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KVU - Handling of Norwegian Spent Fuel and other Radioactive Waste
Task 3 - Storage concepts

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Abstract

A selection of storage concepts have been developed for the Norwegian inventory of spent fuel and other radioactive waste (ORW) and evaluated according to their compliance with evaluation criteria comprising technical, economical, safety and ethical aspects. All proposed storage concepts fulfil technical as well as fundamental safety requirements. In order to ultimately decide appropriate concepts additional weightings need to be applied to the evaluation criteria in order to reflect the relative importance attributed to the criteria by the stakeholders. Any decision process needs to consider the implications of the time frames for storage and operation, because of the long-term accumulation of operation costs as well as the potential need for flexibility.

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List of abbreviations and acronyms

BWR	Boiling Water Reactor
HBWR	Halden Boiling Water Reactor
FA	Fuel Assembly
HM	Heavy Metal
IFE	Institutt for Energiteknikk
KVU	Concept Selection Analysis (KonseptValgUtredning)
LILW	Long-Lived Intermediate Level Waste
LLLLW	Long-Lived Low Level Waste
ORW	Other Radioactive Waste

1 INTRODUCTION AND METHOD

1.1 PURPOSE

The purpose of Task 3 within the KVU - Handling of Norwegian Spent Fuel and other Radioactive Waste is to develop general concepts for interim storage of Norwegian spent fuel and long-lived intermediate and low level active waste, evaluate the proposed concepts with respect to their compliance with international and national guidelines and a selection of evaluation factors associated with technical, economical, safety and ethical aspects. Task 3 partly depends on the results from Task 1, which describes the radioactive waste inventory in Norway, and Task 2 which summarizes the treatment options for unstable metallic fuel. Similarly Task 3 has an overlap with Task 4, the determination of options for store localisation, and Task 5, which examines the requirements for store design and localisation from the perspective of protection of the environment, natural resources and society.

1.2 METHODOLOGY

The analysis briefly reviews international and national guidelines as well as international experiences of interim storage of spent fuel and long-lived intermediate active waste. A selection of storage concepts have been developed based on the initial review, the amount and conditions of spent fuel and waste and their current storage conditions. The term “storage concept” has been interpreted as the combination of the actual technical storage solution and the building containing the storage solution, *i.e.* the actual technical *storage concept* and the *building concept* have been treated as fairly independent components in the proposed overall storage concept. The term “storage concept” will consequently denote both the technical storage solution and the overall storage concept depending on the context. The terms will be used interchangeably, but in order to avoid confusion the additional terms “overall” and “technical” have been used to emphasize the significance. Although, the building concept and the storage concept are to a large extent independent and will be analysed separately, there are some interdependencies as further pointed out in section 5.5.

The storage and building concepts are finally evaluated on the basis of compliance with a selection of evaluation factors associated with technical, economic, safety, ethical and public acceptance aspects of the overall storage concept.

The reference numbering used in this report is based on the numbering in a database that is used for the main project.

1.3 SCOPE, DELIMITATIONS AND ASSUMPTIONS

The scope of the analysis is the storage and building concepts constructing the overall concepts for interim storage of spent fuel and long-lived waste in Norway. As emphasized in section 1.2 the interim storage concept is interpreted as a combination of the actual technical storage solution and the building containing the storage solution.

In accordance with [D310] [D259] long term storage is considered to be storage beyond approximately 50 years and with a defined end point at less than 100 years. Since this period of time exceeds the normal design lifetime of civil structures, particular emphasis needs to be put on the selection of materials, operating methods, quality assurance and quality control requirements in order to achieve desired passive safety features while maintaining retrievability.

The term ORW (Other Radioactive Waste) will be used for all waste intended for the storage, since not all waste technically will qualify as ORW. Some of the waste will rather be Short-Lived, some of the waste will fall out from the category due to activity reasons and some waste would technically be classified as Long-Lived Low-Level Waste (LL-LLW). It is emphasized that a precise boundary between LLW (Low-Level Waste) and ILW (intermediate level waste) cannot in general be provided, as the limits on the acceptable level of activity concentration will differ between individual radionuclides or groups of radionuclides.

Two interfaces with a major impact on the storage solution have been identified; the present storage solution and the final disposal solution. The present storage solution is defined by the condition of the historic spent fuel, the storage containers and available infrastructure at the current sites (*e.g.* lifting capacity, the available compartments designated for repackaging the fuel, available transport casks and vehicles etc.) and the condition and amount of ORW.

No further assumptions have been made on the ultimate disposal solution, but it has been concluded that a reconditioning step is nevertheless inevitable before disposal. The reconditioning can be performed adjacent to the interim storage, adjacent to the disposal site or on a third location, *e.g.* the existing facilities. If the reconditioning is performed on the interim storage site there is no need for additional transport casks, except for the transport casks developed for the final disposal package. However, any preparation for final disposal, in terms of packaging etc., for spent fuel requires a developed disposal concept. There are presently no available storage containers licensed for final disposal. It is emphasized that there are fundamental differences between an interim storage site and a disposal site for spent fuel in terms of the necessary site investigations, depths for underground facilities, packaging of the spent fuel, safety analysis etc. In order to isolate the ORW or spent fuel from the human population additional barriers in terms of rock volumes and completely different disposal and other potential environmental receptors, are needed for disposal compared to storage (see the Task 4 report). Disposal will require the geosphere to function both as a barrier and to ensure suitable conditions for the adequate long-term functioning engineered barriers. In contrast, the geosphere does not need to function as a barrier in the case of a store. This difference means that whereas a store can be located at the surface or in the shallow sub-surface, a repository for final disposal will need to be at considerable depth; 500 m is typical for deep geological repositories proposed for LLILW and spent fuel internationally. The safety analysis for a final repository needs to consider a wider selection of potential radionuclide release mechanisms than does a safety assessment for a store. Such an assessment for a repository needs to consider release scenarios operating on very long timescales (up to 1 000 000 years is typical). Development of a repository for final disposal of long-lived waste requires site characterisation to support these long-term assessments, including detailed geological, hydrogeological, geochemical and seismic characterization of the site. In contrast, site characterisation required for a store will be more akin to the investigations usually associated with civil engineering projects, such as large building construction or tunnelling depths are needed, typically 50-100 m for LL-LLW and 500 m for spent fuel and LLILW. The corresponding safety analysis need to consider a wide selection of release mechanisms including scenarios evaluated on a basis 100 000 to 1 000 000 years scale requiring detailed geological, hydrological, geochemical, seismic and meteorological characterization of the site. A surface based storage will to a lower extent interfere with the site investigations and disturb the prevailing geo-hydrological conditions. Even for a disposal site entirely for ORW considerable additional site investigations, safety analysis etc. would be needed. The estimated costs for site characterization and analysis are in the same order as the estimated constructions cost.

