposal.	N/A
Full Inventory Full Lifecycle	• Not full inventory; some of the experimental SNF requires a mitigation. • Potential issue with contaminants from Al cladding, but this is the supplier's issue. • Accounts for the full lifecycle from a Norwegian perspective; all materials remain out of country.	N/A
Engineering Considerations	• High TRL of PUREX reprocessing technology. • High TRL of universal containers. • Does not keep other options open, once SNF is reprocessed no further options are available. • Reprocessing technologies that produce a wasteform more resistant to misappropriation, e.g. COEX, may develop higher TRLs in future [25].	
National and International Considerations	• It is against French law that the waste is not returned to Norway; this makes this option illegal and therefore is rejected on this point alone.	Rejected
Capacity and Competency	• No required domestic capacity.	N/A
Ease of Implementation	• No domestic infrastructure or knowledge transfer required.	N/A
Final Evaluation Result		**Rejected**

Option 2aii – International Reprocessing – HLW		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• The Met. Lab-II and Bunker Building will require upgrading if they are to meet safety standards; dependant on the timeframe in which Orano are able to retrieve the SNF. • After reprocessing, the waste form and waste package returned to Norway (assumed to just be HLW), safety and robustness of the waste form would have improved. • Some secondary impacts out of country including generation of secondary wastes during reprocessing. • Requires international transport. • Minimises number of final waste forms for disposal, no re-packaging required.	Viable
Full Inventory Full Lifecycle	• Not full inventory; some of the experimental SNF requires a mitigation. • Potential issue with contaminants from Al cladding, but this is the supplier's issue. • Accounts for the full lifecycle from a Norwegian perspective; all materials remain out of country.	Contingent
Engineering Considerations	• High TRL of PUREX reprocessing technology. • High TRL of universal containers. • Does not keep other options open, once SNF is reprocessed no further options are available. • Reprocessing technologies that produce a wasteform more resistant to misappropriation, e.g. COEX, may develop higher TRLs in future [25].	
National and International Considerations	• Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy. • Returns a product that is in a form resistant to proliferation. Fissile material will remain at the reprocessing facility, so may not be in-line with Norwegian views on the use of the fissile material[42].	Viable
Capacity and Competency	• No significant required domestic capacity; only for storage and disposal of HLW.	Viable
Ease of Implementation	• Some difficulty in upgrading of facilities anticipated.	Viable

[42] The Norwegian Ministry of Defence's views on this are to be published in an up-coming paper

Option 2aii – International Reprocessing – HLW		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• Will require construction of pre-GDF storage, GDF, and re-packaging facilities.	
Final Evaluation Result		**Viable**

Option 2aiii – International Reprocessing – U, Pu and HLW		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• The Met. Lab-II and Bunker Building will require upgrading if they are to meet safety standards; dependant on the timeframe in which Orano are able to retrieve the SNF. • After reprocessing, the waste form and waste package returned to Norway, safety and robustness of the waste form would have improved. • Significant security and safety considerations for the storage and disposal of the fissile material. • Some secondary impacts out of country including generation of secondary wastes during reprocessing. • Requires international transport. • Minimises number of final waste forms for disposal, no re-packaging required.	Rejected
Full Inventory Full Lifecycle	• Not full inventory; some of the experimental SNF requires a mitigation. • Potential issue with contaminants from Al cladding, but this is the supplier's issue. • Accounts for the full lifecycle from a Norwegian perspective; all materials remain out of country.	Contingent
Engineering Considerations	• High TRL of PUREX reprocessing technology. • High TRL of universal containers. • Does not keep other options open, once SNF is reprocessed no further options are available. • Reprocessing technologies that produce a wasteform more resistant to misappropriation, e.g. COEX, may develop higher TRLs in future [25].	Contingent
National and International Considerations	• Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy. • Returns a product that is in a form resistant to proliferation. Fissile material will be under Norwegian ownership; Norwegian views on the use of the fissile material are currently unknown[43].	Contingent
Capacity and Competency	• No significant required domestic capacity; only for storage and disposal of HLW.	Viable
Ease of Implementation	• Some difficulty in upgrading of facilities anticipated. • Large difficulty in the security measures required for guarding of fissile material. • Long-term management and disposal of fissile material presents significant challenges. • Will require construction of pre-GDF storage, GDF, and re-packaging facilities.	Rejected
Final Evaluation Result		**Dormant**

Option 2b – Domestic Oxidation		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Not expected to move the SNF out of current storage; facilities will require upgrading • High risks associated with chemical oxidation technology • Generation of secondary wastes resulting from chemical treatment. • Does not improve the safety of the wasteform until reprocessing. • Impact of building new oxidation facility. • Domestic transport required. • Number of handling and treatment processes.	Rejected

[43] The Norwegian Ministry of Defence's views on this are to be published in an up-coming paper.

