KVU - Handling of Norwegian Spent Fuel and other Radioactive Waste

Task 4: Safety and Security and Emergency Preparedness: Localisation Aspects

Richard Metcalfe

Alan Paulley

James Penfold

QRS-1669A-1

Version 1.0

November 2014

Quintessa

Document History

Title:	KVU - Handling of Norwegian Spent Fuel and other Radioactive Waste
Subtitle:	Task 4: Safety and Security and Emergency Preparedness: Localisation Aspects
Client:	Ministry of Trade, Industry and Fisheries
Document Number:	QRS-1669A-1

Version Number:	Version 0.8 (Draft)	**Date:**	October 2014
Notes:	Modified from Draft Version 0.7 to address comments received from other project partners on 25th September 2014 and 3rd October 2014		
Prepared by:	Richard Metcalfe, Alan Paulley, James Penfold		
Reviewed by:	Alan Paulley, James Penfold[1]		

Version Number:	Version 1.0	**Date:**	November 2014
Notes:	Modified from Draft Version 0.8 to address comments by the internal reviewer		
Prepared by:	Richard Metcalfe, Alan Paulley, James Penfold		
Reviewed by:	George Towler		

Approved by: Richard Metcalfe

[1] Alan Paulley and James Penfold reviewed Richard Metcalfe's and each other's contributions

Quintessa Limited
The Hub, 14 Station Road
Henley-on-Thames
Oxfordshire RG9 1AY
United Kingdom

Tel: +44 (0) 1491 636246
Fax: +44 (0) 1491 636247
info@quintessa.org
www.quintessa.org

Contents

1 Introduction and Method

1.1 Purpose

The aim of Task 4 was to determine options for intermediate store localisation, such that safety, security and emergency preparedness are ensured. The task was closely related to Task 5 (Paulley et al., 2014), which concerned protection of the environment, natural resources and society.

More specifically, the objectives of Task 4 were to:

1. identify the general attributes required of a location for different possible designs of store for spent fuel (SF) and long-lived intermediate level waste and long-lived low level waste (LL-ILW and LL-LLW respectively), including environmental attributes, infrastructure attributes and human resource attributes;
2. identify kinds of localities that have these attributes;
3. summarise how these attributes vary between the different kinds of location;
4. determine options at each kind of location for achieving:
    a. safety;
    b. security;
    c. emergency preparedness; and
5. rank these options to the extent possible.

Hence, the implications for these options of adding low-level waste (LLW) and short-lived ILW (SL-ILW) to the inventory are determined, given that provided its size is sufficient, a site with general attributes that are suitable for an LL-ILW store or SF store will be suitable for a store for the increased inventory as well. Consideration was also given to the storage of High Level Waste (HLW) that might be returned to Norway following reprocessing of SF abroad, should this management option be taken.

Finally, an overview of the implications for eventual disposal of the waste for the store options was determined. This final part of the task required:

1. identification of different general attributes required of locations for the development of a repository for the eventual disposal of the different kinds of waste, including environmental attributes, infrastructure attributes and human resource attributes;
2. determining whether any of the kinds of sites that could be options for store construction could also be options for repository construction;
3. determination of other general options for repository development; and

4. identification of the implications for store options of the different options for different kinds of repository.

Based on the above analysis, Task 4 aimed to rank the kinds of storage locations, leading to recommendations for store options to be considered.

1.2 Methodology

The approach was to work from general principles to specific options through a step-wise process consisting of five broad steps:

- In the first step general attributes required of any site for a store were identified by reviewing guidance and regulatory documents produced by international and Norwegian agencies. The reviewed materials included documents produced in Norway during past activities to define a management solution for Norwegian SF and LL-ILW. This step also took into account the characteristics of the SF and LL-ILW described by Task 1 (Huutoniemi, 2014), and the SF treatment options identified in Task 2 (Nordlinder, 2014). The attributes included those that are needed to meet requirements for emergency planning and security planning, again based firstly upon a review of international requirements and experience in other countries, and secondly upon the requirements of regulations and the needs of relevant stakeholders within Norway.
- The second step identified areas within Norway where there are sites that have these attributes and assessed whether it is feasible to identify specific sites based on present knowledge. The work began with a high-level review of the geology of Norway to identify the general geological attributes of different regions of the country. Meetings were held with geologists at the Norwegian Geological Survey (NGU) and representatives from the regulator (NRPA), security agencies (PSR, PST) and IFE. These meetings aimed to obtain information from Norwegian experts about relevant geological, safety, security and emergency preparedness issues in the Norwegian context. This led naturally to identification of broad areas where there will be sites that have the general attributes identified in the first step.
- The third step identified combinations of store designs (output from Task 3; Cronstrand and Anunti, 2014) and the kinds of localities with suitable characteristics identified in the second step. Two workshops were held involving project team members with varied expertise, having the aim of defining ranking criteria for the different combinations and applying them to the kinds of locality identified in the second step.

- The differences between the locality / store design combinations that would impact upon safety, security and emergency preparedness were identified as an input to the detailed analysis of options.
- The implications for achieving safety, security and emergency preparedness of each of the different locality / store design combinations were determined.

The major consequences of adding LLW and SL-ILW to the inventory were identified by assessing how the following aspects would change from those identified in the previous steps:

- the required attributes of a site;
- kinds of site that meet these attributes;
- locality / store design combinations;
- options for achieving safety, security and emergency preparedness.

Similarly, the major consequences of different final disposal options for the store localisation / design options and corresponding options for achieving safety, security and emergency preparedness were identified. The approach involved firstly determining how stores and repositories differ from one another, including key points from relevant literature published by various international and national agencies. Various specific disposal concepts that potentially could be suitable for the Norwegian wastes were identified. Finally potentially viable combinations of these disposal concepts and store options were identified.

1.3 Scope, Delimitations and Assumptions

This Task Report covers intermediate store localisation, such that safety, security and emergency preparedness are ensured. The task takes as input information about the waste inventory produced in Task 1 (Huutoniemi, 2014), information about SF treatment options produced in Task 2 (Nordlinder, 2014) and options for store designs produced in Task 3 (Cronstrand and Anunti, 2014). The task also complements Task 5 (Paulley et al., 2014), which provides more detailed consideration of the specific issues associated with protection of the environment, natural resources and society.

Broadly, the distinction between Task 4 and Task 5 is that Task 4 concerns the facility itself and operations that directly impact upon the facility, while Task 5 concerns the surroundings of the facility (and associated human and environmental receptors), and safety or security related events that could impact upon it. However, options for protecting the environment, natural resources and society will depend to some extent on key site characteristics. These characteristics are covered by the present Task Report and cross-referenced by the following report for Task 5 where appropriate. Transport of the wastes is covered by both Task 4 and Task 5 from different perspectives; Task 4 considers how transport-requirements are specifically affected by the locality, while Task 5 considers more widely the potential impacts of transport.

At the commencement of the project the scope called for consideration of options for an intermediate store for SF and LL-ILW. However, it was also recognised that if it is decided to reprocess SF, HLW would be produced. In this case storage facilities would be needed for the HLW.

Additionally, mid-way through the project, at the request of NHD, the scope was widened to include SL-ILW and LLW as well; that is all wastes that have been or will be generated in Norway, except for those generated by the hydrocarbons and mining industries (e.g. Naturally Occurring Radioactive Material, NORM), for which management plans are being implemented separately. This change to the scope recognised the fact that management options for different wastes need to be optimised.

Initially the project was tasked only with identifying options for an intermediate store. Such a facility is one that provides for the containment of the waste, with the intention of retrieval (IAEA, 2003a). That is, storage by definition is an interim measure. In contrast disposal refers to the emplacement of waste in an appropriate facility without the intention of retrieval. However, storage options do impact upon the eventual disposal options that might be considered and vice versa. Hence, to determine the most appropriate option for an intermediate waste store in the context of an overall waste management programme, some consideration of disposal options and requirements is necessary. Consequently, part of the way through the project, NHD requested that the scope be widened to include consideration of waste disposal options in addition to interim waste store options. It should be noted however, that the widened scope did not cover detailed evaluation of all possible disposal options, but rather considered disposal at a high level, reflecting a primary aim of evaluating implications of disposal for characterising storage options. For example, the flexibility of some storage options to be converted to disposal might be considered a benefit potentially reducing overall management costs, or waste treatment to produce a waste-form might helpfully ensure a passively stable product over disposal timescales as well as storage timescales.

It was within the remit of Task 4 to establish which regions of Norway are likely to contain sites that potentially could have suitable characteristics to site a store. It was also within the remit to evaluate whether such potentially viable localities are more likely to be situated in some regions as opposed to others. In the latter case, it was aimed to identify the factors that might cause one area to be favoured (or indeed considered less advantageous) over another one. It was also within the scope to review the 6 sites recommended for further consideration by the Phase 2 Committee (also known as the "Stranden Committee" (Stranden Committee, 2011; see Section 2.1)). However, it is not appropriate to recommend actual areas or sites as there are too many plausible individual site location options for which relevant data are not yet available as they have not been investigated for the purpose. It is also important to recognise wider non-technical issues that need to be taken into account in site selection (see Section 4).

It is not within the scope of this Task Report to estimate costs for the facilities, but rather to provide input to the cost analysis.

2 Background

2.1 Present situation in Norway

The nature and quantities of the wastes that exist in Norway and that will be generated in the future are described in the Task 1 report.

Management strategies for Norwegian radioactive wastes have been in development for many years and a process to find a long-term management solution for Norwegian LLW and ILW was commenced in 1989 (NRPA, 2003). A governmental committee initially considered disposal options and potential sites for a disposal facility for these wastes. It was recommended that the facility should be constructed underground for reasons of perceived security benefits. The process led to an impact assessment being carried out for three sites in 1992. Based on these assessments the site of Himdalen, located about 26 km to the southeast of the reactor site at Kjeller was recommended (Sorlie, 2001). In 1994 the Norwegian government decided that this site should be developed, but as a combined disposal and storage facility, with Pu-bearing ILW being stored while the facility is operated. The decision led to the Combined Disposal and Storage Facility (KLDRA) for LLW and ILW coming into operation in 1999.

There is little detailed information available concerning the site selection process for the KLDRA. However, it appears that initially the whole of Norway was considered, at least generally. Site screening seems to have been undertaken on the basis of geology, hydrogeology, topography, ease of transportation, and population distribution:

- **Geology**: The rocks had to be stable, homogenous and well away from any significant faulting or fracture zones (though the criteria for considering a rock to be homogeneous and faulting or fracturing to be insignificant are unclear).
- **Hydrogeology:** Underground facilities were required to be self-draining, meaning in practice that the groundwater table is sufficiently deep, and inflows are sufficiently low. There also needed to be no surface water bodies above the facility.
- **Topography:** The topography needed to allow the facility to be constructed at sufficient depth below the surface that the overburden affords sufficient protection, while at the same time allowing access to be via adequately short slightly inclined tunnels.
- **Ease of transportation:** Distances from the sources of the wastes (the reactor sites at Kjeller and Halden) needed to be sufficiently short and the site needed to lie close to an existing road.

- **Population distribution:** The site needed to be sufficiently remote from urban areas and permanent housing.

The KLDRA consists of four rock caverns, each one containing two concrete sarcophagi. The parts of the facility for disposal and storage have similar designs, with stored Pu-bearing wastes being emplaced in one of the sarcophagi in disposal-ready form. Prior to eventual closure of the KDLRA, a decision will be taken either to remove these wastes for disposal elsewhere, or else encase them in concrete where they are presently located.

Prior to the construction of the KDLRA, about 1000, 210 l drums of LLW and ILW were located in a 4-metre deep, clay-covered trench at the Kjeller reactor site. Emplacement of these wastes in the trench took place in 1970 and had been intended as a final disposal solution. However, in 2002 the trench was re-opened, and the emplaced wastes were retrieved, reconditioned and re-located to the KDLRA.

All the previously treated LLW and ILW that had been conditioned and stored at IFE's facilities is now stored or disposed of in the KLDRA at Himdalen. According to the present policy of the Norwegian government all Norwegian LLW and ILW apart from NORM, high activity disused sealed sources and larger amounts of long-lived waste, will be emplaced within the KLDRA. The KVU Task 1 report (Huutoniemi, 2014) identifies that the facility is estimated to have sufficient capacity to take all the long-lived LLW and ILW wastes arising until 2015 (excluding those wastes noted above), including the long-lived waste from future decommissioning of IFE facilities.

The Bergan Committee was established by the Norwegian Government in 1999 to consider long-term management options for Norwegian SF (Bergan et al., 2000). Sending the fuel abroad for reprocessing was rejected because to do so would be against the policy of the Norwegian government. Also considered was a "zero option" to maintain the present situation. However, it was recognised that this option is only viable while the research reactors at Kjeller and Halden remain in operation. It was also considered that maintaining the existing stores within populated areas is undesirable. The committee therefore recommended that there should be intermediate storage of the SF at a new Norwegian facility for 50 – 100 years, followed by disposal.

The Bergan Committee also considered options for the eventual disposal of the SF. The outcome was a recommendation to delay a decision on a final disposal concept until the disposal concepts being developed in other countries become more advanced.

The recommendation that a new intermediate store for SF should be developed in Norway having been made by the Bergan Committee, in 2004 the Phase 1 (Forhaug) Committee was established by NHD to consider options for such a store more specifically (IFE, 2013). The committee was tasked with defining the requirements for a store, investigating technical solutions, identifying critical decision points and proposing a mandate for a Phase 2 Committee (IFE, 2013). The Phase 1 Committee recommended further investigation of dry storage in a concrete structure or transportable storage containers. It also recommended that the final technical solution and location of the storage facility should be chosen by the Phase 2 Committee.

Following the recommendation of the Phase 1 Committee, in 2009 the Phase 2 Committee (also known as the "Stranden Committee") was appointed by the Norwegian government (Stranden Committee, 2011). The committee had a broad membership of experts from varied disciplines and was tasked with finding the most suitable technical solution and site for intermediate storage for SF and LL-ILW and for proposing a schedule for implementation of the solution.

The Stranden Committee was advised by a separate Technical Committee that was appointed by NHD and consisted of representatives from IFE, the IAEA and Studsvik who considered options for the treatment of unstable SF (Technical Committee, 2010). Three main options were considered:

- The first option is to dispose of fuel assemblies in the physical and chemical form in which they were removed in the reactor, which is termed "direct disposal".
- A second option is to store the waste and postpone decisions regarding treatment, further storage and disposal.
- The third option is reprocessing to separate different SF components that can be managed separately, for example by producing new fuel from some components and converting the remainder (HLW) into a separate waste form for disposal or storage.

The first option is contrary to the recommendation of the Phase 1 Committee and was not considered further by the Stranden Committee. The Technical Committee highlighted that the fuel has to be stabilized before final disposal, which does have implications for storage too, since the timing and nature of stabilization will determine the form in which the waste is to be stored.

The Stranden Committee considered three general storage options:

1. storing the waste at Kjeller and/or Halden;
2. storing the waste at a new facility near to Kjeller or Halden;
3. constructing a new facility elsewhere in Norway.

The committee concluded that safe storage could be provided by facilities above ground or below ground. However, each kind of facility would have different advantages and disadvantages.

In addition to Kjeller and Halden, 10 other localities were assessed for their suitability to site a store, with support being provided by the Geological Survey of Norway

(NGU). The 10 localities all lie in the south of Norway which is known to be tectonically stable and in which there are large igneous bodies, which were thought likely to be suitable bedrock for a facility. The detailed reasoning for the identification of these sites is unclear from the published information, but it appears that transportation (including the distribution of roads) and proximity of potential sites to the present locations of the waste were taken into account by the committee, in addition to the geology.

The Stranden Committee asked NGU to compile existing geoscientific information for the 10 sites, which is presented in NGU (2010a, 2010b). This information consisted of:

- geological map information;
- information from databases of water wells, including water level data (although in many cases this data was considered unreliable);
- In the Oslo area, outputs from the GEOS (“Geology Oslo”) project, which had been undertaken between 2000 and 2003; and
- airborne geophysical data, to provide information about baseline radioactivity from which it was possible to deduce the likely radon hazard.

In addition, although not considered by NGU, the quality / nature of roads and other infrastructure were considered by the Stranden Committee when making recommendations.

Based on this information, the Stranden Committee identified the following 6 sites:

- Mysen Nord (Locality 1), between Kjeller and Halden;
- Tomter Vest (Location 2), between Kjeller and Halden;
- Vardeåsen (Locality 7), near Kjeller;
- Grimsrød (Locality 8), near Halden;
- Bjørneholen (Locality 9), near Kjeller; and
- Klaretjernhøgda (Locality 10), near Halden.

These locations are illustrated in Figure 2-1.

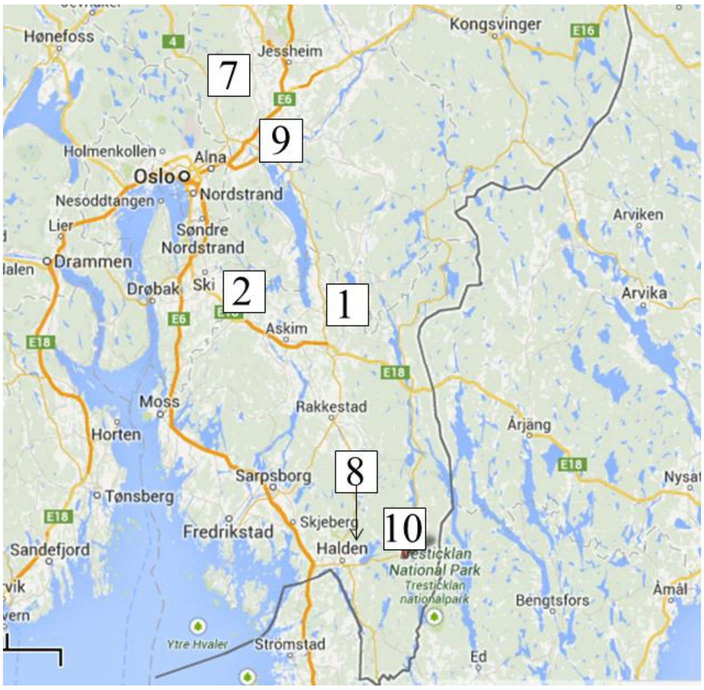

Figure 2-1: Locations proposed in the Stranden Report (Stranden Committee, 2011). 1- Mysen Nord, 2-Tomter Vest, 7-Vardeåsen, 8-Grimsrød, 9-Bjørneholen 10-Klaretjernhøgda.