Irrespective of the proposed storage solution, a transport cask is assumed to be needed for transporting the spent fuel from the present storage sites to the interim storage. Even for storage solutions based on a cask, some over-pack may be needed. There will clearly be additional costs and work associated with the purchase and licensing of a transport container, but the costs will differ between storage concepts.

The technical solution as well as the licensing procedure is, however, assumed to be similar for a transport container as for a dual purpose cask. The transport casks are assumed to designed with a minimum cooling time, typically in the interval 5 to 40 years

Concerning the ORW, the “waste form” refers to the waste in its physical and chemical form after immobilization treatment. The waste form and its enclosing waste container form the waste package. The requirement to retain the waste packages prior to disposal puts requirements on the package beyond what normally is applied for ORW waste packages aimed for direct disposal. The typical standard drums would corrode in a humid atmosphere. Thus, it is essential to control the atmospheric conditions in the designated storage area in order to reduce the corrosion rates.

The analysis assumed implicitly that the storage for spent fuel and ORW is co-localized. The storages for each kind of waste can be localized independently of each other, but at a significantly higher cost due to the need for establishing two separate sites, infra-structure, organizations etc. If present storage sites are reused, however, there may be reasons to localize the storage at different sites.

2 BACKGROUND

2.1 PRESENT SITUATION IN NORWAY

The amount and the condition of spent fuel and other nuclear waste in Norway are summarized in the Task 1 and 2 reports of the KVU - Handling of Norwegian Spent Fuel and other Radioactive Waste.

2.2 SPENT FUEL

The present storage solutions for spent fuel in Norway are all, with the exception of shorter interim storage in the spent fuel pool, based on various types of dry storage, mainly because of the low residual heat of the spent fuel and low cost associated with dry storage.

All spent fuel produced at the Kjeller site is stored at the Kjeller site. The major part of the spent fuel produced at the Halden site is stored there, with the exception of experimental fuel to be analysed further at the Kjeller site, which is stored at the Kjeller site.

2.2.1 Halden site

The fuel assemblies employed by the HWBR at Halden each contain 8 fuel rods [D163]. The spent fuel is initially stored in the spent fuel storage pool in the reactor hall. The storage concept is similar to that typically employed for power reactors, where water is used for shielding and cooling. The water requires active pumping with cooling and purification circuits. Water height and composition is monitored on a regularly basis. Ventilation is performed through filters and all air released is monitored. There are in total 83 storage positions, each containing one fuel assembly. Lifting of the fuel assemblies is performed by overhead crane with a maximum capacity of 30 tonnes.

In addition to the spent fuel storage pool there is a storage pool in the bunker building. Unlike the storage pool in the reactor hall the fuel assemblies are disassembled and transferred to a storage basket in order to increase storage density. Each storage basket contains 16 standard fuel rods. The fuel has decayed and the remaining residual heat is consequently significantly lower than in the reactor hall. After one year of decay in the spent fuel storage pool the decay heat has decreased down to the lie between 20 and 50 W/fuel rod, *i.e.* between 160 and 400 W/fuel assembly according to Task report 2. Any loss of forced air circulation will, according to the safety analysis, therefore lead to only a minor temperature increase with insignificant impact on the fuels integrity. Handling of fuel assemblies in the bunker building is performed by overhead crane with a maximum lifting capacity of 30 tonnes.

The major horizontal dry storage is a massive concrete construction with 202 horizontal storage tubes of 7 m length. Inert gas, *e.g.* helium, is used, neither in the storage cavity, nor in the storage tube. The walls of the construction have a thickness of 2 m and inside the construction there are steel structures supporting the storage tubes. In front of the concrete structure there is an additional shielding block of concrete with a wall thickness of 1 m.

The annual amount of spent fuel produced during the last 10 years is typically 18 fuel assemblies (approximately 80 kg). The dry storage has, according to Task report 2, sufficient capacity for the next 10 years given the current production rate of spent fuel. The storage cavities can, in addition to spent fuel, contain other active components.

Transport of spent fuel within the site is performed with the aid of an overhead crane and a transport trolley, which is constructed to run on a railway between the reactor hall and the bunker buildings.

The transport of experimental fuel from Halden to Kjeller is performed by road using a small transport cask.

The transport cask consists of an inner containment steel vessel, a shielding container of steel and an outer wooden overpack [D145]. The outer dimensions are 3614 mm long, 1030 mm diameter with a gross mass of 5600 kg. Depending on the content, large radioactive sources or spent fuel, different activity regulations apply. For radioactive sources the activity limits are 2400 TBq as contributed by Cs-137, Zr-95 and Nb-95 and 30 TBq from Co-60. For spent fuel there are, in addition to an activity limit of 1800 TBq from mixed fission products, also limits for heat production of 300 W and a criticality safety index.

2.2.2 Kjeller site

The fuel assemblies employed by the JEEP II reactor consists of 11 fuel rods arranged in a circular assembly [D158]. The spent fuel from the JEEP II rector is allowed to decay in the storage well adjacent to the reactor. The JEEP II storage well consist of a water filled cylindrical metal tank with a cooling circuit. The tank contains a movable frame with the capacity for 13 fuel assemblies.