Option 2b – Domestic Oxidation		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• Minimises number of final wasteforms for disposal. • Facility must also be decommissioned in future; secondary waste creation.	
Full Inventory Full Lifecycle	• Full inventory and full lifecycle; will require a combination of oxidation, mechanical treatment and the reduction treatment for thorium. • Potential issues with Al cladding of SNF.	Contingent
Engineering Considerations	• TRL of the Studsvik oxidation process is medium at present; the process has been performed on smaller scales but needs to up-scaled [35]. • Process would have to be taken from Studsvik – otherwise would take very long time to develop a domestic process. • TRL of the reduction process for thorium is low; not yet evidenced on thorium fuel [19]. • Makes disposal of SNF more feasible if all in oxide form. • Keeps some future options open; forecloses direct disposal but keeps option for reprocessing available if so desired.	Contingent
National and International Considerations	• The SNF will remain is not in a form resistant to proliferation; however, if SNFs are blended then the wasteform will be in a less vulnerable form. • Coherent nuclear strategy. • Planned disposal of oxide fuel is a current SNF strategy for numerous countries.	Viable
Capacity and Competency	• Very high capability required of supply chain. Would have to rely on using international expertise to achieve such an operation. • Significant training of SQEP required. • Incredibly demanding domestically.	Rejected
Ease of Implementation	• Will require construction of new oxidation facilities, pre-GDF storage and GDF. • Significant knowledge transfer required. • Significant improvement in all domestic infrastructure and resources required. • Very difficult to implement.	Rejected
Final Evaluation Result		**Rejected**

Option 2bi – International Oxidation – No Waste		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Requires international transport. • Generation of secondary wastes from chemical treatment; some secondary wastes to be disposed of arising from mechanical treatment (e.g. graphite, cladding etc.). • No materials for disposal.	N/A
Full Inventory Full Lifecycle	• Full inventory and SNF lifecycle; from a Norwegian perspective.	N/A
Engineering Considerations	• TRL of the Studsvik oxidation process is medium at present; the process has been performed on smaller scales but needs to up-scaled [35]. • TRL of the reduction process for thorium is low; not yet evidenced on thorium fuel [19]. • Does not keep other options open, once SNF is sent to Sweden no further options are available.	N/A
National and International Considerations	• It is against Swedish law that the waste is not returned to Norway, or that waste is stored at Studsvik; this makes this option illegal and therefore is rejected on this point alone.	Rejected
Capacity and Competency	• No required domestic capacity.	N/A
Ease of Implementation	• No domestic infrastructure or knowledge transfer required.	N/A
Final Evaluation Result		**Rejected**

Option 2bii – International Oxidation		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• The Met. Lab-II and Bunker Building will require upgrading if they are to meet safety standards; dependant on the timeframe in which Orano are able to retrieve the SNF. • After oxidation/other treatments, the waste form and waste package returned to Norway (assumed to be in oxide form), safety and robustness of the waste form would have improved significantly. • Requires international transport. • Minimises number of final waste forms for disposal, no re-packaging required. • Generation of secondary wastes from chemical treatment; some secondary wastes to be disposed of arising from mechanical treatment (e.g. graphite, cladding etc.).	Viable
Full Inventory Full Lifecycle	• Full inventory; if the chemical treatment for thorium is feasible. • Full lifecycle if the treated SNFs are disposed of in Norway in a GDF.	Viable
Engineering Considerations	• TRL of the Studsvik oxidation process is medium at present; the process has been performed on smaller scales but needs to up-scaled [35]. • TRL of the reduction process for thorium is low; not yet evidenced on thorium fuel [19]. • Does keep other options open, forecloses direct disposal but keeps other options such as reprocessing available if desired.	Contingent
National and International Considerations	• The SNF will remain is not in a form resistant to proliferation; however, if SNFs are blended then the wasteform will be in a less vulnerable form. • Coherent nuclear strategy. • Planned disposal of oxide fuel is a current SNF strategy for numerous countries.	Viable
Capacity and Competency	• International supplier has extensive experience transporting and handling similar SNFs [19]. • No domestic SQEP required.	Viable
Ease of Implementation	• Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Viable**

Option 2c – Domestic In-Can Vitrification		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Not expected to move the SNF out of current storage before facilities will require upgrading. • Safety risks associated with ICV technology • Does not improve the safety of the wasteform until vitrification. • Only vitrifies the SNF, does not improve the chemical safety of the SNF. Study required into the safety of the use of this technology on SNF. Still may carry criticality concerns. • Impact of building new vitrification facility. • Domestic transport required. • Number of handling and treatment processes. • Minimises number of final wasteforms for disposal. • Facility must also be decommissioned in future; secondary waste creation.	Dormant
Full Inventory Full Lifecycle	• Full inventory and full lifecycle; if compatible with all SNF and waste is geologically disposed in a Norwegian GDF. • Potential issues with Al cladding of SNF.	Contingent
Engineering Considerations	• TRL of ICV is low for use on SNF. • TRL of ICV in Norway is zero. • No OPEX on the disposal of vitrified SNF. • Does not keep other options open, once SNF is vitrified no further options are available. • Facilities constructed are likely to only have a use for the management of the Norwegian SNF inventory. It's possible that the facilities could be used for other SNF from other countries if desired in future.	Rejected