It should be noted that here these localities retain the numbers that they were assigned in the original longer list of sites that were presented in NGU (2010a). Four of the sites in the original list were screened from further consideration by the Stranden Committee:

- Lokalitet 3 – Bøleråsen
- Lokalitet 4 – Høgmåshøgda
- Lokalitet 5 – Vindsknatten
- Lokalitet 6 – Breidmåsan

It is noteworthy that no rock permeability / hydraulic conductivity data were available and that no hydrogeological modelling was undertaken in the evaluation of the sites. Similarly, geotechnical information was not used when recommending the 6 sites. No geochemical data were available either, although U concentrations in the rocks were estimated from the available airborne radiometric data.

NGU was asked to undertake field investigations at the 6 sites shown in Figure 2-1, to verify the geological information available. At two of the sites the geology was not as expected; in particular it was shown to be gneiss rather than gabbro.

Following this "ground truthing" the localities were ranked based on the following criteria: geology, topology, accessibility, potential for alternative use, and possible conflicts of interests. Based on this ranking the top 3 sites were considered to be: Gimsrød (Location 8), Vardeåsen (Location 7) and Tomter Vest (Location 2).

2.2 International experience and recommendations

There is a very large amount of international experience in the siting, development and operation of stores for different kinds of radioactive wastes (IAEA, 2006c; 2011a). Internationally waste stores are very variable, in terms of the wastes stored, their sizes, their designs and their design lives. There are more kinds of LLW and ILW than SF or HLW. Furthermore, different countries have different proportions and kinds of wastes, reflecting the different scales and natures of the nuclear programmes that exist in different nations.

Depending upon the nature of the wastes, purposes of stores can be to (IAEA, 2006c):

- allow short-lived radionuclides to decay sufficiently that the radioactive waste can be cleared from regulatory control, authorised for discharge, disposed to a facility that accepts lower radioactivity wastes than the initial pre-decay storage wastes, or recycled/reused;
- accumulate a quantity of waste that is sufficient to allow its efficient transfer to another facility for treatment and conditioning;
- accumulate a quantity of radioactive waste that is sufficient to allow its efficient disposal;
- allow the rate of heat generation by SF and/or any HLW produced by its reprocessing, to decrease before its disposal and under some circumstance before predisposal management steps; and
- maintain the radioactive wastes in a safe state until a final disposal facility has been constructed.

The international guidance distinguishes between long-term storage and short-term storage (IAEA, 2006c). Broadly the former refers to cases where storage is intended to hold the waste until a final disposal solution becomes available, and may be sub-divided into cases where:

- the period of waste storage is longer than the initial design life of the containers and storage facilities, as might occur where disposal is postponed; or alternatively
- cases where waste packages and storage facilities are designed for relatively long periods of storage (e.g. 100 years) in recognition of the fact that these long time periods will be needed to find a final disposal solution.

In contrast, short-term storage holds wastes only for long enough to allow them to be passed to the next waste treatment process. For example a storage period of only a few days, weeks or months may be needed for decay to occur sufficiently that the waste can be transferred to another facility for treatment.

It is generally accepted that the period of time for which wastes, particularly lower-active wastes, are stored should be minimised unless there are benefits from a period of storage (e.g. in relation to radioactive decay). Where it is necessary to store wastes, for example because there is insufficient capacity for its immediate disposal, the requirements for storage of LLW and ILW are mainly concerned with:

- ensuring inventory control and traceability;
- ensuring the integrity of waste packages;
- minimizing the need for active management of waste (e.g. with a passively safe wasteform);
- operational radiological protection for workers and minimization of discharges; and
- facilitating inspection and retrieval of waste packages.

The key requirements for SF storage are similar to those for other radioactive wastes, but there are greater demands for security, shielding, environmental control, etc.:

- Inventory control and the ability to comply with nuclear material accountancy/safeguards protocols, means that the stored fuel has to be readily accessible to be verified.
- The maintenance of environmental conditions that preserve fuel cladding (effectively, the primary "container") is a central objective. Due to heat and radiation output, storage is initially necessary in water, so corrosion control is a key consideration.
- For "wet storage" of fuel, the main design consideration is the fuel pond, which needs to have a high degree of structural integrity together with facilities for controlling water conditions.
- Subsequent dry storage requires suitably designed casks to provide adequate shielding, and facilities for inspecting and retrieving wastes from the casks (unless they are designed to be used to transport wastes to the final disposal facility). Cooling and ventilation is also an important consideration.
- Remote handling is a prerequisite for all aspects of SF management.
- There is considerable international experience with the design, construction and operation of radioactive waste stores for SF (as there is for other waste materials also).

If the SF is reprocessed, concentrated liquid solutions of nuclear fission products will be produced and must be immobilized in a solid phase. This solidification is usually achieved vitrification to produce a glass matrix (e.g. Ojovan and Batyukhnova, 2007), although there are alternative means of solidification, such as the so-called SYNROC process (Ringwood et al., 1979). The solidified HLW will be in a shielded container. The handling and storage of these containers will be similar to the handling and storage of SF containers.

Generally, the requirements for waste package integrity and radiological protection for stores are most influenced by the waste category (the activity concentration) and the key aspect is typically related to gamma radiation rather than the quantity of alpha radioactivity, because gamma radiation is more penetrating. More robust containers are required for higher activity wastes, and more substantial shielding. Higher (gamma) activity wastes are also more likely to require remote movement and inspection.

In principle, all the requirements for stores, whatever the kind of wastes, can be achieved through engineering and management measures, so there is no strong dependence on site characteristics or location (except insofar as it may be less costly and easier to implement where there is established nuclear infrastructure).

Guidance on siting of waste stores is provided by IAEA (2006c), which states that:

- "A storage facility for radioactive waste may be established in connection with, or as part of, an existing nuclear installation. In this case, the site may be selected on the basis of factors that are important for the main facility and the waste storage facility may not require any additional considerations. The safety assessment performed for the siting of the main facility may demonstrate that the waste storage facility meets the radiological protection criteria in normal operation and in incident and accident conditions. If the siting requirements for the waste storage facility are more stringent than those for the main facility, then the safety case for storage should be addressed separately." and
- "In cases where the waste storage facility is built separately from other licensed nuclear installations, the Safety Requirements publication on Site Evaluation for Nuclear Installations (IAEA, 2003b) and the associated safety standards on the management system (IAEA, 2006a) and (IAEA, 2006b) establish requirements and provide guidance that can be applied to waste storage facilities. The application of the requirements in respect of siting will, for waste storage facilities, depend on the potential radiological hazards posed by the waste stored."

However, the guidance (IAEA, 2006c; 2011a) says little about the characteristics that must be possessed by a site in order for it to be suitable for a storage facility, other than that the site must be such that a store can be constructed and operated to meet the requirements for safety, security and protection of the environment. The store may be sited at the installation where the waste is generated, for example a nuclear power plant, hospital or a laboratory. Alternatively, the store may be at a different locality, such as a national facility for treating and storing the waste. All nuclear reactors for electric power generation have storage facilities for SF, albeit some of this storage is short-term, for example to allow initial cooling of SF in ponds prior to its transfer to longer-term storage or reprocessing facilities. Whether long-term storage occurs at the facility generating the waste or a centralized facility depends upon a wide variety of factors, including stakeholder views and national governmental policy, and varies considerably from country to country. Furthermore, in any one country the approach to storage may vary over time. For example, in 2010, about 70% of all U.S. sites with operating nuclear reactors had associated dry storage facilities, partly reflecting the fact that the U.S. does not reprocess SF. In contrast, in the UK SF generated by the country's 7 Advanced Gas-cooled Reactor (AGR) power stations is presently stored for a short period in wet storage facilities (cooling ponds) before it is transferred to the Sellafield reprocessing facility for reprocessing and further storage. However, in the UK the present government policy is that nuclear power plant operators cannot assume that reprocessing will be possible in future. Consequently, dry stores are presently under development at a number of reactor sites.

The safety needs are derived from the international Basic Safety Standards (BSS) of the IAEA, (IAEA, 1996; 2006c) as implemented nationally. This sets out a system of radiological protection which defines limits on exposure, and requires optimization to be applied in all situations involving radioactive material. There also needs to be an adequate management regime that can apply these principles. These needs themselves require the application of a system of radioactive waste management such as described by IAEA (2009).

The fundamental needs for a nuclear security regime are founded on the principles of radiological protection, but are designed to deal with situations in which adversaries could result in the loss of control of radioactive material. The needs are therefore quite specific, and are described by IAEA (2013) (see also Task 5).

Emergency preparedness also encompasses situations in which control over radioactive material has been lost, albeit because of an incident rather than an adversary. The primary need is to ensure that all practical efforts are made to prevent and mitigate nuclear or radiation accidents (IAEA, 2002) (and Task 5).

Internationally, most LLW is disposed of in surface or shallow sub-surface facilities following only very short periods of storage; there are many operating disposal facilities for these kinds of LLW. Some kinds of SL-ILW are disposed of in similar kinds of facility. In contrast, there is only one final disposal facility for LL-ILW, the Waste

Isolation Pilot Plant (WIPP) in New Mexico, U.S.A[2]. Final disposal facilities for certain kinds of LL-LLW, LL-ILW, HLW and SF have yet to be constructed, although projects to site and develop such facilities are in various stages of advancement in many countries. However, it is widely recognised that stores should be designed and operated bearing in mind the requirements for eventual disposal. Furthermore, there is a large body of experience of siting and characterising potential sites for deep geological repositories.

Guidance for siting repositories is broadly similar to guidance for siting stores, but there is specific guidance for surface facilities (IAEA, 2003), and deep facilities (IAEA, 1990, 2011b, 2011c).

Whereas it would be technically possible to construct a store almost anywhere (given sufficient resources), not all localities would be suitable to site a repository. This difference means that selecting options for repository locations is much more challenging than selecting options for store locations. Repository siting would require a prolonged process, involving information gathering and stakeholder engagement. General stages in the siting of underground repositories are:

1. a conceptual and planning stage;
2. an area survey stage, leading to the selection of one or more sites for more detailed consideration;
3. a site investigation stage of detailed site specific studies and site characterisation; and
4. a site confirmation stage.

Underground repository concepts are being developed in most countries with nuclear power programmes. Many alternative concepts have been developed (Baldwin et al., 2008; Hicks et al., 2008; Metcalfe and Watson, 2009; Bond et al., 2010; IAEA, 2011c), but generally proposed repositories consist of mined underground cavities (typically tunnels and / or caverns) that are accessed from the ground surface by ramps or shafts. Depending upon the kind of waste and packaging, waste containers would be emplaced directly within the cavities or tunnels, or within horizontal or vertical holes excavated from the cavities or tunnels.

A possible disposal alternative solution that is being considered in several countries is disposal in deep boreholes (Nirex, 2004; Brady et al., 2009; Arnold et al., 2013). This concept envisages drilling deep (c. 5000 m) boreholes. Waste canisters are then placed in the lower portion, while the upper portion is sealed, most likely with a combination of bentonite and concrete. Such a borehole could potentially accommodate up to several hundred waste canisters. The safety case for such a concept would place great

[2] The wastes that are emplaced in the WIPP are classified in the U.S.A as "TRU-Waste", which equates broadly to LL-ILW according to classifications used in Europe.

emphasis on the great depth of burial, which ensures that the wastes remain isolated from the accessible environment. Given the relatively small quantities, a single borehole in Norway could be sufficient to accommodate all Norwegian SF (or alternatively HLW that would be produced by SF reprocessing outside Norway, and then returned to the country).

3 Conclusions and Recommendations

The main conclusions and recommendations are as follows (summarised from Section 4).

The safety, security and emergency preparedness of an intermediate store for SF and LL-ILW can be ensured by the same kinds of measures as those employed at the existing nuclear facilities in Norway. The ease with which these measures can be employed and the associated costs will depend to a large degree on the distance of a facility from the sources of the waste and from population centres where relevant expertise exist. However, the remoteness of a locality from the waste sources and population centres would not itself preclude the feasibility of establishing a store at the locality and indeed from certain perspectives could be an advantage. The main effect of increasing remoteness would be increasing costs of transporting the waste to the facility and on providing necessary personnel with the required skills. There would inevitably be some increased risk associated with transporting the wastes to the facility, though the risks associated with conventional transport accidents will greatly outweigh radiological risks for properly packaged wastes and are nevertheless be small. This slightly increasing risk with increasing transport distance should be balanced against remoteness itself being seen as an advantage by certain stakeholders. The same general issues would be relevant to the storage of HLW, should this be generated by reprocessing.

An intermediate store for SF (or HLW) and LL-ILW of some kind could be constructed in almost any area of Norway, given sufficient resources. Again, the distance of a locality from population centres where there are relevant services (skilled personnel and equipment) would influence the cost of constructing a facility at the locality, but would not preclude doing so. Generally, the greater the distance of a locality from centres that can supply relevant services, the greater will be the construction costs.

Given that Norway's solid geology at depths that are relevant to a store is overwhelmingly fractured crystalline rock, almost certainly any sub-surface store will be constructed within or on such a rock; there are few areas where other lithologies occur and there would be no obvious advantage to selecting such an area.

The Norwegian construction industry has extensive experience of tunnelling through fractured crystalline rocks and of constructing underground facilities for varied purposes in such rocks; the Himdalen facility is an example. Additionally, in many countries fractured crystalline rocks have been investigated extensively in order to site stores or repositories for varied radioactive wastes, or to conduct research as a basis for such facilities. Consequently there is a significant body of experience and expertise, supported by fundamental research that can be drawn on when siting a store.

Before a store can be constructed, extensive site investigations will be needed. The characteristics of these investigations will depend upon whether the store is to be a surface facility or a sub-surface facility. The investigations will be needed to obtain information for two main purposes: 1. Construction; and 2. Environmental Impact Assessment. For the former, there is a need to determine ground stability, hydrogeological characteristics and surface hydrology. For the latter, there is a need to determine the characteristics and distribution of potentially impacted environmental receptors. The kinds of investigation for a store will be similar to those required for any surface structure or underground excavation.

In contrast a repository site will require much more extensive investigations. A store is a managed facility which relies on engineered barriers to ensure containment of the waste. These barriers will need to be effective for the relatively short period of storage (likely up to about 100 years). Thus the geosphere has no barrier function and it is not necessary to determine how the geosphere will evolve over time periods longer than the period that the store is under management. In contrast, confidence in the safety of a repository will need to be provided effectively indefinitely; quantitative safety assessments for SF and other long-lived wastes typically consider time periods of c. 1Ma. Note that this focus does not necessarily greatly enhance the cost of a facility especially where the total radiological hazard is not especially large, but it does require a different focus to design and investigations. Such time periods are longer than those for which the integrity of engineered barriers can be guaranteed and consequently the geosphere surrounding a repository will have a role as a natural barrier. Thus, site investigations for a repository will need to obtain information to demonstrate this long-term safety function. This information will include geological, geophysical, hydrogeological and geochemical information. For a repository it is also necessary to characterise a much larger volume of rock than for a store. This reflects the long timescales that need to be considered, which make it possible for gases, liquids and solutes (including radionuclides) that might be released from a repository, to be transported a relatively great distance. Site characterisation for a repository also needs to obtain information that allows the effects of long-term environmental changes to be evaluated.

The combination of option(s) for an intermediate waste store and eventual disposal that is / are chosen will impact upon the overall cost of waste management. If both the disposal site and the store are located at the same site, the overall costs for transportation of the waste will be lowered in comparison to the case where the disposal site and store are remote from one another.

It is recommended that the overall waste management strategy, including intermediate storage and final disposal, are optimised together to minimise the effort, costs and risks associated with waste management. From these perspectives it would be best to avoid transporting the wastes to an interim store and then later transporting them to a final repository at a different locality. Additionally, interim storage that avoids the need to repackage waste for final disposal would be desirable (note this requires up-front understanding of the packaging requirements for both the storage and disposal phases).

Increasing the inventory to include SL-ILW and LLW would increase the volumes to be stored / disposed. However, the volumes of waste are very small compared to those in countries with nuclear energy programmes and should not fundamentally alter storage locality options; a locality that would be suitable for a SF and LL-ILW store would almost certainly also be suitable for a store that includes SL-ILW and LLW as well. Furthermore, the kinds of store would be broadly similar. However, final disposal of SL-ILW and LLW could be achieved with a surface or near-surface facility (as well as deeper facilities). In contrast a deep geological facility would almost certainly be a requirement for LL-ILW and SF. Given its small volumes in Norway it might be possible use the deep borehole concept to dispose of the SF (and / or any HLW).

4 Task Analysis

4.1 Required Attributes of Locations

This section reviews the general attributes required of localities that are potentially suitable to host a store of some kind. It is stressed that the considered attributes were specified with the objectives of the KVU in mind, which in the case of Task 4 concern identification of options for localisation. The actual development of a store would require characterisation of a site at a level of detail that is much greater than covered here.

The attributes were identified based on a review of international guidance and experience in other countries. It should be noted that it is not possible to give precise quantitative criteria against which to judge these attributes, such as a minimum value required for uniaxial rock strength. This impossibility arises because different factors interact so that whether or not a particular site is suitable will need to be judged using information about all the site's characteristics together, in an integrated fashion. For example, the minimum required value for uniaxial rock strength at the site for an underground store will depend to a large extent upon the budget available to engineer the facility to ensure that adequate rock stability is ensured; thus geomechanical characteristics and economic factors (among other factors) need to be considered together. Section 4.3 evaluates in general terms where in Norway there are likely to be sites at which the required characteristics can be met. For some site attributes it is possible to describe requirements in general terms; for other attributes it is feasible only to describe favourable states.