After the initial decay period of one year the decay heat has decreased down to 65 W/fuel assembly and the spent fuel is transferred to Met lab II which is a combined storage facility for spent fuel from JEEP II, experimental fuel from the HBWR and nuclear waste from the laboratory [D162]. The spent fuel from JEEP II is not dissembled and is stored as intact fuel assemblies. The storage at Met Lab II is dry and consists of a concrete block with 84 vertical storage cavities. Each storage cavity has a diameter of 0.254 m, 32 of the cavities are 3 m deep and 52 are 3.5 m deep. The corresponding storage tubes of steel inserted in the cavity have a diameter of 0.08-0.1 m and a wall thickness of 2 mm. The top shielding and seal of the storage cavity is a lead plug. Inert gas, *e.g.* helium, is used neither in the storage cavity nor in the storage tube. The storage tubes may in addition to spent fuel in terms of intact fuel rods also contain segmented fuel rods, turnings, irradiated samples with high radioactivity.

The handling of the fuel assemblies is performed by an overhead crane with a maximum lifting capacity of 25 tonnes.

The spent fuel is transferred to the storage (Meta Lab II) after 3 months of decay in the well and has a maximum burnup of 20 MWd/kg. The annual production of spent fuel from JEEP II is typically 4 fuel assemblies (approximately 45 kg) according to Task 2 report. The capacity at Met Lab II for storing spent fuel generated from the operation of JEEP II and experimental fuel from Halden is sufficient for the foreseeable operation time.

Historic fuels from the NORA and JEEP I reactors are stored in the JEEEP I storage well. The storage consists of a concrete block with 97 vertical storage cavities formed by steel tubes. Each tube has a metal cover with a gasket and is not filled with any inert gas, *e.g.* helium.

2.2.3 Concluding remarks

After an initial decay period in a spent fuel storage pool all spent fuel is transferred to various types of dry storage, see Table 2-1.

The common storage concept for all dry storage solutions consists of storage cavities in a concrete block which provides the required radiation shielding and the structural integrity. The containment function of the storage cavities is provided by steel tubes which all, with exception of the Halden dry storage, are oriented vertically. The transfer of residual heat is performed through natural convection of air. The sealing of the storage cavities is made by a single plug attached by screws. The cavity is not rendered inert by injection of agas such as helium, which if used could significantly reduce the corrosion rates of the fuel. Several commercially available storage tubes/containers feature a helium atmosphere in order to reduce corrosion rates, and also to minimize releases from the containers in accident scenarios with elevated temperatures.

The handling equipment consists mainly of overhead cranes with maximum lifting capacities in the order of 25-30 tonnes. In order to transfer spent fuel from the storage cavities to modern high-density transport casks additional infrastructure is needed. The evaluation of the transport container should evaluate the advantages or disadvantages of reusing the present storage tubes versus the option to repack the fuel rods when loading the transport container. The available transport cask for transporting spent fuel from Halden to Kjeller is inadequate for transporting the present inventory of spent fuel from the current storage sites to an interim storage mainly due to the low capacity.

The spent fuel produced at Halden is stored as single fuel rods, whereas the spent fuel from the JEEP II is stored as intact assemblies. An exception to this general rule is historic fuel.

The decay heats are significantly higher for spent fuel from HBWR (160-400 W/fuel assembly) than for spent fuel from JEEP II (65 W/fuel assembly).

The buildings enclosing the storage solutions at the Kjeller site are mainly conventional industry buildings with no specific enforcement to withstand external threats, such as aircraft crashes or attacks by terrorists. Halden on the other hand has, because of its location within a rock cavern, an inherent protection against external threats.

During interim wet storage in spent fuel pools the decay heat is removed by forced cooling circuits, whereas the dry stores rely on natural convection. In the present dry stores the activity released is primarily airborne and monitored within the ventilation systems. Water borne activity release through drainage is only monitored at Met lab II.

Table 2-1. Summary of the present storage concepts for spent fuel.

Site	**Storage**	**Storage type**	**Capacity**	**Capacity**
			storage positions (tubes)	fuel rods/position
Kjeller	JEEP II lagerbrönn	Wet	13 (1 FA/tube)	11
	Met. Lab II	Dry vault, vertical storage	84 positions	
	JEEP I stavbrönn	Dry vault, vertical storage	97 positions	
	Brenselager I lagerbygg I	Dry		
Halden	Spent fuel pool reactor hall	Wet	83 positions (1 FA/position)	
	Spent fuel pool bunker building	Wet	97 position	16
	Dry storage bunker building	Dry, horizontal storage	202 storage tubes	

2.3 LONG-LIVED INTERMEDIATE LEVEL WASTE

2.3.1 Kjeller

At the waste treatment facility at Kjeller various types of nuclear waste is solidified and conditioned into standardized containers, which are steel barrels [D161]. Solid wastes in the form of plastic, glass and electronic components are compressed in these steel barrels. In contrast, metallic, mainly mechanical components, medical radiation sources and smoke alarms are placed in the barrels after being disintegrated. Liquid waste, in the form of evaporator concentrate and ion exchange resins, is solidified by cement. The standard container for all operational waste is a 210 liter steel drum.

2.3.2 Halden

Ion exchange resin and compressible waste have been transported to Kjeller.

2.3.3 Himdalen

KLDRA is a combined store and repository for low and intermediate level radioactive waste. The store consists of four storage halls of which one is designated for interim storage and three halls are used for final disposal. Each hall has a capacity of 2500 steel barrels. The acceptance criteria for disposal regulates that the activity from long-lived alpha-emitters should not exceed 4 000 Bq/g in a single waste package and not more than 400 Bq/g over a selection of waste packages [D356].

The store is remotely monitored to identify any intruders, record dose rates, identify any fire that may occur, ensure adequate ventilation, and determine that electric power is maintained.