Option 2c – Domestic In-Can Vitrification		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
National and International Considerations	• Results in a product that is in a form that is resistant to proliferation. Will have ownership over fissile material. • Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy.	Contingent
Capacity and Competency	• Very high capability required of supply chain. Would have to rely on using international expertise to achieve such an operation. • Significant training of SQEP required. • Incredibly demanding domestically.	Rejected
Ease of Implementation	• Will require construction of new reprocessing facilities, pre-GDF storage and GDF. • Significant knowledge transfer required. • Significant improvement in all domestic infrastructure and resources required. • Very difficult to implement.	Rejected
Final Evaluation Result		**Dormant**

Option 2ci – International In-Can Vitrification – No Waste		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Not expected to move the SNF out of current storage before facilities will require upgrading. • Safety risks associated with ICV technology • Does not improve the safety of the wasteform until vitrification. • International transport required. • Number of handling and treatment processes. • No material for disposal.	N/A
Full Inventory Full Lifecycle	• Full inventory and full lifecycle; if compatible with all SNF and waste is geologically disposed in a Norwegian GDF. • Potential issues with Al cladding of SNF.	N/A
Engineering Considerations	• TRL of ICV is low for use on SNF. • No OPEX on the disposal of vitrified SNF. • Does not keep other options open, once SNF is vitrified no further options are available.	N/A
National and International Considerations	• It is against many countries' international law that the waste is not returned to Norway, or that waste is stored at the treatment facility; this makes this option illegal and therefore is rejected on this point alone.	Rejected
Capacity and Competency	• No required domestic capacity.	N/A
Ease of Implementation	• No domestic infrastructure or knowledge transfer required.	N/A
Final Evaluation Result		**Dormant**

Option 2cii – International In-Can Vitrification		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
Safety & Environment	• Not expected to move the SNF out of current storage before facilities will require upgrading. • Safety risks associated with ICV technology • Does not improve the safety of the wasteform until vitrification. • Only vitrifies the SNF, does not improve the chemical safety of the SNF. Study required into the safety of the use of this technology on SNF. Still may carry criticality concerns. • International transport required. • Number of handling and treatment processes.	Dormant

Option 2cii – International In-Can Vitrification		
Evaluation Criteria	**Description of Evaluation**	**Evaluation Result**
	• Minimises number of final wasteforms for disposal.	
Full Inventory Full Lifecycle	• Full inventory and full lifecycle; if compatible with all SNF and waste is geologically disposed in a Norwegian GDF. • Potential issues with Al cladding of SNF.	Dormant
Engineering Considerations	• TRL of ICV is low for use on SNF. • No OPEX on the disposal of vitrified SNF. • Does not keep other options open, once SNF is vitrified no further options are available.	Rejected
National and International Considerations	• Results in a product that is in a form that is resistant to proliferation. Will have ownership over fissile material. • Reprocessing is an internationally recognised method of SNF management. • Norway have recently agreed to reprocess some of their un-used SNF in the UK [41]. Would align well to that part of their SNF strategy.	Dormant
Capacity and Competency	• No international supplier with experience using technology on SNF. • No domestic SQEP required.	Dormant
Ease of Implementation	• Will require construction of pre-GDF storage, GDF.	Viable
Final Evaluation Result		**Dormant**

D.2. Secondary Evaluation Criteria

It was acknowledged that there are many secondary aspects that are present in the fundamental criteria. Whilst these are not considered at this stage in the evaluation, such aspects were identified in this section and may be used for future assessment of options in the next stage of assessment, KS2. These criteria require further development of the options and can be viewed as 'optimising' criteria, as opposed to fundamental; they are details that may make options more preferable to others, but not of such importance that one might totally reject an option based upon it. These optimisation criteria would be used to assess details of the different options and would be more useful in order to provide a more quantitative scoring (i.e. sensitivity analysis) that could be used to identify fewer preferable options (when sufficient information is available). These criteria are commonly associated with Best Available Technique (BAT) assessments, an assessment framework employed in the UK nuclear industry.

- Security
- Minimise opportunity for misappropriation of fissile material
- Transport
- Environmental Considerations
- Cost
- Resources
- Public Acceptance
- Retain total amount of original activity
    - The original atoms are returned after any treatment