Siting of stores and repositories must be carried out so that the requirements outlined in the Task 5 report (Paulley et al., 2014) are met. Guidance on siting of waste stores is provided by IAEA (2006c) which states that:

- "A storage facility for radioactive waste may be established in connection with, or as part of, an existing nuclear installation. In this case, the site may be selected on the basis of factors that are important for the main facility and the waste storage facility may not require any additional considerations. The safety assessment performed for the siting of the main facility may demonstrate that the waste storage facility meets the radiological protection criteria in normal operation and in incident and accident conditions. If the siting requirements for the waste storage facility are more stringent than those for the main facility, then the safety case for storage should be addressed separately."; and
- "In cases where the waste storage facility is built separately from other licensed nuclear installations, the Safety Requirements publication on Site Evaluation for

Nuclear Installations (IAEA, 2003b) and the associated safety standards on the management system (IAEA, 2006a, 2006b) establish requirements and provide guidance that can be applied to waste storage facilities. The application of the requirements in respect of siting will, for waste storage facilities, depend on the potential radiological hazards posed by the waste stored."

Additionally, requirements of a store were determined during the needs, goals and requirements analysis carried out during this KVU and reported in detail elsewhere. In summary these requirements are:

1. Requirements derived from societal needs are:
    a. Environmental protection requirements should be satisfied.
    b. Radiation to personnel should be within permitted limits (50mSv in any one year, or 20 mSv per year more generally).
2. Requirements derived from technical needs are:
    c. There should be sufficient capacity to receive and store all the radioactive waste which will be generated for the foreseeable future.
    d. There should be sufficient flexibility to receive waste that has yet to be identified.
    e. The facility should be upgradable to comply with future requirements to maintain Safety, Security, Health and Environmental Protection (SHE).
    f. The facility must be completed and commissioned in advance of decommissioning the radioactive waste storage facility at Kjeller.
    g. Best Available Technology (BAT) must be employed.
    h. There must be efficient waste handling where cost and risk are both taken into account.

Thus, the guidance and requirements are not prescriptive as far as the physical and chemical characteristics of the site are concerned.

A workshop was held on 4th and 5th February 2014 with participants from DNV-GL, Quintessa, Westinghouse and Studsvik to:

- discuss the attributes of different localities in Norway;
- establish the extent to which these attributes match those required for a store; and
- devise and apply a ranking scheme to the different areas.

This workshop identified technical and non-technical general characteristics that should be considered when determining whether a site can host a safe and secure store at which adequate emergency preparedness can be ensured. The philosophy adopted when identifying these characteristics was to minimise their number, while at the same time covering all major factors that could potentially impact significantly upon safety, security and emergency preparedness. It was also aimed to specify characteristics that could be judged based on existing information. This approach was taken to avoid unnecessary complexity and hence difficulty in evaluating the characteristics at different sites, commensurate with the requirements of the KVU.

Owing to following this approach, certain important site characteristics that would need to be determined by site characterisation prior to developing a store are excluded from consideration. For example, it will be necessary to determine the level of the water table and groundwater flow directions and fluxes before developing an underground store. However, the required hydrogeological information is lacking for most of Norway and therefore “Hydrogeological information” is not included among the identified characteristics. Instead the importance of hydrogeology is recognised implicitly in the specification of “Lithology”, which includes rock permeability (see below).

The identified characteristics are as follows:

- **Lithology (nature of the rock)**: This characteristic refers to the macroscopic nature of a rock, which reflects the identities and proportions of the solid phases that it contains. If these solids are granular then the lithology reflects the grain sizes / grain size distributions, grain shapes and spatial relationships between grains (textures). The rock should have mechanical strength (geotechnical properties) sufficient to support foundations for a surface store, or the excavation of underground tunnels / caverns in the case of an underground store. Furthermore, in the case of underground facilities the permeability of the rock should be sufficiently low that it is practicable to engineer groundwater inflows that are sufficiently small not to compromise the integrity of the waste containers or the buildings that contain them, or the functioning of equipment needed to handle the wastes. Such inflows also need to be sufficiently small that the water can be managed in a safe and environmentally sound way (e.g. without causing groundwater quality standards to be exceeded). It is quite possible that water inflows will naturally contain chemical components derived from water / rock reactions that would exceed these standards without suitable treatment. However, there is insufficient information with which to judge these groundwater compositions in a consistent fashion. The overall heterogeneity of the rock is also a factor to consider in that, generally, the more heterogeneous the more complex will be site characterisation and construction, which is likely to imply increased cost. Lithological heterogeneity will be a more important issue for underground stores than for surface stores.
- **Structural characteristics of the rock (fracturing and faulting):** Fractures are macroscopic discontinuities in the rock formed by brittle deformation. Faults are fractures within the rock across which the rock on one side has been

displaced relative to the rock on the other side, parallel to the fracture. Faults and fractures occur at a wide range of spatial scales, from the sub-mm scale to the scale of many 10's of km; discontinuities at the smaller scales tend to be classified as fractures, whereas those at larger scales are invariably faults. In the context of selecting a site for an intermediate waste store, fractures and faults are important because they may affect the mechanical and hydrogeological properties of the rock. Often, a rock that is cut by many frequent faults and fractures will have lower mechanical strength than one that is cut by less frequent faults and fractures. However, if faults and fractures have been mineralized (new minerals have been formed along them), they are not necessarily mechanically weaker than the rocks in which they occur. Fractures and faults that will be of most concern in selecting a site for an intermediate store will be those that are more permeable than the rocks that they deform. However, mineralization of the fractures or faults, or the occurrence of gouge along fault planes, may render fractures or faults less permeable than the host rock. Generally, at a site for a store at the ground surface or underground, the frequencies of fractures and faults in the rock will need to be sufficiently small that the rocks' mechanical strength is not decreased to the extent that construction costs are uneconomically large. At the site of an underground store the fractures and faults will need to be sufficiently infrequent and / or sufficiently impermeable that water inflows to the facility do not become uneconomic to manage.

- ▲ **Weathering:** This refers to the characteristics of the rock that are due to physical degradation processes and chemical alteration processes relatively near to the surface (typically depths of up to a few tens of metres, but may be several 100 metres) at low-temperature (similar to temperatures at the earth's surface, excluding those where temperatures are elevated due to magmatic or hydrothermal activity). Weathering is relevant to selecting a site for a store for similar reasons to fracturing and faulting; weathering will generally decrease the mechanical strength of the rocks relative to unweathered rocks and may render the rock more permeable. Hence, a site should not be weathered to the extent that the rock is weakened mechanically to the extent that it becomes uneconomic to construct a facility. For an underground facility, weathering should not have rendered the rock to be so permeable that water inflows to the facility cannot be managed economically.

- ▲ **Seismicity (earthquakes)**: This refers to rock displacements along faults and associated vibrations. During the period of operations any locality should be not be affected by seismic activity that is sufficient to compromise the integrity of the waste containers or the buildings that contain them, or the functioning of equipment needed to handle the wastes.

- **Sufficiency of space**: The chosen site must have sufficient space to allow construction and operation of a store that is large enough to store the required volumes of waste.
- **Proximity to urban populations:** The distance between a store and urban populations is a non-technical factor that will influence the suitability of a site. There is a general expectation that it will be harder to win stakeholder acceptance (principally the acceptance of local people) in close proximity to an urban centre than at a site that is remote from urban centres. Additionally, it will probably be harder (though not impossible) to make a safety case for a store in or near an urban centre than one in a rural setting owing to the greater impacts of accidents in an urban environment (noting that the most likely accidents are actually non-radiological in character). Thus, there is an expectation that generally, the further from an urban centre a store is located, the more likely it will be that stakeholder acceptance can be obtained and the easier it will be to make a safety case.
- **Proximity to required infrastructure: (transport routes, power supplies etc.):** A certain amount of infrastructure will be needed to construct and operate any store. This infrastructure is principally transport-related (roads, railways etc.), power-related (electricity supply in particular), communications-related (e.g. cell phone coverage), security-related (facilities of security services) and water-supply / management related. It is desirable to make optimal use of existing infrastructure, to avoid unnecessary expense.
- **Distance between the sources of the waste and the store:** Generally, the further the waste store from the source of the wastes, the more costly and potentially complex will be the transport of the waste to the store. Additionally, all other factors being equal, greater transport distances imply a greater risk of road accidents and potentially present more security threats. Thus, it is desirable to minimise the distance between sources of waste and the store as far as practicable, taking into account other site requirements.
- **Availability of competent workers to construct and operate the facility:** Skilled and competent workers will be required to both construct and operate a facility. Potentially these personnel will be more readily available near to some localities rather than others. While it will be possible to transport workers with required skills to anywhere that they are required, clearly there will be costs associated with doing so that will increase with increasing store remoteness. Furthermore, the more remote the locality the more difficult it may be to attract competent workers who are needed to reside for a prolonged period close to the facility. This issue is likely to be more important for operations than for construction.

- **Remoteness from other human activities / sensitive environments**: It is necessary to ensure that the store does not interfere unacceptably with human activities in the surrounding area, particularly those connected with economic activity and / or leisure, or impact significantly on particularly sensitive environments. This requirement can be met in large part by selecting a site that is sufficiently remote from economic activities such as farming, resources such as groundwater aquifers or reservoirs and mineral deposits, amenities such sports facilities, or sensitive environments such as national parks or nature reserves.
- **Potential for flexibility**: It is desirable that the flexibility of any store to accept greater quantities of waste than planned initially and / or different kinds of waste than initially envisaged should be maximised as far as practicable, taking into account other requirements. Flexibility to site a final repository at the same site as a store would also be advantageous since it would minimise future costs associated with selecting a final disposal site and avoid the transportation (and possibly repackaging costs) that would be associated with siting a repository at a different locality.

The various required and favourable characteristics are not defined precisely and in any case overall suitability will depend upon relationships between these characteristics. Therefore, it follows that from a technical perspective, different sites with widely differing geological, hydrogeological and geochemical characteristics could potentially prove suitable locations for a store from a technical perspective; at sites with widely differing characteristics it would be technically feasible to construct and operate a facility of the required size safely while maintaining security. Given the relatively short period for which wastes would be stored in a facility (up to c. 100 years) safety and security can be ensured by engineered store components (see Task 3 report, Cronstrand and Anunti, 2014). Therefore, the characteristics of a site are important in so far as they allow the engineered components to be constructed and to function properly, and allow the facility to be operated as required, but it is not required to ensure that the geosphere itself has a barrier function to prevent radionuclide migration. Similarly, from the perspective of emergency preparedness, a site's suitability depends upon its location relative to potentially impacted receptors (people, animals, plants and economic resources), emergency services (e.g. police, military, maintenance services, medical services) and infrastructure (e.g. road access, hospitals etc.). It is apparent that the required safety, security and emergency preparedness could be achieved by appropriate store concept selection, design measures and operational procedures.

The identified requirements differ in several respects from the criteria considered by NGU and presented in NGU (2010a; 2010b). NGU's criteria are:

- The rock should have sufficient strength, be of sufficiently low permeability, and should not be highly fractured.
- It should be possible to characterise the site based on well data.
- The topography should enable construction of an underground facility that can be accessed via a near-horizontal drift and is large enough to accommodate the required waste handling equipment.
- There should be decreasing rock permeability with increasing depth.
- Areas of deep weathering (which in southern Norway can extend to depths of c. 100 – 150 m beneath the present land surface) should be avoided.
- Populated areas should be avoided.
- The area should be remote from rivers and lakes.
- There should be sufficient space for construction and operations.
- Areas with special protection restrictions (e.g. nature reserves) should be avoided.
- Areas with high natural radon emissions from rocks should be avoided.
- It could be advantageous if there is a sedimentary cover on top of the site.

While the ease with which a site can be characterised is a reasonable factor to consider when choosing between sites (all other factors being equal one would tend to choose a site that is likely to be the easiest to characterise), it would be possible to characterise any kind of site to the required standard given sufficient resources. The topographical criterion used by NGU is reasonable if the intention is construct a facility similar to Himdalen, which is accessed from a hillside by a slightly inclined tunnel. However, since the KVU is considering all options initially, and since it would be possible to construct a facility of some kind in almost any kind of topography, this criterion has not been used here. The criterion concerning decreasing rock permeability with depth is not relevant to a store at the surface. Though desirable from the point of view of siting an underground facility increasing permeability would not necessarily make a site unsuitable; the key point for a store is to ensure that economically viable engineering measures can be taken to ensure that inflow rates of groundwater are sufficiently small. While low radon emissions could be argued to be advantageous in that high levels of radon in buildings or underground excavations that are not sufficiently well ventilated can pose a health risk, radon hazards are readily mitigated. Hence this criterion, too, is not been used here to distinguish between areas. Sedimentary cover above a site would only be an advantage for an underground store and then only if the permeability is lower than the underlying rock.

An overall conclusion is that, provided sufficient resources are deployed and subject to sufficient stakeholder acceptance, it would be technically feasible to construct an intermediate store almost anywhere within Norway. The most important aspect of site selection is therefore to match a particular store concept and design to the attributes of a particular locality at which a store will be constructed and operated. The site characteristics above influence the suitability of a site for one particular store concept and design as opposed to another are site attributes that influence:

- the useable space (i.e. whether there is sufficient space to construct a facility of the required size, taking into account not only the volume of the packaged waste to be stored, but also the space required for supporting infrastructure, including buildings for waste handling and access);
- the effectiveness of engineered components;
- the ease of constructing the engineered components; and
- the ease of operating a facility so as to achieve safety, security and emergency preparedness.

Given the small volumes of waste to be stored in Norway, it is likely that space will not be a significant discriminant between alternative store sites.

The footprint of a site will depend upon a number of factors:

- the volume of the buildings or underground excavations that can be constructed practicably taking into account safety, security, emergency preparedness, and environmental impacts;
- the volumes of the waste to be disposed;
- the nature of the waste packaging (which governs the packaged volume);
- the particular store concept (e.g. whether wet storage, dry storage surface vaults, silos, casks, surface or underground), although in practice it is anticipated that most store concepts will occupy similar areas.

4.2 Size of Locality Required

The size required for the locality will depend to some degree upon the particular store concept that is adopted, although the Task 3 report points out that the required facilities are comparable between different concepts. Another factor that will determine the size of the facility required is the length of time for which operations are continued at Kjeller and Halden and the quantities of waste generated by organisations external to IFE. These latter waste sources will presumably continue beyond the planned operating period of a store (i.e. up to 100 years). The remit of this KVU does not extend to considering options for the wastes generated outside IFE beyond the operating lifetime of the store.

The quantities of SF present in Norway are presented in the Task 1 report (Huutoniemi, 2014) and are summarised in Table 4-1.

Table 4-1 Summary of quantities of SF presently in existence, derived from the Task 1 report.

Location		UO2	Metallic U	UO2 From Converted Metallic U (assuming fully converted)	Total UO2 if Metallic U Converted
Kjeller	kg	2309	3130	3551	5860
Halden	kg	4202	6725	7629	11831
Total	kg	6511	9855	11180	17691

In addition to the SF quantities given in Table 4-1 the Task 1 report states that approximately 125 kg of SF arise per year from operation of the HBWR (about 80 kg/year) and JEEP-II (about 45 kg / year). The capacities of the stores at Kjeller and Halden will allow for operation of the reactors up to 2032 and 2025 respectively (Stranden Committee, 2011). However no firm decision on the length of time for which the reactors will continue to operate has yet been taken. Hence there is considerable uncertainty about the quantity of SF that will be generated in addition to that already in existence.

The precise storage volume that would be needed for these quantities of SF will depend upon the storage concept that is adopted and the associated waste packaging, which is yet to be decided. An analysis of possible storage concepts is given in the Task 3 report and identified vault or cask storage as the most promising options, based on a range of criteria that were not weighted according to their significance to stakeholders; it was stated to be outside the scope of the analysis to determine and apply a weighting scheme and noted that the ranking of concepts might change if such a scheme were to be used. Assuming that either vault or cask storage was to be employed, the Task 3 analysis estimated an area of about 200 m^2 would be needed to accommodate all the SF that has been produced or will arise in future. A vault would be about 7 m in height, with about 3 m below the floor, whereas 10-25 casks would be needed depending upon the cask design. Casks would be 3 – 6 m high and the building (if a surface facility) or cavern (if an underground facility) would need to be 2 m higher than this.

The wastes other than SF are presently packaged in a number of different forms, which are not necessarily the ones in which these wastes will be deposited within an intermediate store. The Task 1 report presents waste quantities of each kind of waste in terms of “drum equivalents”, which represent the number of 210 litre drums that would be generated if the waste were to be packaged in such drums. It is pointed out in the Task 1 report that "drum equivalents" are not scalable to the unpackaged waste volumes directly, because the volume of waste that could be emplaced within a given 210 l drum would depend upon the waste characteristics. Nevertheless, from the perspective of estimating the footprint of a site and the required volume of the facilities, it is the packaged volume that is important and the number of drum equivalents is therefore a good basis on which to proceed.

There is considerable uncertainty about the classification of the wastes other than SF and hence it is not possible to state precisely the likely quantities of long-lived waste besides the SF. Furthermore, the time for which the reactors at Kjeller and Halden will continue to operate is unknown and therefore it is possible to estimate waste quantities only for illustrative future operating times.

The Task 1 report describes an attempt to classify these long-lived wastes other than the SF, using inventory information. The Task 1 report also gives details of quantities of wastes that are / will be produced by different activities (operations at Kjeller, operations at Halden, decommissioning of the various facilities etc.).

An attempt has been made to divide these quantities among the different waste categories (LLW, ILW, long-lived, short-lived) in order to estimate approximately the quantities of these long-lived wastes that will need to be stored. The results of this estimation, for various illustrative periods of continued reactor operations at Kjeller and Halden, are summarised in Table 4-2. When estimating the quantities in this table, a conservative approach has been taken that tends towards overestimating the volumes of waste to be stored. The philosophy is that it is better to plan to store larger quantities than might be necessary at the outset, than to underestimate volumes and need to revise plans for a store later. Therefore, the quantities in Table 4-2 include any waste that might potentially qualify as long-lived.