2.3.4 Concluding remarks

The standard storage container for intermediate level waste, including waste from external producers, is a 210 liter steel drum, see Table 2-2. Additional containers include concrete and steel boxes.

Table 2-2. Present storage solutions for long-lived intermediate level waste.

Site	Storage	Storage container	Capacity
Kjeller	Waste treatment facility	220 l steel drums Steel boxes (210x135x111) Concrete boxes (80x120x100 cm)	
Himdalen	KLDRA	210 l steel drums	4x2 500 steel drums

3 INTERNATIONAL EXPERIENCE AND RECOMMENDATIONS

3.1 INTERNATIONAL TECHNICAL GUIDELINES

3.1.1 Spent fuel

General guidelines concerning radiation protection and nuclear safety, as compiled by for instance the International Commission on Radiological Protection (ICRP), [D320-D323] are less applicable for deriving specific requirements for the design and layout of an interim storage.

More specific requirements for the interim storage can be derived from applicable international guidelines, such as [D314], [D252], [D312] and [D316].

The Standard review plan [D318] for dry cask storage systems outlines general expectations for achieving compliance with the NRC Regulations (10 CFR) part72 [D357], licensing requirements for the independent storage of spent nuclear fuel and high-level radioactive waste. The key technical requirements for design and operation can be broken down into six categories;

- Criticality,
- Heat removal,
- Shielding,
- Sealing,
- Structural, and
- Operational

Similar overall technical requirement can also be derived from [D259] and [D314]. Although derived for dry storage, the set of general requirements are also applicable to wet storage. More specific requirements for wet stores are summarized in [D358].

3.1.2 Requirements for design and layout

The subcriticality of the spent fuel needs to be maintained under both normal and potential accidental conditions. The civil construction should in particular ensure heat removal, ventilation and leak control.

Dose rates to plant operators, the public and the environment should be minimized by selecting appropriate siting and shielding. Additionally, airborne contamination should be avoided by ensuring leak-tightness and filtered ventilation. Storage facilities should be designed to allow the control of any contamination from gaseous or liquid releases. Gas generation during normal operation or possible accident conditions should be detectable and taken care of by adequate ventilation. Provision for fire protection and for decontaminating individual containers and facility surfaces should also be made.

In order to maintain long-term integrity of the stored waste packages and prevent possible degradation from corrosion effects it is essential to provide protection from various adverse environmental conditions, e.g. by keeping humidity at acceptable levels, preventing elevated temperatures or unacceptably steep temperature gradients, and preventing temperature cycling.

The storage design should include provisions for the inspection and monitoring of stored waste, as well as record keeping and unique identification of each stored waste package.

The design should meet physical protection requirements. A suitable system to ensure the prevention of unauthorized access should also be recommended.

The conceptual design should facilitate maintenance and the subsequent decommissioning of the storage facility, whilst minimizing the generation of secondary wastes or contamination.

The storage area must be designed to ensure heat removal, ventilation and cooling, gas dissipation, radiation protection. Engineered barriers must be provided to limit the release of radioactive material. Design measures are needed to control leaks and prevent criticality. The selection of design features is not restricted to the requirements for normal operation, but need to include additional measures to prevent accident scenarios and mitigate the effects of such scenarios should they be realized.

3.1.3 Requirements for operation

The operational requirements of the storage concepts refer to the activities undertaken at the facility:

- Receipt and emplacement of wastes;
- Integrity control;
- Retrieval and dispatch; and
- Security and emergency preparedness (see Task 4 and 5).

Requirements during the receipt of wastes are associated with the control of the waste packages and the verification of compliance with appropriate package acceptance criteria, while maintaining radiological protection. In addition to the waste package control, it is essential to facilitate a record keeping system that can be linked/cross-referenced easily with a similar system maintained by the senders of waste.

Throughout the storage time there should be provisions both for monitoring the waste package and those conditions in the storage area which could have a potential impact on the long-term integrity of the waste containment. In addition to remote surveillance, additional means are required for performing visual inspections while keeping the exposure of personnel as low as reasonably achievable.

Similar to the reception of waste packages, the requirements for retrieval and dispatch are associated with the control of the waste package and the maintenance of storage records.

The primary functions categories are summarized in Table 3-1.

Table 3-1. Definitions for primary function categories [D317].

Function	**Description**
Containment	The components and supporting materials that are incorporated into the container design for the purpose of retaining the radioactive material during normal and accident conditions.
Criticality control	The components and supporting materials that are incorporated into the container design and the overall concept for the purpose of maintaining the contents in a subcritical configuration during normal and accident conditions.
Shielding	The components and supporting materials that are incorporated into the container design for the purpose of reducing radiation emitted by the contents during normal and accident conditions
Heat transfer	The components and supporting materials that are incorporated into the container design for the purpose of decay heat removal under normal conditions and protecting temperature-sensitive components (e.g., lead shielding and seals) under accident conditions.
Structural integrity	The components and supporting materials that are incorporated into the container design for the purpose of maintaining the structure in a safe condition during normal and accident conditions.
Operations support	The components and supporting materials that are incorporated into the container design for the purpose of routine use (e.g., loading, unloading, use maintenance, monitoring, and transportation).

In order to fulfil requirements for physical protection the storage facility needs to have a controlled and limited admittance for personnel as well as a safeguard system.

It is essential that the technical solution and facility design should function as an integrated part of a systematic waste management system.

In order to comply with the operational requirements the storage facility needs to be divided into an operations area and a storage area. In the operations area the initial handling, maintenance, and inspections take place. The waste packages are controlled and verifications of compliance with appropriate package acceptance criteria are made before allocating each waste package to the storage area. The operations area is shielded from the storage area in order to reduce dose rates, but may partially share handling equipment. The operations area must contain provisions for monitoring and controlling the conditions in the storage area.

It is emphasized that international regulations do not set any quantitative limits on activity release. The actual dose limits as well as the level and scope of the corresponding safety analysis are determined by the national authorities.

3.2 LONG-LIVED INTERMEDIATE LEVEL WASTE

The requirements for nuclear waste (long-lived intermediate level waste) are in general less stringent due to the low decay heat and absence of criticality issues. Requirements for the waste forms and storage have been summarized in [D252] and [D259]. The waste should be immobilized and the physical and chemical characteristics of the resulting waste form and container should be matched to the anticipated storage conditions, to ensure that the waste form and container are sufficiently stable.

The storage should adopt a multi-barrier approach with a high degree of passive safety. Any need for monitoring, inspection, or prompt corrective action in the event of an incident should be minimized. The lifetime of the waste storage building should be appropriate for the storage period prior to disposal of the waste. Unlike the packaging for spent fuel, the waste package for LLW should be acceptable for final disposal.

Since the interim storage for long-lived intermediate level waste will share some functions with the interim storage for spent fuel, most of the measures taken in order to comply with the stricter regulations for spent fuel automatically will result in compliance with the requirements for the storage for long-lived intermediate level waste. Similar to spent fuel are the actual limits on activity release, formulated as dose limits, set by the national authorities. The safety analysis demonstrating the compliance with the limits is written by the licensee, but the level and scope is developed in communication with the national authorities.

3.2.1 International experience

International experience with interim storages for spent fuel have been summarized and reviewed in a series of fairly extensive series of publications from IAEA [D310], [D309], [D305] and [D313]

Interim storage for long-lived intermediate level waste is a less well documented field than the final disposal of waste [D314].

3.2.1.1 Wet storage

Wet storage of spent fuel represents a mature technology with wide international experience. At least 30 away-from-reactor (AR) sites are recognized worldwide, with a total design capacity of 55 000 t HM, see Table 3-2. The requirements for a wet storage are in principle the same as for spent fuel storage at a reactor site [D358].

The storage solution can, with an appropriate design and layout, comply with all requirements summarized in Table 3-1.

The storage pool is constructed using reinforced concrete and often has a stainless steel lining. The pool is filled with deionized water. The auxiliary systems typically comprise water purification and cooling systems and systems for monitoring of radiation and water composition and to identify, quantify and locate any leakage that unexpectedly occurs.

Subcriticality is ensured by providing sufficient spacing between fuel elements within the storage racks or baskets. In order to increase the storage density various neutron absorbing materials have been introduced in storage racks and baskets, such as boronated stainless steel. Provisions for maintaining adequate water levels are important, not only for fuel cooling, but also to ensure that the shielding effect is maintained.

A wet store can provide a high storage density which, for a sufficiently large number of fuel assemblies, will correspond to a low cost per fuel assembly. However, wet storage is also a more complicated storage method than dry storage and requires more auxiliary systems (water purification, cooling circuit/heat exchangers), which in turn generates secondary waste in the form of ion exchange resins. Since the safety of a wet store depends on maintaining water levels in the storage pool and the proper functioning of cooling circuits, a wet store it is more sensitive to accidents or external assaults. A single accident that breaches one barrier can thereby jeopardize the whole inventory in the storage pool, whereas the potential consequences during dry storage in general are more localized. Thus, more spent fuel is at risk in an accident or attack, the potential consequences are more severe, and the recovery less trivial. International experience with wet stores is summarized in Table 3-2.

Table 3-2. Summary of international experience with wet stores [D309]. The summary is not intended to be complete and is only provided to give a general indication of capacities and the years of construction.

Country	**Site**	**Number of Pools**	**Storage capacity (t HM)**	**Inventory (t HM)**	**Year of construction**
Argentina	PHWR	2	1450	1200	1975-
Bulgaria	WWER-440	4	480	121	1974-
	WWER-1000	2	520	266	1988-
Canada	CANDU	10	31 407	22555	1971 -
China	PWR	3		177	1991-
Czech Rep.	WWER	4	480	306	1985-
Finland	BWR/WWER	4	666	251	1978-
France	900 MW PWR	34	5870	4187	1979-
	1300 MW PWR	20	5420	1608	1985-

Country	**Site**	**Number of Pools**	**Storage capacity (t HM)**	**Inventory (t HM)**	**Year of construction**
Germany	Operating PWR	13	3176	2011	1975-
	Operating BWR	6	1385	821	1977-
	Shut down	8	526	-	1968-
Hungary	WWER	4	480	350	1982-
Italy	LWR	3	253	253	1981 -
Japan	PWR	20	6460	2070	1970-
	BWR	23	8410	3050	1970-
	Others	2	280	120	1966-
Korea, Rep.	PWR/PHWR	12	5875	3072	1978-
Lithuania	RBMK	2	2093	1380	1984-
Mexico	BWR	2	984	80	1991 -
Romania	CANDU	1	940	100	1996-
Russian	WWER-440	6	480	320	1966-
	WWER-1000	7	1200	460	1978-
	RBMK	11	3560	2700	1975-
Slovakia	WWER	4	480	150	1981-
Slovenia	PWR	1	410	205	1984-
South Africa	PWR	2	670	392	1984-
Spain	PWR/BWR	9	3820	2000	1969-
Sweden	PWR/BWR	12	1500	730	1973-
Switzerland	PWR/BWR	5	705	150	1970-
Ukraine	WWER-440	2	240	92	1980-
	WWER-1000	11	2170	1156	1982-
	RBMK	3	600	380	1977-
UK	Magnox	20	1500	330	1956-
	AGR	14	230	154	1976-
	PWR	1	936	30	1995-
USA	Operating LWR	110	59000	38343	1957-
	Shutdown LWR	8	1700	957	1957-

In conclusion, the average capacity is approximately 4000 t HM and even the lowest storage capacity exceeds 200 t HM. Most of the facilities were constructed in the interval 1975-1985, and only a few wet stores have been constructed as late as 1995.