Table 4-2 Estimated quantities of total waste, long-lived waste and short-lived waste, for different assumed times (years after the present) of reactor shut-down. All quantities are given in 210 l Drum Equivalents (derived from the Task 1 report, Huutoniemi (2014)).[3]

Wastes Other Than SF, Classified According to Longevity	**Illustrative Years of Continued Operations of Reactor Facilities (Assume Both Kjeller and Halden continue as at Present)**			
	0	10	20	30
Total Waste to be Stored / Disposed Of:				
Wastes in store	29	29	29	29
Decommissioning Wastes	5146	5146	5146	5146
Operational Wastes (IFE and External to IFE)	0	1805	3610	5415
Total	*5175*	*6980*	*8785*	*10590*
Long-Lived Wastes to be Stored / Disposed Of:				
Total Stored Long-lived Waste Excluding Spent Fuel	29	29	29	29
Long-Lived Decommissioning Waste:	3829	3829	3829	3829
Total Long-lived Operational Waste, Excluding Spent Fuel (IFE and External to IFE)	0	1570	3140	4710
Total	*3858*	*5438*	*7018*	*8598*
Short-Lived Wastes to be Stored / Disposed Of:	1317	1524	1767	1992

The quantities of waste arising can be compared with the existing volume present in the KLDRA combined store and repository at Himdalen (Sorlie, 2001) which is summarised in Table 4-3.

Table 4-3 Summary of wastes presently stored / disposed of in the KLDRA at Himdalen (information from the Task 1 report, Huutoniemi (2014)). All quantities are given in 210 l drum equivalents.

Hall	**1**	**2**	**3**	**4**	**Total**
Current Purpose	Intermediate Storage	Disposal	Disposal	Disposal	
Quantity of Waste Emplaced	166	375	2500	2500	5541
Available Space for Waste	2334	2125	0	0	4459

[3] The data in Table 4-2 and Table 4-3 reflect a range of assumptions. The figures given are subject to uncertainty and should not be considered definitive "accurate" predictions. Rather, they provide basic estimates of volumes sufficient to inform in broad terms on the potential size requirements for a storage solution.

It can be seen by comparing Table 4-2 and Table 4-3 that there would be sufficient space for the long-lived waste other than SF to be emplaced in the KLDRA provided that the reactors at Kjeller and Halden are shut down in the near future; given the various simplifying assumptions made when calculating the waste quantities, if the reactors were to be shut down in 4 years, the long-lived waste produced would match the available capacity at Himdalen. If the reactors were to continue their operations for the next 10 years, then the total volume of long-lived waste would be around 5500 drum equivalents, whereas the quantity would increase to around 9000 drum equivalents if operations continued for 30 years. Roughly 100 drum equivalents are generated annually by producers external to IFE and are included in the quantities given in Table 4-2 for the considered time periods. These quantities could presumably continue to arise after the shut-down of the reactors and therefore, potentially, would need to be stored; if the store were to be operated for 100 years beyond the time when the reactors are shut down, then there would be a further 10,000 drum equivalents that would need to be emplaced in the KLDRA at Himdalen. Taking a conservative approach (i.e. using the largest plausible volumes of waste) it would therefore be prudent to plan for an intermediate store being sufficient to take 16000 drum equivalents of long-lived waste (c. 20,000 drum equivalents of waste that will be generated in total minus the c. 4500 drum equivalents that could be sent to Himdalen).

The likely size of facility that would be needed to store such waste can be illustrated by reference to the present Himdalen facility. This facility consists of 4 halls, each of 50 m length and 12 m width, beneath a rock overburden of c. 50 m and accessed by a tunnel that is 150 m in length (Sorlie, 2001; IFE, 2011). When a hall is fully filled with waste, the hall contains two concrete sarcophagi, each 5 m high, 10 m wide and 20 m long. Based on these figures, the actual volume needed to emplace the waste (the size of the sarcophagi) for 10,000 drum equivalents of waste is 8000 m^3. Assuming similar packaging and emplacement to that employed in Himdalen and scaling to accommodate 16,000 drum equivalents of waste, a new intermediate store would require sarcophagi with a volume of 12,800 m^3. Assuming that these would have a similar height and width to the sarcophagi at Himdalen, the area required would be 2560 m^2. The actual floor area of the storage / disposal halls in Himdalen is 2400 m^2. Scaling this area in the same way as for the area of the sarcophagi, an area of 3840 m^2 would be needed. To obtain the total footprint of the store, to this area would need to be added the area of access tunnel (if the store is sub-surface) and areas between storage halls. The total footprint might be around twice the area occupied by the wastes, perhaps about 8000 m^2. While the precise area will depend upon the concept chosen and the nature of the particular site (e.g. size of caverns that can be constructed practicably), it is clear that the area required for these long-lived wastes is very much greater than the area required for the SF (perhaps 200 m^2). Nevertheless, the area is still relatively small and it seems reasonable to suppose that a site with dimensions of around 100 m x 100 m would likely be sufficient. It is probable that a site of this size with the characteristics required to ensure constructability, safety and emergency preparedness could plausibly be found in any county (Fylke) of Norway.

4.3 Norwegian Areas Where Required Attributes Occur

4.3.1 Geological Attributes

4.3.1.1 Overview of Geological Attributes

The solid geology of mainland Norway at depths below the surface that are relevant for an intermediate waste store (or indeed for a final repository) is dominated by crystalline igneous and metamorphic rocks (Figure 4-1) (Bergstrøm et al., 2009). There are, however, some occurrences of sedimentary rock that overlie the crystalline rocks. For example, a thin (10 m) sequence of Jurassic sedimentary rocks occurs in a fault zone encountered in a subsea road tunnel near Bergen (Fossen et al., 1997). However, these areas of sedimentary rocks are very small in comparison to the overall area of the country and there is no clear reason why such rocks would be chosen for an intermediate waste store in preference to crystalline basement rocks that are extremely widely distributed. Generally sedimentary rocks that overlie crystalline basement rocks thicken towards the offshore area (Ottesen et al., 2009). However, again, there would be no obvious advantage to siting a store in these offshore rocks (for example in a sub-surface facility that might be accessed via tunnel from the onshore area).

There are also many offshore islands under Norwegian jurisdiction, including the large islands of Svalbard. It is to be expected that there will be many locations among these islands that would have geological attributes that would be favourable for constructing an intermediate waste store. These geological attributes are very variable, depending upon the location of the island; sedimentary, metamorphic and igneous rocks are all represented. In the Svalbard archipelago crystalline Pre-Cambrian basement rocks are overlain by a sequence of varies sedimentary rocks; the structural characteristics of the whole are complex.

Published geological information about Norway, including geological maps produced by the Norwegian Geological Survey (NGU; e.g. Figure 4-1), were reviewed. Additionally, to learn more about the available geological information a meeting was held between representatives of DNV-GL, Quintessa and NGU on 16th March 2014, at NGU's offices in Trondheim.

Although geological maps are available for the whole of Norway, the level of detail with which geological information is recorded is quite variable. Mapping at 1:250,000 scale commenced in 1858 and subsequently progressed throughout the country. However, as the mapping proceeded, the interpretations of the data obtained changed. Consequently geological formation boundaries and structures shown on presently available map sheets do not necessarily continue across the boundaries of the map sheets.

It is possible that some structural features (principally faults) are not represented or are under-represented on maps. It is noteworthy that the faults and fracture zones shown on the geological maps are all steeply dipping. However, there could also be sub-horizontal faults and fracture zones that have not been recognised by virtue of their geometry. In water extraction wells horizontal fractures are commonly recognised. These fractures are caused by stress release due to unloading following the end of the last glaciation.

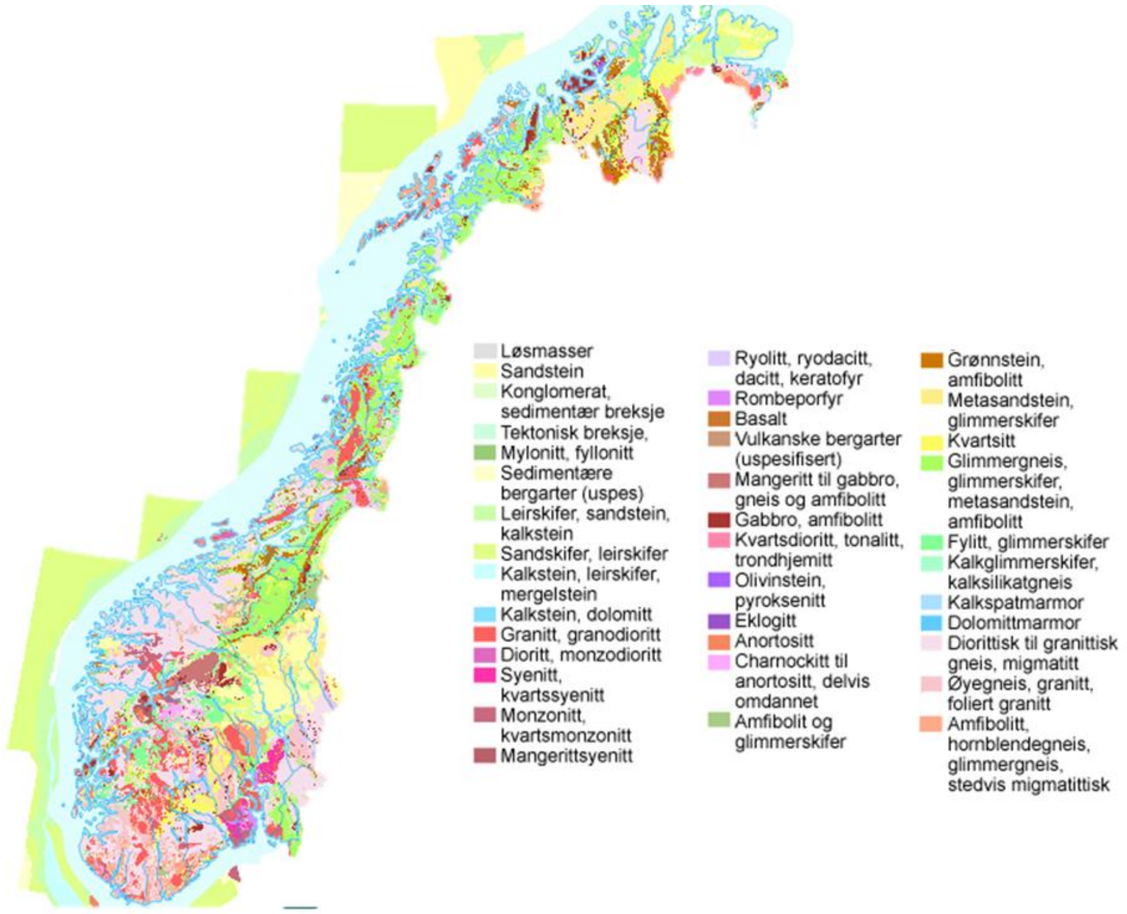

Figure 4-1: Geological map of mainland Norway, produced by the Geological Survey of Norway (NGU); Norwegian geological maps are accessible on the web site: http://www.ngu.no/kart/arealisNGU/

The workshop held at the offices of DNV-GL in Høvik on 4th and 5th February 2014, with participants from DNV-GL, Quintessa, Westinghouse and Studsvik evaluated the extent to which the attributes listed in Section 4.1 could be used to discriminate against different localities. A further workshop was held on 18th March 2014, also in Høvik, to review the results of the earlier workshop and assess the extent to which engineered solutions could compensate for any geological or hydrogeological shortcomings in a site. Participants in this second workshop were representatives of DNV-GL and Quintessa and Dr Arild Palström, a specialist in engineering geology and rock engineering. The outcomes of the evaluations carried out at the two workshops are described in the following sections.

4.3.1.2 Lithology (Nature of the Rock)

It is technically possible to build a store of some kind that will meet required safety standards on / in almost any type of rock provided that sufficient budget is available.

An outcome of the earlier site selection work by NGU was a recommendation that the search for a suitable site should focus on the south of Norway, because there are more areas in this region with rock characteristics that might make it easier to construct a store than elsewhere. However, it cannot be concluded from NGU's work that there would not be suitable sites at other localities in Norway. It should be noted that although initial work undertaken by NGU, and presented in NGU (2010a, 2010b), aimed to site a store, many of the criteria / factors they used to rank sites are more appropriate for siting an underground repository. Furthermore, several of these criteria/factors would not be relevant to siting a store at the surface (e.g. the criterion concerning the desirability of decreasing rock permeability with increasing depth).

From the lithological information available it is not possible to rule out any mainland Norwegian county (fylke) as a possible store locality. Crystalline rocks (metamorphic and igneous rocks) are very widespread in Norway (Figure 4-1) and would generally have geomechanical and hydrogeological properties that would facilitate construction of a store. While in principal a store could be sited on / in sedimentary rocks, there are few areas with sedimentary rocks. Furthermore, certain kinds of sedimentary rock (e.g. poorly consolidated clay) would have properties that would make store construction more difficult and hence costly than would be the case for a store sited on crystalline rocks. For these reasons, it seems that crystalline rocks should be the focus of a siting exercise.

4.3.1.3 Structural Characteristics of the Rock (Fracturing and Faulting)

Within any region of Norway there are will be fractures/faults over a continuum of spatial scales (e.g. from millimetres to many kilometres). Furthermore, different fractures will have differing geomechanical and hydrogeological properties (e.g. some fractures may be more permeable than the rock they cut, whereas other fractures may be less permeable than the unfractured rock). Fracturing and faulting often occur in zones that are related to one another. There may be several sub-parallel faults within a distance of metres to kilometres, as measured perpendicular to the fault trace (i.e. the orientation of the actual break within the rock). Each fault may be surrounded by a zone of fracturing, with a width that is related to the magnitude of the fault, which is in turn related to the magnitude of the fault's displacement. Faults with displacements of 10's of kilometres may have fracture zones surrounding them that are hundreds of metres wide.

The occurrence of fractures and faults should not necessarily rule out a site from being considered for a store; indeed it will be practically impossible to avoid selecting a site with at least some fractures in the bedrock. For example, SKB would allow deposition positions for SF canisters in the Forsmark repository to be intersected by fractures so long as the fractures meet certain physical criteria, as described in SKB's recent SR-Site safety assessment report (SKB, 2011). The key point from the perspective of a store is that the more fracturing and faulting in an area the more likely it is that there will be difficult conditions for constructing a store (e.g. unpredictable rock properties, low rock strength, high groundwater flows). Clearly fracturing will be more important for an underground facility than for a surface facility, although even for a surface facility the design and construction of foundations will need to take into account the geomechanical properties of the bedrock beneath the facility. These characteristics will depend upon the nature of fractures and faults that are present.

The availability of information with which to judge the characteristics and distributions of faults and fractures in Norway is variable across the country. The greatest level of detail is available in south-eastern Norway. Therefore, it is not possible to objectively compare different areas. For example, different frequencies of faulting in different parts of the country may reflect data coverage rather than the structural differences between the areas. However, it is more likely that large structures (several kilometres to tens of kilometres in length) are accurately represented in maps than are smaller structures. Hence, for an initial screening, it would be appropriate to rank areas with lower frequencies of faults on these scales than areas with higher fracture frequencies.

When this approach is taken it is not possible to distinguish clearly between different regions of Norway; there are areas with similar levels of large-scale (kilometres to tens of kilometres) throughout the country. Hence, in the basis of available structural information it is inappropriate to rule out any particular region.

4.3.1.4 Weathering

Deep tropical weathering is widely recognised in Norway and is thought to be ancient, most likely of Mesozoic age (probably weathering occurred more than c. 65 Ma ago) (Olesen et al., 2012). Between fracture zones, this weathering has been removed by glaciation, but within fracture zones it can be preserved, often to a depth of 150 – 200 m. These weathered features have relatively low strength and high permeability compared to the crystalline rocks in which they occur. Tunnelling activities (e.g. the Romeriksporten and Hanekleivtunnelen tunnels; Olesen and Rønning, 2008) have encountered rock stability problems and / or high groundwater inflows where they have intersected such weathered fracture zones. However, these fracture zones with deep tropical weathering are recognised as topographical lows and hence can be avoided when siting a store. Furthermore, the geotechnical and hydrogeological issues that they present are not insurmountable given sufficient resources. Hence, the occurrence of deep weathering would not preclude the construction of a store at the surface or underground, although the significance of weathering for construction of an underground store would be greater than for a store at the surface.

If when siting a store major zones of fracturing and faulting are avoided, as described in Section 4.3.1.3, then naturally many areas of deep tropical weathering would also be avoided. Based on the available information is not possible to rule out any Norwegian county as a possible host for a store on the grounds of deep weathering.

4.3.1.5 Seismicity (Earthquakes)

Were they to occur with sufficient intensity, seismic events could compromise the safety of surface structures. The vibrations associated with seismicity become less intense with increasing depth, which means that underground stores would be less affected than surface ones at the same locality, unless the fault movement causing the seismicity occurred within the footprint of the facility. However, while not aseismic, Norway is in a relatively tectonically stable intra-plate environment and seismic events sufficient to cause damage are rare (Figure 4-2).