Wet storage is a storage concept that is mainly relevant for countries with power reactors, where a typical store needs to have a capacity above 1 000 t HM. Only a few smaller stores, with capacities in the order of 200 t HM, have been constructed

3.2.1.2 Dry storage

Dry storage systems are defined as the canister or bare metal cask, the concrete overpack and the concrete foundation storage pad. Various dry spent fuel storage technologies have been developed to meet the specific requirements of different reactor fuels; e.g. maximum allowable cladding temperature, cover gas environment (air, CO_2, or helium). In comparison with wet storage solutions, dry storage provides larger flexibility, lower cost, passive cooling and requires a lower level of supervision. Dry stores employ passive heat dissipation which limits the maintenance and generation of secondary waste.

There are several generic types of dry storage technologies available from vendors in the international market.

The available constructions ranges from stationary vaults with storage wells to transportable dual-purpose casks, licensed for storage as well as transport. Intermediate solutions are massive concrete modules (silos) with several storage cavities. Vaults, silos and non-transportable casks are regarded as single purpose solutions solely employed for storage, whereas dual purpose casks allows for both storage and transport to and from a storage facility without repackaging of fuel assemblies. A silo may be transportable internally within the storage site, but in contrast to dual-purpose casks is not intended for external transport.

Vaults

Dry storage systems were initially mainly single purpose systems and vaults represent the first prototype for these systems, with no capability or authorisation for transport off site without re-handling and reloading the fuel into transport casks. Vaults typically consist of above or below ground concrete structures with arrays of vertically orientated storage cavities. Heat removal is normally accomplished by forced or natural convection of air or gas over the exterior of the storage cavities. Radiation shielding is provided by the exterior structure. The atmosphere within a storage cavity can consist of air or an inert gas, such as helium, in order to reduce corrosion rates. The concept has a high degree of modularity and the storage capacity can easily be adapted to the designated inventory, from small scale applications, as in the present facilities at Kjeller, to large scale applications for several hundreds of t HM, see Table 3-3. However, because of the limited support for off-site transport, internationally the storage concept has gradually been replaced by cask-based systems.

Table 3-3. Summary of sites employing vaults as a storage solution for spent fuel [D309]. The summary is not intended to be complete and is only provided to give a general indication of capacities and the years of construction.

Country	**Site**	**Fuel**	**Storage capacity (t HM)**	**Inventory (tHM)**	**Year of construction**
Canada	Gentilly 2	CANDU	3648	20	1995-
France	CASCAD	HWR	180	180	1990-
Hungary	Paks	WWER-440	162	54	1997-
UK	Wylfa	Magnox	958	680	1971-
USA	Fort St. Vrain	HTGR	15,4	15,4	1991-

Silos

Silo systems are monolithic or modular concrete reinforced structures and are to some extent intermediate between stationary vaults and transportable storage casks. Instead of being located in stationary vaults arranged in an air filled building, the storage cavities are located within a massive concrete block which may or may not be partially movable within the site or storage hall by heavyweight forklift, crane or air cushions. The storage solution is thereby slightly more flexible than a vault-based solution and the storage capacity may be expanded by adding additional storage blocks as long as there is sufficient space in the storage hall. The concrete typically provides shielding, while containment is provided by either a separate sealed metal canister or an integral inner metal vessel (liner). The range of typical storage capacities is summarized in Table 3-4.

Table 3-4. Summary of sites employing silos as a storage solution for spent fuel [D310]. The summary is not intended to be complete and is only provided to give a general indication of capacities and the years of construction.

Country	**Site**	**Fuel**	**Storage capacity (t HM)**	**Inventory (t HM)**	**Year of construction**
Argentina	Embalse	CANDU	1000	-	1993-
Armenia	Medzamor	WWER	73.5	0	Planned
Canada	Whiteshell Laboratory	CANDU	25	25	1977-
	Gentilly 1	CANDU	67	67	1985-
	Douglas Point	CANDU	298	298	1987-
	NPD	CANDU	75	75	1989-
	Point Lepreau	CANDU	1 026	472	1991-

Country	**Site**	**Fuel**	**Storage capacity (t HM)**	**Inventory (t HM)**	**Year of construction**
	Gentilly	CANDU	3648	401	1995-
	Pickering	CANDU	1375	381	1996-
Korea, Republic of	Wolsong-I	CANDU	609	609	1992-
	Wolsong-1	CANDU	812	0	Planned
USA	Calvert Cliffs	PWR	1 112	154	1992-
	Davis Besse	PWR	360	33	1995-
	H.B. Robinson	PWR	26	26	1 986-
	Oconee	PWR	980	375	1990-
	Oyster Creek	BWR	190	0	Planned 1998
	Rancho Seco	PWR	202	0	Planned 1998
	Susquehanna	BWR	343	0	Planned 1998

Although the concepts mainly have been applied to large scale applications, the modularity of the concept makes it possible to employ it for small amounts of spent fuel.

Casks

Cask based storage systems are based on sealed metal canisters housed inside a massive metal or concrete storage cask. The inner canister or basket provides structural strength and maintains sub-criticality and may also, depending on the overpack, take care of the containment function. Metal casks may be monitored for leak tightness and usually have a double lid closure system that may be bolted or welded shut. The overpack typically provides physical protection and shielding and contributes to heat removal. Different overpacks are typically used for storage, transport and disposal, but may also remain the same, depending on the license. Casks are inherently robust and may be enclosed in buildings or stored in an open area. Casks represent the most modular and also movable storage concept, and some casks are licensed for a dual-purpose function, *i.e.*, both storage and off-site transportation. Table 3-5 summarizes some of the commercially available cask-based storage systems. The summary is not intended to be complete and the dimensions and capacities vary between different storage/transport configurations. The summary is supplied mainly to give a brief overview of general features of available concepts and containers and specifically to point out the weights and dimensions of the casks.