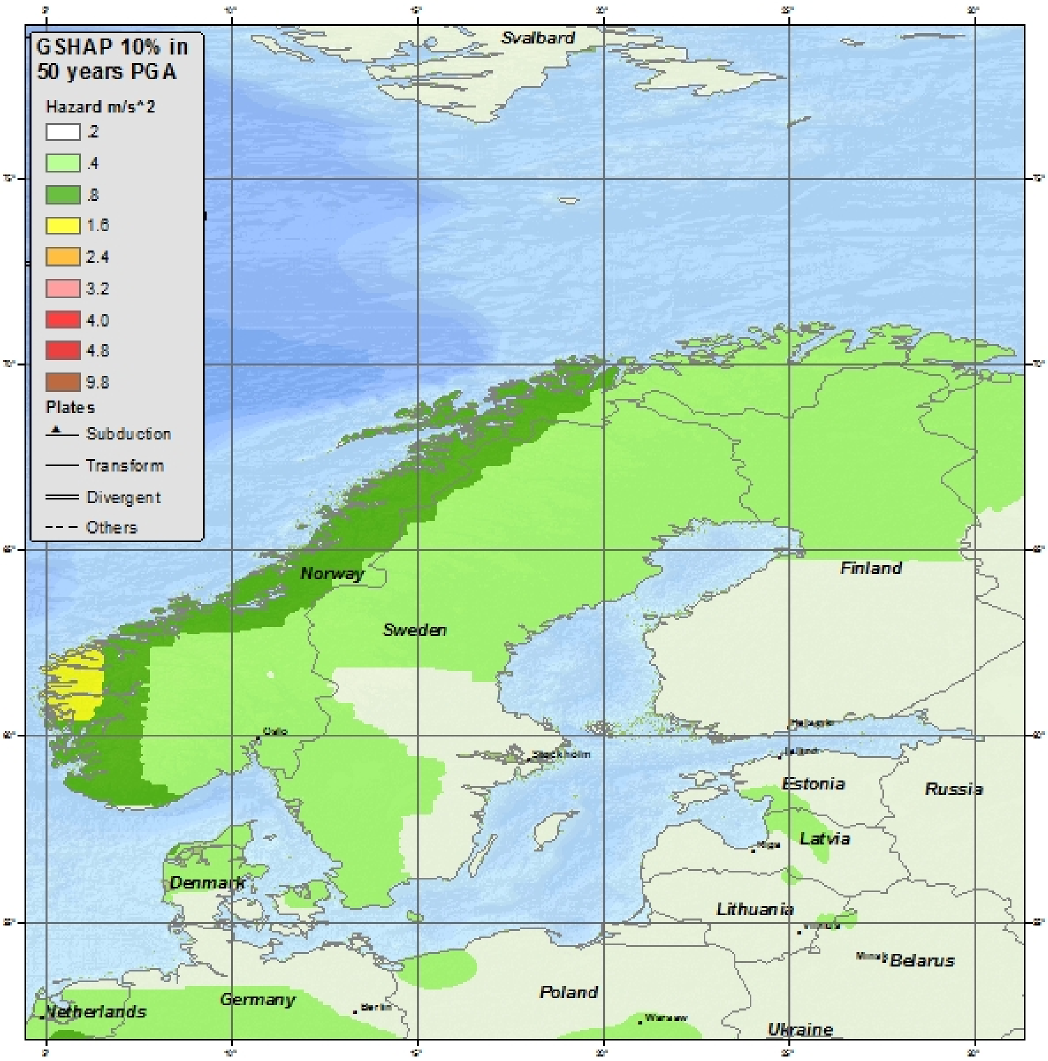

Figure 4-2 The USGS seismic hazard map for Norway. The scale shows the peak ground acceleration (pga) with a 10% chance of exceedance in 50 years.

While seismicity is, relatively, more probable in western Norway than in eastern Norway, even in the west the probability of significant seismic events is very low. Furthermore, it is perfectly feasible to engineer facilities so that they will be undamaged should an earthquake occur. This possibility can be illustrated by reference to Japan, which lies at the margin of several tectonic plates and which is one of the most seismically active countries in the world. There seismicity itself has not directly caused significant radiological protection issues. Even the magnitude M 9 Tohoku earthquake in northeastern Japan in 2011, the 4th largest ever recorded, did not cause major building damage sufficient to result in leakages of radiation from any of the nuclear facilities in the area; the damage to the Fukushima plant resulted primarily from later inundation by the resulting tsunami. For comparison, in mainland Norway the largest earthquake ever recorded occurred in the Rana region in 1819 and is estimated to have had a magnitude of M 5.8 (NORSAR web site:

http://www.norsar.no/seismology/Earthquakes/SeismicityNorway/), almost 1600 times smaller than the 2011 Japanese Tokoku earthquake in terms of energy released.

It is therefore judged that seismicity is not a challenge in regards to meeting the technical standards required for a store, at least not in the scale of Norwegian seismicity. Furthermore the regional differences in seismicity are not sufficient to cause one region to be preferred over another one.

4.3.1.6 Sufficiency of Space

As discussed in Section 4.2 a facility with a footprint of around 100 m x 100 m, whether at the ground surface or underground, would be sufficient to accommodate all the wastes likely to be generated. It seems unlikely that such a small area could not be available within any Norwegian county. Therefore, this requirement cannot be used to distinguish between areas.

4.3.1.7 Potential for Flexibility

A site that offers potential for flexibility when constructing and operating a store, and/or flexibility to locate a final repository there would be given a higher ranking during site selection than a site that does not offer such flexibility (all other factors being equal). Flexibility during construction and operation covers both extension of the store to accommodate more waste than planned initially and / or adaptation of the store to accept different kinds of waste compared to those planned at the outset.

Given the relatively small footprint that will be required for a store (see Section 4.3.1.6), it seems reasonable to suppose the flexibility to extend will be offered by most sites that would meet the other requirements for suitability. The limitations on flexibility to extend are more likely to be non-technical, related, for example, to public acceptance and the possibility of permission being granted by local planning authorities.

Given available information, it is difficult to imagine that wastes that have presently not been identified could in future require storage in the intermediate waste store. Existing wastes are already quite diverse and the facility will need to be designed to accept them from the outset.

Flexibility to locate a repository at the same site as the store would be highly advantageous for a number of reasons, not least because it would avoid the need to transport the waste to a separate locality for disposal, with associated costs and risks. However, the suitability of a site to host a repository, as opposed to only a store, cannot be determined without a substantial site characterisation programme. Hence it is not possible to state a priori it might be possible to site a repository at the same location as a store. On the other hand, based on existing knowledge it ought to be possible to identify sites that would definitely be unsuitable as repository sites. Such sites could then be given a lower ranking (other factors being equal) than sites that are not clearly unsuitable sites for a repository. This approach (i.e. assessing "unsuitability" criteria) is similar to the approach adopted in many countries during the initial site selection for a deep geological repository for radioactive wastes. However, it is outside the scope of this KVU to develop and apply such an approach.

4.3.2 Non-Geological Attributes

4.3.2.1 Proximity to Urban Populations

The proximity of a store to an urban population should present no insurmountable issues regarding safety; stores are already operated at the reactor sites in Kjeller and Halden, which are both situated in urban centres. The higher the density of the population surrounding a store, the higher would be the risks associated transportation of waste to the store. However, provided that the waste is packaged for transportation in line with international norms, the main transport risks are non-radiological and relate to conventional accidents; waste transport containers are designed to be very robust and to maintain their integrity even during transportation accidents. Wastes, including SF are already transported by road between Halden and Kjeller. Wastes produced external to IFE are also transported to Kjeller by road.

The proximity of a store to urban populations is important mainly because it is related to public acceptance and influences the extent and kinds of stakeholder engagement that are needed to obtain such acceptance. In an urban centre there will be more local people who will need to be engaged than in a rural setting. Although siting a store in a rural setting implies some transportation of wastes, and a consequent need to obtain consents from communities along the transport routes, waste is already transported and transportation would continue to be required even if the store were to be located at either Kjeller or Halden.

4.3.2.2 Proximity to Required Infrastructure

Any need to develop infrastructure especially for a store would increase the overall costs of store construction and operation. However, it would be technically feasible to provide the required infrastructure at any site provided that sufficient budget is made available.

Infrastructure is more likely to be available closer to urban centres than in more remote localities. Hence it follows that there will be more sites with the necessary infrastructure in the south of Norway than in the north.

4.3.2.3 Distance Between the Sources of the Waste and the Store

The further that the waste must be transported between its source and the store, the greater will be the associated costs and the higher will be the risks. It is emphasised that provided the waste is packaged for transport in line with international norms these risks dominantly concern conventional road accidents and are non-radiological; transport containers are designed to be robust and to survive transport-related accidents.

Approval for transportation needs to be obtained from communities and planning and regulatory authorities. Clearly, the longer the transport route the more complex, and hence potentially time consuming, will be the activities required to obtain these approvals. For example, the more municipalities the waste will need to traverse, the more local authorities will need to be consulted to obtain permission.

It will also be more challenging to meet security requirements during transportation for longer transport routes than for shorter ones. However, waste is already transported considerable distances within Norway and mechanisms for ensuring security during transport are well-established.

The wastes to be stored are already presently at Kjeller and Halden, or else will be generated at these sites or (in the case of Kjeller) pass through them. Therefore, provided that they meet the other requirements, sites closer to Kjeller or Halden would be more favourable from the perspective of transportation than sites further away. However, a site should not necessarily be considered unsuitable solely on the grounds that it is located a long way from Kjeller and Halden.

4.3.2.4 Availability of Competent Workers to Construct and Operate the Facility

Workers with many different kinds of skills and competences will be required to construct and operate a store. Therefore, the availability of these personnel needs to be considered when siting a facility. Wherever in Norway a facility is located it will be possible to transport workers with the necessary skills and competences to it and / or to relocate workers to its vicinity. However, there will be costs associated with doing so. Additionally, if the facility is in an area that is remote and / or considered an undesirable place to live, then it might be difficult to recruit the required workers to work there. This latter consideration is more relevant to the operational phase than the construction phase, which will be of limited duration. In practice, however, it is unlikely that this issue would be insurmountable, as can be appreciated from the fact that there are facilities of many kinds in remote areas of Norway (e.g. certain hydroelectric power plants, military facilities etc.).

Skilled and competent workers are more likely to be available close to larger population centres than near to smaller population centres. With increasing distance between a site for a waste store and urban centres it will become progressively more costly to obtain / recruit the required workers. Thus, it is likely to be easier to obtain the necessary personnel nearer to the population centres of southern Norway or central Norway. However, localities elsewhere, in more remote locations, cannot be ruled out on the basis of access to skilled and competent workers.

4.3.2.5 Remoteness From Other Human Activities / Sensitive Environments

The construction and operation of a store should not impact unacceptably upon other human activities or sensitive environments such as nature reserves or national parks. Therefore, in principle it is desirable to site an intermediate store at a location that is as far as possible from these human activities or sensitive environments. However, in practice it will be impossible to avoid impacting upon at least some other human activities or sensitive environments to some extent. It will be necessary to undertake a comprehensive environmental impact assessment prior to a store being licensed, in order to determine the nature and magnitude of these impacts. A dialogue will need to be held involving all relevant stakeholders, including regulators and licensing authorities, to determine whether the impacts can be considered acceptable. These activities are outside the scope of the KVU. Nevertheless, as an initial ranking criterion it is reasonable to state that sites should not be located within national parks or nature reserves.

4.3.3 Integrated Assessment of Requirements

Sections 4.3.1 and 4.3.2 assessed the different site requirements individually. This section aims to consider these criteria together.

It can be appreciated that there are no regions within Norway where there are clearly no sites that have the required attributes. It should be noted, however, that offshore islands were not included in the evaluation since there was no clear reason why these might be preferred as sites relative to a site on the mainland, given that clearly there are likely to be many mainland sites that would fulfil the requirements. Typical offshore islands would have advantages associated with being remote from major population centres, but would conversely have disadvantages arising from this same remoteness (large distances from the waste sources, relative difficulty of obtaining skilled workers etc.).

Given the available information there are no clear technical reasons to suspect that it would not be possible to build a store of some kind within any mainland county of Norway. Ranking of one site more favourably than another will largely be a matter of:

- it being judged more expensive to construct a store at one site than another, reflecting the:
  - technical difficulty of constructing a store, given a site's characteristics;
  - existence of infrastructure / need to construct new infrastructure;
  - proximity of the site to the sources of the waste, greater distances making it more expensive to transport the waste;
  - proximity of the site to skilled and competent personnel.
- it being judged more expensive to operate one site compared to another, reflecting largely:
  - the expense of maintaining security (a function of the nature of the store concept and site and the distance from security personnel and related facilities);
  - the expense of maintaining infrastructure (a function of proximity of remoteness from population centres);
- it being judged more likely to secure acceptance from all stakeholders, including the public, regulators and government, at one site compared to the other.

Based on the available information the following localities identified by the Stranden Committee (Stranden Committee, 2011) would meet the technical requirements:

- Mysen Nord (Locality 1), between Kjeller and Halden;
- Tomter Vest (Location 2), between Kjeller and Halden;
- Vardeåsen (Locality 7), near Kjeller;
- Grimsrød (Locality 8), near Halden;
- Bjørneholen (Locality 9), near Kjeller; and
- Klaretjernhøgda (Locality 10), near Halden.

However, a relatively large amount of reliable geoscientific information is available for these sites, compared to that which is typically available for Norwegian sites. It cannot be ruled out that if consistent information were available, so that localities elsewhere could be assessed on the same basis as these localities, it might be judged that somewhere different would be more suitable technically to host a store.

These 6 sites identified by the Stranden Committee all have the advantage that they are located relatively close to the sources of the waste to be stored (i.e. Kjeller and Halden) and also to existing infrastructure and sources of suitably skilled and competent personnel.

4.4 Potentially Feasible Store Design – Locality Combinations

This section identifies combinations of potentially suitable store designs and localities, based on the general required attributes described in Section 4.1 and the particular areas where these different attributes are likely to occur identified in Section 4.3. The identified locality-store design combinations are all judged to have a high probability of meeting the required criteria for constructability and radiological protection.

At any particular site, a subset of several options will be viable for locating a store. These options are illustrated schematically in Figure 4-3.

Which locality is chosen will depend upon many factors, but at a general level, cost and obtaining consents from stakeholders, including regulators and government, will dominate.

Generally, the costs for underground storage of a given size will increase with increasing depth of facility below the ground surface and / or increasing length of access tunnel. Decreased topography (thereby implying a more inclined access tunnel and / or one that is longer) would tend to make an underground store at a given depth below the ground surface more expensive to construct than one at shallower depth. A further contributor to increased costs of construction and subsequent operation could also be the increased costs of drainage and water management in a deeper facility compared to a shallower one. At one extreme a facility located above the water table within a hill might be accessed by an upwardly-inclined tunnel, such that drainage might occur under the influence of gravity at relatively low cost. At the other extreme, a deep facility located beneath the water table would need to be accessed by a downwardly inclined tunnel and drainage would require pumping, thereby incurring greater expense. On the other hand, if a major cost is judged to be the treatment and management of water pumped/drained from the facility, and if it is shown that the

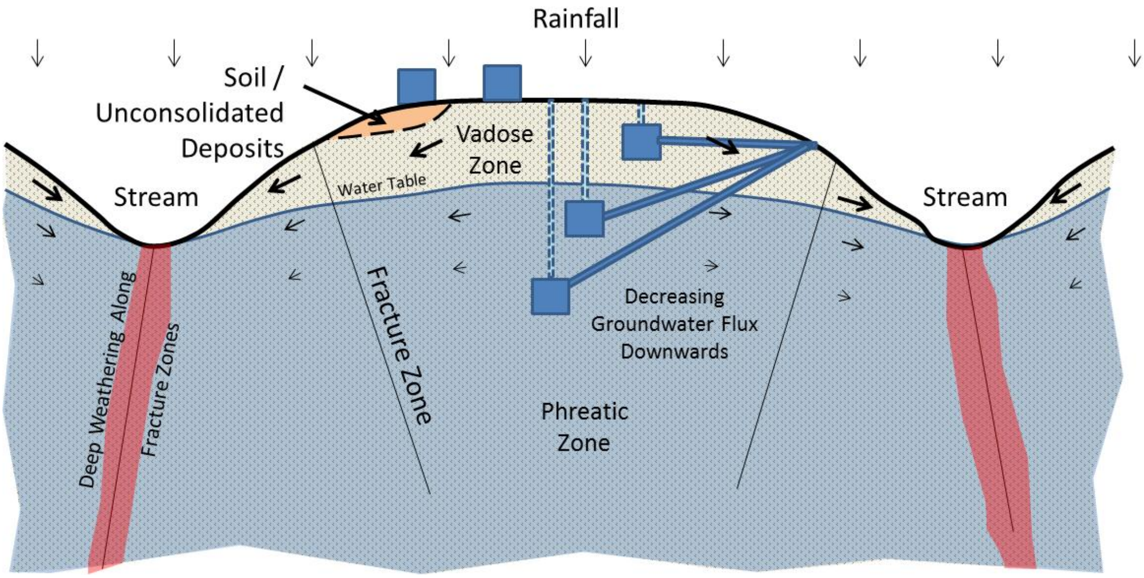

Figure 4-3 Schematic illustration showing the different general kinds store location. In principle access to an underground facility could be via tunnels or shafts. However, a shaft option would likely be much more costly to implement, principally because it would make operations more difficult; for completeness these options are shown in light blue, with dashed lines.

rock permeability and / or driving head gradients decrease downwards, then it might be desirable to locate an underground facility at greater depth. In this case, the increased cost of constructing the store deeper would need to be balanced against the decreased cost of water management during construction and operations.

For an underground facility the costs of ventilation also need to be considered. However, while generally these costs will be greater for deeper facilities than for shallow facilities, there will not be such a difference as for water management.

For surface facilities, too, topography and drainage are important factors that will influence costs. A site with greater topographical relief may require more preparation (e.g. ground levelling) than a site with lower topographical relief or a flat site. The more site preparation is needed, the greater will be the cost. Surface drainage will also be an important consideration. It will be necessary to locate a store where flooding will not occur and / or take engineering steps to prevent flooding by managing surface water. A naturally well-drained site will require less anti-flood engineering than a site that is poorly drained; naturally well-drained sites will therefore be less costly to develop than poorly drained sites, all other factors being equal. An implication is that a flat upland area / plateau (little levelling required, well-drained) would likely be preferable to valleys in a hilly area (close proximity to rivers, lakes).

The nature and thickness of any sediments overlying the crystalline rock at the site (as noted in Section 4.1, a site with crystalline rocks is almost certain to be chosen, given the widespread near-surface occurrence of these rocks) will also influence the costs of surface facilities. If poorly consolidated sediments or soils occur at the surface, these will need to be removed or stabilized in order to construct the foundations of a store. There will be costs associated with doing so, which generally will increase with increasing thickness of the deposit.

Fracture zones and faults, and zones of deep weathering (which are usually related to fractures and faults) will also influence rock stability and hydrogeological properties of the rock. If these kinds of feature occur at a site, costs would be incurred to mechanically stabilize the rocks (important for both surface and underground facilities) and potentially to limit groundwater flows through these feature (important for underground facilities). However, as discussed in Section 4.3.1, these features can be avoided at the site selection stage (Figure 4-3).

The Task 3 report identified and described four promising overall storage concepts, each one consisting of a containment concept and a building concept, based on a range of un-weighted criteria. It was pointed out in the Task 3 report that if the criteria were to be weighted according to their significance to stakeholders, the identified concepts might be ranked differently. However, it was also stated to be outside the scope of the analysis to determine and apply a weighting scheme. Consequently this section evaluates where these concept might be implemented.

The four overall concepts identified in the Task 3 report are:

A Vault storage in industry building;

B Vault storage in underground facility;

C Cask storage in industry building; and

D Cask storage in underground facility.

Any of these concepts could be implemented at almost any locality, provided sufficient resources are available. The ways in which the attributes discussed in Section 4.1 and 4.3 would influence the choice of one concept as opposed to another are summarised in Table 4-4.

Table 4-4 Summary of the relative importance of geological and non-geological attributes in the selection of storage concepts. Note that “<” indicates an attribute of lesser importance for the concept type corresponding to the row, compared to its importance for the concept to the right of the sign; “>” indicates an attribute of greater importance, and “=” an attribute of similar importance.

		Lithology	Structural characteristics of the rock	Weathering	Seismicity[4]	Sufficiency of space	Potential for flexibility	Proximity to urban populations	Proximity to required infrastructure	Distance between the sources of the waste and the store	Availability of competent workers to construct and operate the facility	Remoteness from other human activities / sensitive environments
		Geological Attributes						Non-Geological Attributes				
A.	Vault storage in industry building	<B[1], <D, =C[2]	<B, <D, =C	<B, <D, =C	<B, <D, =C	=	=	>B, >D, =C	=	=	=	=
B.	Vault storage in underground facility	>A[3], >C, =D	>A, >C, =D	>A, >C, =D	>A, >C, =D	=	=[5]	<A, <C, =D	=	=	=	=
C.	Cask storage in industry building	<B, <D, =A	<B, <D, =A	<B, <D, =A	<B, <D, =A	=	=	>B, >D, =A	=	=	=	=
D.	Cask storage in underground facility	>A, >C, =B	>A, >C, =B	>A, >C, =B	>A, >C, =B	=	=[5]	<A, <C, =B	=	=	=	=

Notes:

1. lithology is a less important factor for determining the viability of vault storage in an industry building than vault storage in underground facility.
2. lithology is equally important for determining the viability of vault storage in an industry building and cask storage in industry building.
3. lithology is more important for determining the viability of vault storage in underground facility than for determining the viability of vault storage in industry building.
4. In an absolute sense seismicity is likely to be less important underground than at the surface because seismic vibrations generally decrease in intensity downwards, although as discussed in Section 4.1 and Section 4.3.1.5 seismicity will not be a significant factor affecting the viability of a store concept in Norway.
5. If an underground store was to be constructed at sufficient depth there might be potential for turning it into a final repository at a later date, although the viability of this possibility would require considerable site characterisation and assessment to establish.

The only non-geological attribute that could be a significant discriminator is proximity to urban populations. Potentially this attribute may cause an underground facility to be preferred over a surface one because of public perceptions. Experience worldwide shows that it is possible to store waste safely in surface facilities; indeed this is done already at Kjeller and Halden. However, in an absolute sense an underground facility can be constructed and operated more securely than a surface facility at the same locality, even though it would be possible to take security measures for a surface facility that would meet all regulatory requirements. Therefore, there will generally be a perception among many stakeholders, especially members of the public, that an underground facility is better. This perception may drive the selection of a facility.

4.5 Implications of Distinguishing Characteristics for Achieving Safety, Security and Emergency Preparedness

4.5.1 Safety-Related Issues

For a store, safety will be ensured by engineering solutions and appropriate operational procedures. Of course these engineering solutions and procedures must be matched to the particular storage concept – locality combination and take appropriate account of site characteristics.

It should be noted that there may also be a perception among certain stakeholders that an underground facility will be safer than one at the surface. However, this is a misguided perception since for a store the geosphere has no barrier function.

There are differences between measures that need to be taken in an underground facility and a surface facility in order to ensure that relevant safety standards are attained and environmental impacts kept within acceptable limits. In a typical underground facility there will be fewer escape routes for personnel than in a typical surface facility. When constructing and operating an underground facility, measures need to be taken to ensure that the relatively small number of escape routes from an underground facility will remain open in the event of an accident and / or refuges need to be provided within the facility where workers can shelter in the event of an accident.

Water management is likely to be another potentially safety-related issue that will differ between surface and underground facilities. It will be necessary to ensure that any underground facility is adequately drained and will not flood. The ease with which this requirement can be met, and the associated cost, will depend upon the groundwater fluxes. These will depend upon the hydraulic head gradients and the permeability of the rock, which will in turn depend upon the existence, frequency and nature of fractures, faults and weathered zones in the rock. The water that is pumped or drained from an underground facility will need to be managed, most likely by pumping or allowing to flow into a natural river or lake or perhaps pumping it into the shallow groundwater system elsewhere. However, before this can be done, steps will need to be taken to ensure that the naturally-occurring dissolved solutes in the drained water do not exceed groundwater quality standards. NB this is for “clean” water drainage water; it will be important to show that the waters have not come into contact with wastes or effluents and do not contain any additional contaminants arising from the wastes.

Another potentially safety-relevant difference between underground facilities and surface facilities is the possible emission of radon gas from the rock. Accumulations of this gas in buildings or underground cavities could potentially pose a health hazard for workers. However, this hazard can be avoided by adequate ventilation. The magnitude of the radon emissions from the rock will depend upon the characteristics of the rock at the site, principally the natural concentrations of uranium and thorium in the rock and the nature of the rock’s porosity. Generally, the higher the concentrations of uranium and thorium, the higher will be the radon flux for a given rock porosity. However, it should be noted that even if the rocks upon / within which a store is constructed have low concentrations of uranium and thorium, there might still be elevated emissions of radon generated in other rocks elsewhere and then transported to the store via permeable pathways in the rock.

4.5.2 Security-Related Issues

Two main classes of security threat exist:

- those that might originate outside the site boundary, such as civil protest; and
- those that might originate inside the boundary, such as sabotage.

There are design basis events associated with these different kinds of potential attack, including theft of material, insider sabotage (maybe leading to radiological release) and use of weapons. The store and security arrangements will be designed to counter these different kinds of threat. Aircraft impact is generally “beyond design basis”. It is noteworthy that a threat of attack can cause significant impacts, even without any intent of actual attack.

The physical characteristics of a site will influence security only indirectly. For example, constructing a store on a hill top may make a store a more visible target for attack; that is the topography has an indirect impact upon security. The characteristics of the area surrounding a store may also influence the security. For example an urban store location may potentially allow attackers more opportunity to come into close proximity to the store. However, these influences are not easy to judge in a generic sense. There could, for example, be security benefits to locating a store in an urban environment, such as closer proximity to security personnel and facilities.

In contrast to the physical characteristics of a locality, a store concept has a more direct impact upon security. There is a clear distinction between surface store concepts and underground store concepts from the perspectives of:

- active security, which is potentially required to a relatively great degree by surface storage, compared to underground storage; and
- passive security, which can be achieved relatively easily (and hence with less cost) for underground storage compared to surface storage.

Generally, active security means that personnel are present to guard the facility. Some active security is always required, but how much depends on the balance between active and passive security chosen and the requirements of regulations. To achieve security by active means there is a relatively low initial cost, but there is life time expenditure and commitment. The overall security requirements for an independently sited store are less onerous than for a combined reactor and store site, but a store constructed at a reactor site would benefit from the existing security arrangements.

Passive security arrangements include fences and physical restrictions to store access. Concepts may have passive security such as barriers to access, and site boundaries that are remote from the store itself, so that there is less vulnerability to weapons fired from site boundary. There may be a large initial capital cost, but thereafter costs would be incurred only to maintain the facilities. Passive security would be less likely to fail due to human issues (error, lack of staff etc.) than active security. It would also be less likely to cause accidental damage than active security (e.g. collateral damage to surrounding property caused by an active response to civil unrest). It should be noted that passive security can be achieved by appropriate package design as well as appropriate store design and that both need to be matched to the locality, in particular whether the facility is above-ground or below ground.

Other than the indirect implications of store localisation mentioned above, localisation impacts upon security by virtue of the non-geological requirements and attributes described in Section 4.1 and Section 4.3.2 respectively. That is:

- proximity to urban populations;
- proximity to required infrastructure;
- distance between waste sources and store;
- availability of competent workers to construct and operate the facility; and
- remoteness from other human activities / sensitive environments.

However, while the relationship of some of these factors have a clear relationship with respect to security, in other cases the relationship is less clear. For example, increasing transport distances between the origins of the waste and the store will pose increasing security risks, at least in an absolute sense (experience internationally and in Norway shows these risks are small and can be managed effectively). Waste is clearly more vulnerable to attack when it is being transported than when it is emplaced within a store, and the opportunities for attacks will increase with increasing distance. On the other hand, the proximity to urban populations has a less clear impact upon security. As noted above, on one hand there might be more security threats in urban areas, but on the other hand security service personnel and facilities (police, military etc.) are likely to be more numerous.

4.5.3 Emergency Preparedness-Related Issues

A site's location will influence emergency preparedness primarily as a result of the non-geological requirements and attributes described in Section 4.1 and 4.3.2. A key discriminant among sites will be the ease with which emergency responses can be undertaken. A distinction is also made between non-radiological emergencies and radiological emergencies. For the existing sites of Kjeller, Halden and Himdalen arrangements for both non-radiological and radiological emergency responses are already in place. At a new site it is likely that capabilities to respond to non-radiological emergencies will already exist nearby, especially if there are other industrial activities in the area; most non-radiological emergencies at an intermediate waste store will be similar to non-radiological emergencies in other industries. However, new local arrangements to respond to radiological accidents would need to be implemented at the site.

The ability and time to respond will depend upon the location of the site with respect to emergency facilities. Urban sites may allow quicker security / emergency responses, but also there could be greater disruption and potentially larger numbers of people could be affected by an emergency. The response to a transport emergency would depend in part on the location and the characteristics / lengths of transport routes. Emergency escape routes from and access to store areas would be an important factor influencing emergency responses, and hence it might be more challenging to respond to certain kinds of emergency in an underground facility than in a surface one.

The vulnerability of a store to impacts from natural hazards, and the likelihood that these natural hazards are realized will depend to some extent upon the characteristics of the location. Relevant natural hazards include natural fires (e.g. in caused by lightening in forests surrounding the facility), flood, landslip/rockslide etc. Also power or communications loss as a result of natural phenomena could cause or contribute to an emergency situation. Passively safe systems, with minimum handing operations etc. are less likely to result in emergencies than systems that require action to ensure safety.

Neighbouring facilities may potentially pose hazards to a waste store. The possible characteristics of accidents at neighbouring facilities and their potential to cause an emergency situation at the waste store need to be assessed during emergency response planning. Conversely, the possibility that the consequences of an emergency at the waste store might depend upon the nature of adjacent facilities and activities should be considered. However, localizing a store so that it is remote from other human activities would avoid potential hazards from neighbouring facilities.

Road accidents are the most likely issue of concern. The worst case is that an accident could cause a partial loss of shielding through container damage. However, the likelihood of this occurring is very small because transport casks are designed to withstand collisions and fire. Errors in loading / securing containers may potentially give rise to an emergency situation, although again the probability is judged to be very small. Road load / access route constraints may impact upon the probability of a road accident and the severity of the consequences should one occur. For example, it might be more difficult to respond to an accident that occurs in a narrow road tunnel than to an accident that occurs on a wide open road. An accident that was to occur in an urban area might be expected to have a higher probability of severe consequences than an accident that occurs in a rural area. Breakdown response has been considered, but is not considered to be a major risk.

When planning emergency responses, challenges to clean-up need to be identified and appropriate clean-up plans made. The nature of the area surrounding the store, including the characteristics of flora, fauna, water resources and human activities within the area, would impact upon the ease with which the consequences of an emergency could be mitigated. The population density could impact upon the response to an emergency, whether at the store itself, or adjacent to a transport route.

4.6 Implications of Increasing the Inventory to Include LLW and SL-ILW

Addition of LLW and SL-ILW to the inventory to be considered (in addition to SF and LL-ILW) has certain implications for the implementation of a particular storage concept at a given locality. Most of these implications are also relevant should final disposal be considered in addition to storage. However, disposal requires greater understanding of the long-term evolution of the materials inventory.

In detail, important issues arising from adding LLW and SL-ILW to the inventory are as follows:

- Introduction of LLW and SL-ILW to the scope will greatly increase the volumes of waste to be considered (albeit these volumes will remain small compared to the volumes generated by nuclear power programmes in other countries).
- Addition to the inventory will require a wider range of waste characteristics to be considered.
- LLW and SL-ILW will be very different waste forms and so treatment and storage / disposal concept requirements are typically very different than for SF and LL-ILW
- Compared to LL- ILW and SF, there are lower activities / risks associated with LLW and SL-ILW. Consequently, the balance of cost/benefit will be different for LLW and SL-ILW than for SF/LL-ILW in terms of treatment, storage and disposal: especially given volume differences, different options might be pursued reflecting differences in hazards and costs.
- Adding in LLW/SL-ILW will mean additional waste category-specific treatment, storage and/or disposal options will be required.
- The total activity of the additional LLW and SL-ILW will be still small; simple conditioning / encapsulation may be sufficient to achieve safety in the cases of LLW and SL-ILW.
- There may be hybrid options where LLW/SL-ILW is treated/stored/disposed as for LL-ILW and SF, but there will also be separate treatment options and so the complexity of the study is increased.
- There is a need to adequately understand LLW/SL-ILW volumes, materials and radionuclide inventories to understand differentiators between those options.
- The consideration of volumes includes post-treatment volumes. LLW needs less packaging than higher activity wastes, for the same disposal system. Also there are more options open for LLW treatment including volume reduction (see specific discussion below).
- It is more challenging to understand the chemical / geochemical evolution of LLW and SL-ILW, owing to the chemically more heterogeneous characteristics of these wastes compared to SF and to a lesser extent LL-ILW.

There is a need to minimise adverse interactions between the different kinds of waste if they are disposed of in the same repository (i.e. if there is co-location).

4.7 Implications of Considering Disposal

4.7.1 Requirements for Disposal

IAEA publishes general safety requirements for all forms of radioactive waste disposal (IAEA, 2011b). A safety guide is also published for geologic disposal (IAEA, 2011c) but not at present for near-surface disposal[4].

There are a total of 26 requirements specified by IAEA. Not all are relevant in terms of the KVU, because some relate to national Government and/or regulatory responsibilities. The key factors in terms of the KVU are those that correspond to disposal facility location and design, and are listed below. Those that emphasise the importance of safety in general terms have not been listed here as they are implicit in the more specific requirements.

- Requirement 5: Passive means for the safety of the disposal facility – the disposal facility should be designed, constructed, operated and closed in such a way as to minimise the need for action after closure.
- Requirements 6 and 15: Site characterisation must be undertaken to attain sufficient understanding of a disposal system (predictable and reliable design and environmental conditions) to give confidence in its performance.
- Requirement 7: Multiple safety functions – there must be multiple safety functions using a number of barriers with no undue reliance on any one.
- Requirement 8: Containment of radioactive waste – wastes must be contained so as to minimise the release of radioactivity to the accessible environment.
- Requirement 9: Isolation of radioactive waste – waste must be isolated from the surface environment for as long as possible.
- Requirement 10: Surveillance and control of passive safety features – surveillance of safety features is required so as to protect and preserve them in order to maximise their lifetime after closure.
- Requirement 16: Design of a disposal facility – a facility must be designed to contain the waste, be compatible with its environment, and to provide the required safety functions.
- Requirements 17, 18 and 19: Construction, operation and closure of the facility must be done in such a way as to achieve the planned safety functions.

[4] Here "near-surface disposal" means surface disposal, or below the ground surface at depths of up to a few tens of metres.

- Requirement 20: Waste acceptance in a disposal facility – criteria must be specified for waste packages and wastes so as to achieve safety targets.
- Requirement 21: Monitoring programmes at a disposal facility – information on key characteristics of the disposal system relevant to safety must be collected.
- Requirement 22: The period after closure and institutional controls – stewardship of the facility must be with minimal intervention so as to preserve passive safety features.
- Requirements 23 and 24: Consideration of the State system of accounting for and control of, nuclear material – the system must enable required security and surveillance of such materials without compromising safety performance.
- Requirement 25: Management systems that assure quality must be applied to the design, construction, operation and closure of the disposal facility.

The Safety Guide for geologic disposal (IAEA, 2011c) goes into more detail concerning the application of these requirements. Some aspects concern the underlying philosophy (the "safety approach"), and it also describes the role and importance in the safety case and safety assessment in the whole process of developing a disposal facility. Finally, it presents more detail on the activities required to achieve the requirements described above. From the perspective of the KVU, the most relevant additional discussion concerns siting requirements. Site-specific characteristics of importance include:

- **geological setting** – including uniformity and ease of characterisation, mechanical and other general physical properties;
- **susceptibility to future natural changes** such as seismicity, volcanism, neotectonics;
- **hydrogeological characteristics,** including the directions and fluxes of groundwater flow, so as to maximise the time for contaminants to return to the accessible environment;
- g**eochemical properties** that are compatible with the engineered materials, and so far as is possible aids the retardation of key radionuclides; and
- **potential for human activities** to disturb the disposal system (which should be minimised).

4.7.2 General implications of Considering Disposal

This section discusses the extent to which adding disposal to the scope places extra requirements on understanding of the inventory. Most of the issues are shared with those that are relevant for a KVU concerning long-term storage. However, in the case of disposal understanding of the materials inventory needs to support analysis of long-term evolution within a disposal system. Additionally, waste packaging requirements may be different for storage and disposal. Waste packages that meet safety requirements for the relatively short period over which a store is operated, may not necessarily be capable of fulfilling required safety functions over the much longer period that would relevant for final disposal. Furthermore, generally the environment (temperature, presence of groundwater, atmospheric characteristics etc.) will be very different in an actively managed store and in a final repository following closure. It is possible that a waste package that has been designed for a store may not be suitable for final disposal. Alternatively, even a package that would be suitable for deep disposal immediately after the package is manufactured and filled with waste, may not be suitable for final disposal after a prolonged period of storage; processes such as oxidation of metal package components during storage may render the waste package unsuitable for disposal. For example, if disposal of SF is carried out at the outset, then only waste packages suitable for disposal will be needed, but if extended (maybe 100 years) storage is undertaken first, then there may be a need to repackage before disposal.

The properties of the radioactive wastes (the inventory) that are important to know are related to the nature of the hazard and how it is controlled in a given context.