Table 3-5. Summary of a selection of available spent fuel casks [D310]and [D313]. The dimensions and capacities vary between different storage/transport configurations; the summary is supplied mainly to give a brief overview of general features of available concepts and containers.

Vendor	**Cask model**	**Diameter (without impact limiter) (mm)**	**Height (mm)**	**Weight (in storage config) (t)**	**Cask capacity (assemblies)**	**Max burnup (GWd/tHM)**	**Maximum Heat Load (KW)**
ACL	TN®24 ER system	1512	2700	37.4	32	16	
	TN NOVATM system	2500	6000	145	24		
	NUHOMS® 32PTH	2350	5010	115	32	60	
	TN®DUO cask	2500	6000	130	32	65	32
	TN 24®E	2520	6008	130	21		31.2
GNS	CASTOR 1C	2320	5508	88	16	35	14.4
	CASTOR-V/19	2380	5844	125.6	19	65	39
	CASTOR-V52	2320	5451	123.4	52	65	40
HOLTEC	HI-STAR	1700	4700	121	68	39	19
	HI-STORM	1700	4700	180	68	58	28
NAC	NAC-STC	2400	4600	127	26	45	22.1

Table 3-6 summarizes sites employing cask storage solutions for spent fuel. The summary is not intended to be complete and is only provided to give a general indication of general capacities and years of construction.

Table 3-6. Summary of sites employing casks as storage solution for spent fuel [D310]. The summary is not intended to be complete and is only provided to give a general indication of capacities and the years of construction.

Country	**Site**	**Fuel**	**Storage capacity (t HM)**	**Inventory (t HM)**	**Year of construction**
Belgium		PWR	800	142	1995-
Canada	Pickering,PhI	CANDU	1421	460	1995-
	Picketing, Ph2	CANDU	5376	0	Planned
Czech Republic	Dukovany	WWER	600	232	1996-
Germany	Ahaus	LWR,HTR ,MTR	3960	15	1992-
	Gorleben	LWR	3800	38	1995-
	Juelich	LWR/HTR	8	5	1993-
	Greifswald	WWER	585	0	Planned 1998
India	Tarapur	BWR	27	27	1990 to present
Japan	Fukushima	BWR	73	73	1995-
USA	Arkansas Nucl.	PWR	150	44	1996-
	Dresden 1	BWR	70	0	Planned 1998
	North Anna	PWR	840	0	Planned 1998
	Palisades	PWR	233	102	1993-
	Point Beach	PWR	447	19	1995-
	Prairie Island	PWR	724	60	1995-
	Surry	PWR	808	347	1986-
	Trojan	PWR	358,9	0	Planned 1999

3.2.2 Concluding remarks

Wet storage is mainly relevant for countries with power reactors where the average storage capacity is above 4 000 t HM. Only a few smaller stores, with capacities in the order of 200 t HM, are operating today. Wet stores were mainly developed during the1970s, though some examples of these kinds of stores have been constructed as late as 1995. The concept is designed mainly for large-scale producers of spent fuel. The high operating costs, the substantial cooling capacity and the continuous generation of secondary waste is not well suited for the smaller amounts of low burnup fuel originating from research reactors.

In contrast dry storage installations have lowered operational and maintenance requirements in comparison with wet storages. In addition, dual-purpose cask systems require simpler transport and installation procedures as the fuel assemblies will not need to be individually transferred from the transport containers to a different storage container. Furthermore, there will be no need to further manipulate the bare fuel assemblies or open the sealed container. Once stored in a cask the multiplicity of fuel types may be treated with standardised equipment.

However, since any design of casks reflects the current knowledge of repository characteristics, any significant changes during the characterization and licensing process imply that the cask need to be reopened and the spent fuel repacked in order to qualify for final disposal. Thus, licensing a container for disposal would require a licensed disposal method, which presently is not at hand. The cask should therefore be considered as a temporary container and will not solve the packaging prior disposal.

3.3 LONG-LIVED INTERMEDIATE LEVEL WASTE

At least 50 storage facilities for nuclear waste have been identified within the member states of the IAEA, see Table 3-7. The waste is typically various forms of LILW immobilized in cement and emplaced in concrete or steel boxes, or in steel barrels. The building types used for the stores include both aboveground warehouses to underground facilities.

Table 3-7. Summary of a selection of interim storages for long-lived intermediate level waste [D314]- Note : SS – stainless steel; MS – mild steel; MSG – mild steel galvanized; PE – polyethylene.

Country	Site	Type of building	Type of package	Storage capacity	Package handling	Engineered features	Operating since
Argentina	-	Warehouse	200 L, 400 L drum	7000 m³	Overhead bridge crane	Forced ventilation	-
Austria	-	Warehouse	200 L drum	3000 m³	Lift truck	Natural ventilation	1982
Belgium	Mol/ Dessel	Warehouse	28 L can 200 L drum	4500 m³	Lift truck	-	1990
Belgium	Olen	-		-	-	-	-
Belgium	Mol	-	1 m³ SS container	500 m³	Lift truck	-	1989
Belgium	Mol	Shelf piling	30 L PE bottles	120 m³	Manual	Ventilation for α waste	1990
Belgium	Mol	Concrete floor with sand walls and roof, underground	30 L MS box, SS 60 L box, PE box	-	Shielded lift truck	Natural ventilation floor drains	1990

Country	**Site**	**Type of building**	**Type of package**	**Storage capacity**	**Package handling**	**Engineered features**	**Operating since**
		steel tubes					
Belgium	Mol/ Dessel	Warehouse	200 L, 400 L, 600 L, drum 665 L cement container 600 L, 1000 L, 1500 L concrete container	17300 m³	Overhead bridge, shielded truck	Natural ventilation	1986
Belgium	Dessel		150 L SS canister	90 m³	Overhead bridge, shielded truck	Forced ventilation	1997
Belgium	Dessel	Concrete bunkers	1200 L asbestos/ cement container 200 L SS drum	732 m³	Overhead bridge, remote operated trolley	Forced ventilation	1997
Belgium	Dessel	Concrete bunkers	700 L asbestos/ cement container 200 L SS drum 200 L MSG drum, 400 L painted drum	4556 m³	Overhead bridge, remote operated trolly	Forced ventilation, filtration of exhausted air, water control in pits	1978
Egypt	Inshas	Modular concept	Concrete canister	-	Overhead bridge crane	Natural ventilation	1997
France	La Hague R7	Heavily shielded concrete vaults	150 L SS canister	4500 canisters	Loading/ unloading machine	Forced ventilation	1989
France	La Hague	Cells	1200 L	2484	Overhead	Forced	1990