For waste stores, the timescales (decades) are such that physical containment can be assumed to be effective except in "fault" conditions (accidents or unexpected failures). Active management of the waste packages (e.g. monitoring, surveillance, environmental controls, security, repackaging) is a key component of mitigating the hazard.

For disposed wastes, the timescales of relevance are much longer with safety assessments typically considering periods of many thousands of years to a million years. Container integrity and human intervention cannot be relied upon to contain the radionuclides, and the safety of the disposal facility depends on passive engineered barriers and natural features such as the geology. However, on such timescales shorter-lived radionuclides will decay and thus the overall hazard will reduce.

With this in mind, the key information requirements for disposal go beyond those for storage and relate to processes that can involve the degradation of the waste form and its surroundings, and the release of contaminants. The waste composition will therefore be important, as the materials present can affect the release pathways – for example, by generating gas (e.g. by organic degradation or corrosion). The location of contamination in the waste materials is also important. Activation radionuclides like Ni-63 or Zr-93 will be present in the solid matrix of metals, for example, and therefore will be released more slowly than surface contamination. The chemical properties of the materials and encapsulant are also important, because these are capable of increasing the retention of key radionuclides by sorption. Finally, the radionuclides of interest to long-term safety assessments required for repositories are different from those necessarily considered when assessing the safety of stored wastes. In particular, long-lived beta-emitting nuclides (e.g. Tc-99, I-129) and alpha-emitting nuclides (uranium, plutonium and americium isotopes) are relatively more important than the (often relatively short-lived) gamma-emitters which dominate the radiological hazard of most wastes in stores.

4.7.3 Specific Implications of LLW Disposal

It is generally accepted that LLW should be disposed of as soon as practicable, because disposal solutions are available in most countries and there are no significant benefits to be gained from a period of decay storage[5]. LLW also arises in relatively large volumes so storage is expensive.

Because LLW is typically consigned for disposal directly, the waste properties of interest from the perspective of disposal performance are well established, and are usually specified as Waste Acceptance Criteria (WAC) for LLW disposal facilities. WAC set limits, conditions and controls on the properties of waste with a view to ensuring that they are compatible with (and if possible contribute to) a LLW facility's long-term performance. Some of the typical properties relevant to waste disposal are:

- **Radionuclide inventory** – It is typically necessary to have a good knowledge of a wide range of specific radionuclides, including long-lived radionuclides.
- **Materials** – Materials that can degrade and influence repository conditions are important, and include cellulosic materials, plastics and metals, noting that LLW is often more heterogeneous than ILW or SF.
- **Encapsulant** – The waste encapsulant provides a key role stabilising the wastes and providing chemical conditioning for radionuclides, as well as filling voids and therefore ensuring a physically robust wasteform.
- **Container** – The main role of the waste container during LLW disposal is for operational waste handling and containment of radionuclides during the pre-closure phase of the facility.

The evolution of the physical and chemical conditions in LLW repositories over timeframes of hundreds to thousands of years is a key issue for LLW disposal. Some of the most important aspects include:

[5] Unless the LLW arises from industrial or medical uses, in which case it is possible to deliberately select short-lived radionuclides that can be decay-stored to safe levels, e.g. Ir-192 for industrial radiography has a half-life of 73.83 days.

- potential for the generation of bulk gas (which can cause engineering to fail) and radioactive gas (a pathway for radionuclide release) as a result of organic decomposition and corrosion reactions;
- chemical conditioning of water in the repository as a result of cementitious materials, in particular grouts, which helps to retain key radionuclides;
- mobilisation of key radionuclides due to the presence of trace chemicals in wastes, such as decontamination agents;
- physical degradation of structures, resulting in an increase in hydraulic and gas permeability.

4.7.4 Specific Implications of ILW Disposal

ILW is a broad category that includes wastes with greater concentrations of radionuclides than LLW, but which are not heat-generating. ILW is usually split into sub-categories according to either the half-life of dominant radionuclides, or the type of radioactive emissions.

In relation to ILW storage, the most appropriate way of splitting the ILW category up is according to the key operational consideration – the dose rate. For example, in the UK ILW is often categorised as “contact handled” (low dose rate, e.g. dominantly alpha emitters) or “remote handled” (high dose rate, e.g. reactor hardware).

In relation to ILW disposal, the most common distinction is in terms of the half-life of dominant radionuclides. Wastes with radionuclides dominantly less than 30 y half-life are referred to as SL-ILW (short-lived), with other wastes being LL-ILW (long-lived). SL-ILW includes sealed sources (Co-60, Cs-137 etc.) and can include some activated metals[6]. The distinction by half-life is important in relation to disposal because in some circumstances the case can be made that short-lived wastes, even if high in activity, can be disposed of in a near-surface facility because the radioactivity will decay very substantially whilst control is maintained over the facility (typically assumed to be 300 y). The question of categorisation is important, because it can determine the subsequent management options for the wastes.

For all types of ILW, the properties discussed in relation to LLW are relevant, but there are some different considerations reflecting the different types of wastes concerned:

- **Radionuclide inventory** – short- and long-lived radionuclides need to be included, and the key radionuclides will typically be the same as for LLW.

[6] There is consequently an overlap with “remote handled” ILW, because many of the dominant short-lived radionuclides such as Co-60 and Cs-137 are strong gamma emitters.

- **Materials** – ILW wastes are typically less heterogeneous than LLW (consisting, for example, of ion exchange resins, activated metal hardware etc.) and are thus typically much more easily and reliably characterised.
- **Encapsulant** – Waste encapsulant performs the same chemical conditioning function as for LLW, but may also be important as a radiation shield.
- **Container** – ILW containers are typically of higher integrity than LLW containers (e.g. ILW containers may be composed of stainless steel rather than mild steel), although this is primarily due to operational safety considerations (mainly relevant to storage) by enhancing shielding and providing greater resistance to accidents.

As with LLW, this information is a key to understanding the long-term behaviour of the waste packages in a disposal facility. Similar processes and issues are of importance when considering ILW (physical integrity, chemical conditions, and reactions). Because ILW is typically more homogeneous in nature, there may be fewer uncertainties in its long-term evolution and it is certainly more readily modelled.

4.7.5 Specific Implications of SF Disposal

An important distinguishing feature of SF is that it is heat-generating. The heat output of a given quantity of SF depends upon:

- the characteristics of the fuel (e.g. increasing ^{235}U enrichment results in increased heat output);
- the degree of burn-up (increasing burn-up causes increasing heat output); and
- the time that has elapsed since the fuel was removed from the reactor (heat output decreases with time).

Light-water reactors used to generate electrical power (Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs)), and AGRs typically have fuel that is enriched to around 3% U^{235}. The JEEP 2 fuel has similar enrichment, but unenriched uranium was used for JEEP 1 and first loading of the HBWR, while the present HBWR fuel is 6% U^{235}.

Among reactors used to generate electrical power, burn-ups in excess of 50 GWd/tHM are common in PWRs and BWRs, and up to 40 GWd/tHM has been attained in AGRs (IAEA, 2011d). In contrast, the SF generated by the Norwegian research reactors generally has much lower burn-ups. The present JEEP 2 fuel has burn-ups of around 15 GWd/tHM, whereas the present HBWR fuel has burn-ups of around 40 GWd/tHM. However, the JEEP 1 fuel had burn-ups of only between 1 MWd/tHM and 1 GWd/tHM.

Overall, at any given time following removal from the reactor the heat output from the Norwegian fuel will be considerably lower than that of fuel produced by power reactors. However, there are considerable differences between the heat outputs of different kinds of Norwegian fuel (reflecting differing degrees of enrichment, burn-up and duration of storage). Much of the Norwegian fuel has already been stored for a considerable period of time (for between 50 and 60 years in the case of JEEP 1 fuel), so that its present heat output is already well below the values when it was removed from the reactor. The natural uranium produced by JEEP 1 in particular has a very low heat output owing to its lack of enrichment, very low burn-up and long duration of storage.

Generally, whilst the fuel's heat output drops very rapidly following removal from a reactor, it still requires cooling in ponds for years, and will remain generating heat even in the future when disposed. For stores, the heat output is managed by cooling with water initially, whilst air cooled stores can be used after some years. When disposed, the local effects of heating need to be taken into account in the repository design. This can affect the spacing of disposals, for example, and requires consideration in terms of container and backfill performance.

SF also has relatively high dose rates and a large inventory of alpha emitters, but these aspects can be managed in largely the same manner as ILW, with appropriate shielding and high integrity containers.

Internationally, most fuel elements themselves have high integrity cladding which is designed to resist corrosion in aqueous conditions. However in the case of the Norwegian SF from the JEEP reactors, the fuel is clad in more reactive Al; the HBWR fuel is clad using Zircaloy. In wet stores, no other containers are used, although high integrity casks are required for transport. The Norwegian fuel is mostly in dry storage; all the metallic fuel and Al-clad fuel, apart from that removed from JEEP 2 in the last 6-12 months (which is stored in wet pools), is presently stored dry (Task 1 Report). The Zircaloy-clad fuel from the HWBR has, by contrast, been in wet-storage for up to several decades (Task 1 report). Whatever the storage, the main consideration is to maintain adequate cooling, shielding and environmental conditions that prevent the degradation of the fuel elements themselves.

Different countries have considered various approaches for disposal of SF, but generally approaches involve the SF being put into disposal containers that may or may not be surrounded by separate overpacks forming part of the overall waste packages to be emplaced in a repository (NEA, 2003). There are two broad groups of container ± overpack (Bond et al., 2010):

- "Longer-lived waste package/overpack" for a waste package (comprising a waste form and waste container, as defined by IAEA, 2003a), or waste package in combination with an overpack, that is expected to provide containment for over 100,000 years, and potentially to the end of the period considered by any safety assessment.

- "Shorter-lived waste package/overpack" for any other waste package, or waste package in combination with an overpack, that is expected to provide some containment following repository closure, but for a shorter period (typically in the order of 100 to 1,000 years).

Whether or not there is a separate overpack that forms part of the waste package depends upon the approach to handling and emplacement within a repository and the functions of other barrier components in the considered disposal concept. For example, an overpack that forms an integral part of the waste package may be needed if the container itself does not provide sufficient shielding on its own.

Because of the high activity of the SF, and its comparatively low volume, whether longer-lived or shorter-lived waste packages / overpacks are employed an appropriate strategy is to seek to maximise the period of containment during which there is no release of radioactivity from the repository. This goal is met by ensuring that the EBS and natural barriers work in concert. The choice of a longer-lived or shorter-lived waste package / overpack depends upon the different safety functions of the other barriers to be employed in a particular concept. For example, in concepts that give greater emphasis to the EBS, longer-lived waste packages / overpacks may be employed, whereas in concepts that give greater emphasis to the geosphere barrier, shorter-lived waste packages / overpacks may be used. The KBS-3 concept that has been developed for use in crystalline rock in Sweden and Finland has waste containers (copper canisters) that can be considered longer-lived; they are designed to provide containment for 100,000 years or more following emplacement within the repository.

In summary, given these considerations, many of the key requirements for SF disposal are the same as those for LLW and ILW, but there are a number of important differences:

- **Inventory** The identities of the radionuclides of interest in SF will be the same as for other types of waste, but the inventory (quantities and proportions of these radionuclides) will be different. The inventory itself can be computed directly for many reactors by neutron modelling codes (the only complicating factor could be if the fuel casing has leaked in which case radioactive contamination may be present on the whole assembly).
- **Materials** The SF materials are well defined, but need to be considered explicitly as individual materials have particular radiological characteristics due to the neutron activation of their components. In the case of the Norwegian SF, Al-clad fuel will need to be de-clad before emplacement in a disposal

container. The Zircaloy-clad fuel could potentially be emplaced in a disposal container without de-cladding.

- **Encapsulant** SF is usually emplaced in high-integrity waste canisters without further encapsulation. However, in some countries consideration has been given to encapsulation of metallic fuels within the containers, using cement or polymer materials. It is generally a requirement to ensure that the SF is dry when it is sealed within its container.
- **Container** Various designs of SF container have been developed, but all are intended to be manufactured to a very high quality in order to preserve integrity for the period required by the concept (100,000 years or more in the case of copper canisters employed in the KBS-3 concept).

At any chosen repository site the different components of the EBS must be carefully matched to one another and to the natural barrier(s) present, to ensure that all barriers work together to ensure safety. Furthermore, it must be established not only that the different barriers will function as required at the present, but also that they will continue to function as required throughout the period for which the SF remains hazardous. To achieve these goals the controls on repository conditions at the present and in the future must be understood and allowed for in disposal concept selection and repository design. Such an understanding must be founded upon a significant programme of site characterisation and supporting research, which is likely to take many years (in many countries such site characterisation and / or research programmes have lasted for several decades).

Given the widespread occurrence of crystalline bed-rock in Norway and the limited spatial distribution of sedimentary rock to depth, it seems most likely that any Norwegian repository for SF would be constructed in fractured crystalline rock. In such a case, based on experience in other countries, notably Sweden and Finland, it seems likely that the KBS-3 concept could be employed in Norway. That is, longer-lived copper canisters emplaced in horizontal or vertical deposition holes and surrounded by a bentonite buffer could be used. The deposition holes would be excavated in tunnels developed at depths of several 100 m and sited so to avoid major fractures.

A possible disposal alternative disposal solution for SF (or HLW) that is being considered in several countries is disposal in deep boreholes (Nirex, 2004; Brady et al., 2009; Arnold et al., 2013). A number of different variants of deep borehole disposal have been proposed, such as:

- variants in which the waste is emplaced after a prolonged period of cooling, so that the rock is not melted and sealing is provided by artificial barriers, such as cement and bentonite; and

- variants in which the waste is emplaced after little cooling, so that within the borehole sufficiently high temperatures are attained to initially melt the rock, thereby providing, after the melted rock subsequently cools and solidified, a low-permeability seal (which is supplemented by artificial barriers at shallower depth).

Given the relatively low heat generated by the Norwegian SF, only the first group of variants are relevant to disposal in Norway. Such a concept would involve drilling deep (several km) boreholes with diameters where the waste canisters are to be emplaced of c. 45 cm. Waste canisters would be placed in the lower portion of the borehole, while the upper portion is sealed, most likely with a combination of bentonite and concrete. It should be noted that the thick-walled canisters, such as the copper canisters used in the KBS-3 mined repository concept, could not be used in a borehole and instead the waste would need to be emplaced in thin-walled canisters. This requirement would need to be born in mind when designing packaging for storage and re-packaging facilities for subsequent disposal.

A single borehole with a depth of c. 5 km could potentially accommodate up to several hundred waste canisters (Brady et al., 2009; Arnold et al., 2013). Hence it is not unreasonable to suppose that all the Norwegian SF (or HLW generated from it) could be emplaced within a single deep borehole.

Such a borehole disposal concept has several benefits for the disposal of small quantities of high-activity, long-lived wastes, notably:

- It can achieve a very high degree of waste isolation.
- Potentially the concept could be much cheaper to implement than a mined repository, at least if the volumes of waste are very small, as in Norway.
- For a given quantity of waste, the engineered barriers needed in a borehole have much smaller volume (i.e. they amount to the borehole seals) compared to a mined repository.
- The footprint of a borehole would be much less than the footprint of a mined repository that would be needed to accommodate the same volume of wastes.

However, there are also a number of possible disadvantages of borehole disposals concept, among them:

- Borehole disposal concepts are all relatively immature and none has been research as extensively as any of the commonly proposed concepts for mined repositories (e.g. KBS-3).
- Related to this drawback, there is a lack of a comprehensive operational and post-closure safety case for any borehole disposal concept.

- It has not been shown that waste packages could be emplaced sufficiently reliably within a deep borehole. If a waste container were to become stuck within the borehole at a depth shallower than the planned emplacement depth it may prove challenging to retrieve the waste (by way of comparison, tools commonly become stuck during the drilling and testing of deep boreholes drilled for other purposes).
- Wastes could not be contained in shielded canisters within a borehole owing its narrow width. Hence, it would be necessary to transfer the waste canisters from their shielding at the point where they enter the borehole.
- Whereas it is possible to allow for retrieval when designing a mined repository according to many of the commonly proposed concepts, this is much more challenging for a deep borehole disposal concept; deep boreholes are typically proposed with the intent of making retrieval difficult.

The safety case for borehole disposal concept would place great emphasis on the great depth of burial, which ensures that the wastes remain isolated from the accessible environment. Given the relatively small quantities, a single borehole in Norway could be sufficient to accommodate all Norwegian SF (or the HLW produced by its reprocessing).

Reprocessing is an option for dealing with the Norwegian SF (see the Task 2 report). If adopted, this option would produce concentrated liquid solutions of nuclear fission products that must be immobilized in a solid phase. In other countries this solidification is usually achieved by vitrification to produce a glass matrix (e.g. Ojovan and Batyukhnova, 2007), although there are alternative means of solidification, such as the so-called SYNROC process (Ringwood et al., 1979). The solidified HLW will be in a shielded container. Such containers would be similar to the SF containers, except that the internal structure of an HLW container would be different to one for SF; there would be little voidage within an HLW container, whereas SF fuel would normally be held within an internal structure and there would be much more voidage.

Although the KBS-3 concept has been developed in Sweden and Finland for SF rather than HLW, copper canisters that are similar to the KBS-3 SF canisters have been proposed for HLW (e.g. Nirex, 2005; Fries et al., 2007). In the copper SF canisters SF assemblies are held within a cast iron insert, which besides supporting the SF are intended to give the overall waste package strength. In a copper canister for HLW the vitrified waste could be accommodated within a cast iron container placed within the copper one in order to impart mechanical strength.

Reflecting their generally similar characteristics of SF and HLW containers, the handling and disposal of these containers will also be similar. Furthermore, the disposal concept adopted for HLW could be very similar to one adopted for SF (e.g. the KBS-3 concept could work just as well for HLW as for SF).

4.7.6 Addition of Disposal to Scope: Location/Siting/Characterisation

Guidance for siting repositories is broadly similar to that for stores outlined in IAEA (2006c) and summarised in Section 4.1, but there is specific guidance for surface facilities (IAEA, 2003c) and deep facilities (IAEA, 1990; IAEA, 2011b; IAEA, 2011c).

Whereas it would be technically possible to construct a store almost anywhere (given sufficient resources), not all localities would be suitable to site a repository. This difference means that selecting options for repository locations is much more challenging than selecting options for store locations. Repository siting would require a prolonged process, involving information gathering and stakeholder engagement.

General stages in the siting of underground repositories are:

1. a conceptual and planning stage;
2. an area survey stage, leading to the selection of one or more sites for more detailed consideration;
3. a site investigation stage of detailed site-specific studies and site characterisation; and
4. a site confirmation stage.

For stores a broadly similar process may be followed, except that the level of detail will depend upon the nature and volumes of wastes to be stored. IAEA (2006c) notes that a proposer of a small facility may not necessarily be expected to go through a formal siting process.

Waste stores are commonly sited at the nuclear facilities (e.g. nuclear power plants) where the wastes are generated. There are several important reasons for this, including:

- The logistics of waste production and management will often require at least some storage capacity to be present at or very close to the site of waste production. Typically there may be little advantage (and several important disadvantages, notably the needs for transportation and to obtain public acceptance) in subsequently transferring wastes to another storage facility.
- There is often a relatively high level of stakeholder acceptance of nuclear industry activities near to existing nuclear facilities.

- Much of the infrastructure required to operate a store (e.g. security infrastructure, waste handling infrastructure) already exists at an existing facility.

Sites near to existing nuclear facilities are also often considered for waste repositories. Examples include:

- the LLWR, a near-surface repository for LLW near to Sellafield in northwestern England (LLWR, 2011);
- a deep (c. 680 m) repository for ILW and LL-LLW proposed for the Bruce site in Ontario, Canada (NWMO, 2011); and
- deep (c. 450 m – c. 500 m) SF repositories proposed for Forsmark in Sweden (SKB, 2011) and Olkiluoto in Finland (Posiva, 2012)

Sites that have surface characteristics appropriate for the safe operation of nuclear facilities, such as power plants, will also generally have characteristics suitable for the construction and operation of surface stores and near-surface repositories for shorter-lived / less hazardous radioactive waste (LLW and some SL-ILW). However, it is not necessarily the case that such sites will have sub-surface characteristics that are suitable for repositories for long-lived and more hazardous wastes (LL-ILW and SF). In particular, the accessible sub-surface conditions (geomechanical, geothermal, hydrogeological and geochemical characteristics) at the relevant depths of several hundred metres may be unsuitable for:

- cost-effectively constructing a repository of the required volume (e.g. rock strength is low and hence construction is difficult and costly);
- maintaining low groundwater fluxes through the repository;
- providing long groundwater / gas travel pathways from the repository to the surface and easily accessible shallow sub-surface;
- ensuring the chemical and physical stability of engineered barriers;
- adequately retarding the migration of radionuclides that may leave the waste canisters;
- providing stable conditions over the long time periods for which the wastes will be isolated.

In Norway, any disposal must be at a site remote from the reactor facilities, which are in urban areas where public acceptance is known to be lacking. In contrast, potentially a new store could be sited at these reactor sites even in the absence of public acceptance, should no other locality be identified; this follows from the fact that the wastes are already stored at the reactor sites, or will be produced at these sites.

A key issue for disposal of any kind of waste is the need to consider much longer timescales in the development of a safety case. A consequence of the extended timeframe is that considerable effort needs to be expended to assess environmental change and part of this involves establishing the past geological history of a site over a comparable timescale to a safety assessment (often around c. 1 Ma for LL-ILW and SF). Additionally, the site characterisation for a deep repository, as opposed to a shallow one, generally needs to consider a much wider area. This need reflects the fact that, given the long transport pathways for any radionuclides that leave the engineered barrier system (EBS) and the long time periods considered, a much wider area could potentially be impacted by any radionuclide releases. Conversely, over this long time period, a deep repository could be affected by processes that operate much further away than in the case of a shallow repository. Examples of such processes are groundwater abstraction or land use changes that impact upon groundwater recharge and hence fluxes.

Generally, the deeper a store or repository, the more time-consuming and costly will be the site characterisation. Characterisation of underground environments will involve a combination of:

- surface-based, non-invasive investigations, including:
  - literature surveys;
  - surface mapping; and
  - geophysical investigations (e.g. seismic surveys, radiometric surveys and electromagnetic surveys);
- surface-based, invasive investigations, involving borehole drilling, sampling and testing (including rock coring, sampling and analysis, groundwater sampling and analysis, hydrogeological testing and geophysical logging);
- underground investigations, during facility construction.

Overall, these factors imply that:

- the time frame and costs of site characterisation for a surface store will be less than for an underground store;
- the time frame and costs of site characterisation for disposal will be greater than for a store; and
- the time frame and costs of site characterisation for a deep repository will be greater than for a shallow repository, which in turn will be greater than for a near-surface repository.

On the basis of what is known now, it is possible to provide an initial ranking/prioritisation of areas most likely to yield a technically suitable site for a repository, taking into account the other factors identified to date for the KVU considering (transport, local available expertise, however not too close to population centres etc.). Approximate costs and timescales can be based upon estimating characterisation work likely to be required, and the potential concepts that are plausible for different rock types assuming initial / generalised assumptions on geology (e.g. assuming site x offers a suitable granitic geological unit for a disposal facility of type y). Some of the considerations in the existing location discussions for storage (e.g. distance from technical expertise) will remain.

4.8 Recommendations for Localisation

The availability of geoscientific information across Norway is variable and, without bringing all relevant data sets up to the same standard by means of new site investigations, it is impossible to carry out a detailed country-wide comparison of potential siting areas on a consistent basis. The required site attributes that have been considered in this analysis were selected to be appropriate for an initial assessment of localisation options and to ensure that, as far as possible, relevant information needed to judge them is available for most of Norway.

An intermediate waste store of some kind could be located within any Norwegian county provided that sufficient resources can be devoted to the task.

Given that crystalline bedrock (both metamorphic and igneous rocks) is very widely distributed throughout Norway and would have certain advantageous characteristics (low matrix permeability, high strength when unweathered, many varieties of crystalline rock show relatively little heterogeneity either laterally or vertically), there is no advantage to seeking a site with alternative bedrock types.

Fracture zones and faults will often (though not always) have characteristics that are unfavourable for siting an underground store; these geological structures will usually have unfavourable geomechanical properties (lower strength) and may have unfavourable hydrogeological characteristics (higher permeability) compared to unfractured and faulted rock. While the occurrence of these kinds of geological structure would not prevent the construction of an underground store, they would make it more complex and costly. It will be impractical to avoid all faults and/or fracture zones during siting, but it is recommended that larger-scale faults and fracture zones (with traces of 100’s of metres and above) are avoided when siting.

Zones of deep weathering (which may extend to depths of up to 200 m along fracture zones and faults) also have geomechanical characteristics (lower strength) and hydrogeological properties (higher permeabilities) that are unfavourable for siting an underground store compared to unweathered rock. Once again, the occurrence of such weathered zones would not prevent the construction and operation of an underground store, but they would add to the complexity of construction and hence the costs. Therefore, it is recommended that these zones are avoided during siting.

The ease of constructing surface facilities would be less impacted by faults and fracture zones, or by zones of deep weathering. However, such geological features could still influence the nature of foundations that are needed owing to being mechanically weaker than unaffected rock. Again, for surface stores it is recommended that larger-scale faults and fracture zones are avoided when siting a facility.

The overall cost of waste management includes not only the costs of interim waste storage but also the cost of final disposal. It is recommended that the approach to final disposal should be taken into account when identifying the most appropriate store locality. Relationships between different kinds of intermediate waste store options and final disposal options are shown in Table 4-5.

Table 4-5 Relationship between different store options and final disposal options.

Waste	Store Options			Repository Options		
	Surface Store	Shallow Underground Store (Few 10's of m)	Deep Underground Store (Several 100 m)	Surface Repository	Shallow Underground Repository (Few 10's of m)	Deep Underground Repository (Several 100 m)
SF	√	√	√	x	x	√
LL-ILW	√	√	√	x	x	√
LL-LLW	√	√	√	x	x	√
SL-ILW	√	√	√	(√)	√	(√)
LLW	√	√	√	√	√	(√)

√= Viable for waste type; (√)Potentially viable but not likely considered; x = Not likely viable

Type of repository that could be constructed after a particular kind of store – same site or different sites

Type of repository that could be constructed after a particular kind of store – same site only

References

Arnold, B.W., Brady, P., Altman, S., Vaughn, P., Nielson, D., Lee, J., Gibb, F., Mariner, P., Travis, K., Halsey, W., Beswick, J., and Tillman, J., 2013. Deep borehole disposal research: demonstration site selection guidelines, borehole seals design, and RD&D Needs. Sandia National Laboratories Report to USDoE, FCRD-USED-2013-000409, SAND2013-9490P. /Dxxx/

Baldwin, T., Chapman, N., and Neall, F., 2008. Geological disposal options for high-level waste and spent fuel. Galson Sciences Report to the Radioactive Waste Management Directorate of the Nuclear Decommissioning Agency, 0736-1 Version 1.1. /Dxxx/

Bergan, G., Bjørlykke, A., Foshaug, E., Kostøl, E., Kveseth, K., Martiniussen, E., Pettersen, E.O., and Pretlove, B., 2000. Vurdering av strategier for sluttlagring av høyaktivt reaktorbrensel: Utredning fra et utvalg oppnevnt ved kongelig resolusjon 22. desember 1999. Avgitt til Nærings- og handelsdepartementet desember 2001. Norges offentlige utredninger 2001: 30. /D047/

Bergstrøm, B, Olsen, L., Sveian, H., Gustavson, M., and Gjelle, S., 2009. Geology and landscape around the Arctic Circle in Norway. Geological Survey of Norway (NGU) Report, 2009 Revision (of the original 1995 report). /Dxxx/

Bond, B., Egan, M.J., Metcalfe, R., Robinson, P.C. and Towler, G., 2010. Understanding controls on the performance of engineered barrier systems in repositories for high-level radioactive waste and spent fuel. Environment Agency of England and Wales Science Report SC060055. /Dxxx/

Brady, P.V., Arnold, W.W., Freeze, G.A., Swift, P.N., Bauer, S.J., Kanney, J.L., Rechard, R.P., and Stein, J.S., 2009. Deep borehole disposal of high-level radioactive waste. Sandia National Laboratories Report, SAND2009-4401. /Dxxx/Cronstrand, P., and Anunti, A., 2014. Storage concepts for the Norwegian inventory of spent fuel and LLILW. KVU Task 3 report. SEW 14-066. /Dxxx/

Fossen, H., Mangerud, G., Hesthammer, J., Brugge, T. and Gabrielsen, R.H., 1997. The Bjorøy Formation. A newly discovered occurrence of Jurassic sediments in the Bergen Arc system. Norsk Geologisk Tidsskrift, 77, 269-287. /Dxxx/

Fries, T., Claudel, A., Weber, H., Johnson, L., and Leupin O., 2007. The Swiss concept for the disposal of spent fuel and vitrified HLW. Proceedings of the International Conference on Underground Disposal Unit Design & Emplacement Processes for a Deep Geological Repository, 16-18 June 2008, Prague. 3-1 to 3-9. /Dxxx/

Hicks, T.W., Baldwin, T.D., Hooker, P.J., Richardson, P.J., Chapman, N.A., McKinley, I.G. and Neall, F.B. (2008). Concepts for the geological disposal of intermediate-level radioactive waste. Galson Sciences Report to the Radioactive Waste Management Directorate of the Nuclear Decommissioning Agency, 0736-1 Version 1.1. /Dxxx/Huutoniemi, T., 2014. Radioactive waste inventory in Norway: Technical report, KVU on interim storage in Norway, Task 1. STUDSVIK/N-14/246. /Dxxx/

IAEA, 1990. Siting, design and construction of a deep geological repository for the disposal of high level and alpha-bearing wastes. IAEA TecDoc Series Publication IAEA-TECDOC-563. /Dxxx/

IAEA, 1996. International basic safety standards for protection against ionizing radiation and for the safety of radiation sources. IAEA Safety Series No. 115, IAEA, Vienna (1996). /Dxxx/

IAEA, 2002. Preparedness and response for a nuclear or radiological emergency safety requirements. Safety Standards Series No. GS-R-2, IAEA et al., 2002. /Dxxx/

IAEA, 2003a. Radioactive waste management glossary. International Atomic Energy Agency, Vienna. /Dxxx/

IAEA, 2003b. Site evaluation for nuclear installations. IAEA Safety Standards Series Safety Requirements No. NS-R-3. /Dxxx/

IAEA, 2003c. Considerations in the development of near surface repositories for radioactive waste. IAEA Technical Report Series No. 417. /Dxxx/

IAEA, 2006a. The management system for facilities and activities. IAEA Safety Standards Series No. GS-R-3. /Dxxx/

IAEA, 2006b. Application of the management system for facilities and activities. IAEA Safety Standards Series No. GS--3.1, IAEA, Vienna. /Dxxx/

IAEA, 2006c. Storage of radioactive waste. Safety Guide WS-G-6.1. /D191/

IAEA, 2009. Predisposal management of radioactive waste: general safety requirements. International Atomic Energy Agency Safety Standards Series No. GSR Part 5. /Dxxx/

IAEA, 2011a. Storage of spent nuclear fuel. specific safety guide SSG-15. /D259/

IAEA, 2011b. Disposal of radioactive waste specific safety requirements. IAEA Safety Standards No. SSR-5, 2011. /Dxxx/

IAEA, 2011c. Geological disposal facilities for radioactive waste. IAEA Safety Standards No. SSG-14, 2011. /Dxxx/

IAEA, 2011e. Impact of high burnup uranium oxide and mixed uranium-plutonium oxide water reactor fuel on spent fuel management. IAEA Nuclear Energy Series, No. NF-T-3.8. /Dxxx/

IAEA, 2013. Objective and essential elements of a state's nuclear security regime. Nuclear security fundamentals. IAEA Nuclear Security Series No. 20, February 2013. /Dxxx/

IFE, 2011. Rapport revidert metode for kontroll av funksjonskrav til KLDRA-Himdalen. /D192/

IFE, 2013. Committees for spent fuel management in Norway. /D055/.

LLWR, 2011. The 2011 Environmental Safety Case. http://llwrsite.com/national-repository/key-activities/esc/ /Dxxx/

Metcalfe, R., and Watson S.P, 2009. Technical issues associated with deep repositories for radioactive waste in different geological environments. Environment Agency of England and Wales Science Report: SC060054/SR1. /Dxxx/

NEA, 2003. Engineered barrier systems and the safety of deep geological repositories, state-of-the-art report. Nuclear Energy Agency (NEA), Organisation for Economic Co-operation and Development (OECD) in Cooperation with the European Commission. Report EUR 19964 EN. /Dxxx/

NGU, 2010a. Geologisk beskrivelse av mulige lokaliteter for nytt mellomlager i Norge. Noqiles Geologiske Undersokelse Rapport 20 10.035. /D050/

NGU, 2010b. Feltbefaring av seks lokaliteter for nytt mellomlager i omradet Lillestr øm-Askim-Halden. NGU Report - 2010.059. /D051/

Nirex, 2004. A Review of the deep borehole disposal concept for Radioactive Waste. United Kingdom Nirex Limited Report N/108. /Dxxx/

Nirex, 2005. Specification for waste packages containing vitrified high level waste and spent nuclear fuel. United Kingdom Nirex Limited Report N/124. /Dxxx/

Nordlinder, S., 2014. Options for treatment of spent metallic uranium fuel: Technical report, KVU on interim storage in Norway, Task 2. STUDSVIK/N-14/226.

Norwegian Radiation Protection Authority (NRPA), 2003. Norwegian National Report: Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Strålevern Rapport 2003:15. /D118/

NWMO, 2011. OPG's Deep Geologic Repository for low- and intermediate- Level Waste – Preliminary Safety Report. NWMO Report 00216-SR-01320-00001. /Dxxx/

Ojovan, M.I. and Batyukhnova, O.G. 2007. Glasses for nuclear waste immobilization. Proceedings of WM'07, Tucson, Arizona, February 25th – March 3rd 2007. /Dxxx/

Olesen, O., Bering, D., Brönner, M., Dalsegg, E., Fabian, K., Fredin, O., Gellein, J., Husteli, B., Magnus, C., Rønning, J.S., Solbakk, T., Tønnesen, J.F., and Øverland, J.A., 2012. Tropical weathering in Norway, TWIN Final Report. NGU Report 2012.005. /Dxxx/

Olesen, O., and Rønning, J.S., 2008. Dypforvitring: Fortidens klima gir tunnelproblemer. In: In: GRåSTeINeN – GeoLoGI FoR SamFuNNeT, s. 101 – 110. /Dxxx/

Ottesen, D., Rise, L., Andersen, E.S., Bugge, T., and Eidvin, T., 2009. Geological evolution of the Norwegian continental shelf between 61ºN and 68ºN during the last 3 million years. Norwegian Journal of Geology,. 89, 251-265. /Dxxx/

Paulley, A., Metcalfe, R., Penfold, J., and Collier, D., 2014. KVU - Handling of Norwegian spent fuel and other radioactive Waste: Task 5: Protection of the Environment, Natural Resources and Society. QRS-1669A-TR2. /Dxxx/

Posiva, 2012. Safety Case for the disposal of spent nuclear fuel at Olkiluoto - Performance Assessment 2012. Posiva Report POSIVA 2012-04 /Dxxx/

Ringwood, A.E., Kessom, S.E., Ware, N.G., Hibberson, W.O., and Major A., 1979. The SYNROC process: A geochemical approach to nuclear waste immobilization. Geochemical Journal, 13, 141 to 165. /Dxxx/

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project (3 volumes). SKB Technical Report TR-11-01. /Dxxx/

Sorlie, A., 2001. The combined disposal and storage facility for LLW and ILW in Himdalen, Norway: now in operation. WM'01 Conference, February 25-March 1, 2001, Tucson, AZ. /D123/

Stranden Committee, 2011. Mellomlagerløsning for brukt reaktorbrensel og langlivet mellomaktivt avfall. NOU2011_2. /D048/

Technical Committee, 2010. Recommendations for the conditioning of spent metallic uranium fuel and aluminium clad fuel for interim storage and disposal. Report prepared by the Technical Committee on Storage and Disposal of Metallic Uranium Fuel and Al-clad Fuels for Nærings- og handelsdepartementet. /D049/