Country	Site	Type of building	Type of package	Storage capacity	Package handling	Engineered features	Operating since
	EDS		container abestos/ cement container fibre concrete container	drums, 1184 containers, 4400 containers	bridge crane	ventilation	
France	La Hague D/ E EDS	Modular concept	150 L SS canister	20000 containers	Overhead bridge crane	Forced ventilation	2000
France	La Hague T7	Heavily shielded concrete vaults	150 L SS canister	3600 containers	Loading/ unloading machine	Forced ventilation	1992
France	Marcoule CEA	Vault	100 L SS canister	-	Overhead bridge crane loading machine trolley	Forced ventilation	1971
France	Marcoule Cogema	Heavily shielded concrete vault	150 L SS canister	2200 canisters	-	Forced ventilation	1978
France	La Hague STE3	Warehouse	200 L drum	20 000 drums	Overhead crane	Ventilation	-
France	La Hague D/EE6	Warehouse	200 L drum	36 000 drums	Overhead crane	Ventilation	-
Germany	Gorleben	Warehouse	Storage/ transport cask CASTOR	400 casks	Overhead bridge crane	Natural convection	1983
Germany	Ahaus	Warehouse	Storage/ transport cask CASTOR	420 casks	Overhead bridge crane	Natural convection	1983
Germany	Greifswald ZLN	Warehouse	Container drum	200 000 m^3	Overhead bridge crane	Natural convection	1997
Germany	Karlsruhe FZK	Warehouse	Container drum	-	Overhead bridge	Natural convection	1980

Country	**Site**	**Type of building**	**Type of package**	**Storage capacity**	**Package handling**	**Engineered features**	**Operating since**
					crane		
Germany	Jülich FZJ	Warehouse	CASTOR casks, drum	-	Overhead bridge crane	Natural convection	1978
Germany	Mitterteich	Warehouse	Contained rum	1500 drums and containers	Overhead bridge crane loading machine	Natural convection	1986
Germany	Gorleben	Warehouse	Drums, container	15 000 m³	Loading machine	Natural convection	1983
Germany	Gorleben	Warehouse	Spent fuel, HLW glass	420 casks	Overhead bridge crane	Natural convection	1983
India	Trombay	Trenches	MS and SS drum	-	Fork lift	-	1961
India	Tarapur	Tile holes	SS canister	-	Crane	Forced ventilation	1972
India	Kalpakkam	Heavily shielded concrete vaults	SS canister	-	Crane	Forced ventilation	1983
Korea	Republic of	Warehouse	MS drums, concrete lined MS drum	-	Lift truck	Concrete shielding walls	-
Netherlands	Vlissingen	Warehouse	200 L, 1000 L container	24 000 m³ or 50 000 containers	Fork lift truck	Natural ventilation	1992
Slovakia	Jaslovske Bohunice	Warehouse	200 L, 100 L MS drum	4600 drums	Shielded lift truck	Natural ventilation	1988
Slovakia	Jaslovske Bohunice	Shielded concrete vaults (4) with rate channels	SS canister	296 canisters	Overhead crane, shielded transport (internal) and loading device	Natural forced ventilation	1996

Country	**Site**	**Type of building**	**Type of package**	**Storage capacity**	**Package handling**	**Engineered features**	**Operating since**
Sweden	Oskarshamn	Underground interim store	Concrete and steel container	14 000 m³	Overhead crane	Forced ventilation	1980
Sweden	Ringhals	Warehouse	Concrete container and steam generator without shielding	17 000 m³	Overhead crane	Forced ventilation	1975 / 1980
Sweden	Barsebäck	Warehouse	-	20 000 m³	Overhead crane	Forced ventilation	1981
Sweden	Studsvik	Underground interim storage	200 L drum, concrete and MS container	20 000 m³	Overhead crane	Forced ventilation	1984
Sweden	CLAB	Underground interim storage with 4 water pools	SS basket	12 000 m³	Overhead crane	Forced ventilation	1985
Switzerland	Würenlingen	Warehouse	MS drum, concrete container	2000 m³	Overhead bridge crane	Forced ventilation	1992
UK	Sellafield	Shielded concrete vaults (3 stores)	500 L SS drum	60 000 drums	Overhead bridge crane	Building ventilation	1990
UK	Sellafield	Heavy shielded vault	150 L SS canister	8000 canisters	Charging machine	Natural convection	1990
UK	Sellafield	Warehouse (several)	200 L MS and 500 L SS drum	50 000 drums	Shielded forklift truck	Monitored ventilation	1960
UK	Sellafield	Concrete vault	3 m³ MS box concrete lined	1836 boxes	Remotely operated trolley	Building ventilation	1990
USA	Hanford	Multiple bldg. Retrievable trenches	Drums, boxes 200 L drum	40 000 drums as needed	Fork lift	USA	1993

Country	**Site**	**Type of building**	**Type of package**	**Storage capacity**	**Package handling**	**Engineered features**	**Operating since**
		Asphalt pad					

The storage facilities for ORW are in general fairly basic constructions equipped with overhead cranes and in some cases with forced ventilation. The storage capacities can easily be adapted to the inventory. Several facilities were constructed during the period 1980-1990 and have been in operation for more than 30 years. The intended lifetime of the facilities is often less than 100 years. It is emphasized that several of the storages are operating as a temporary buffer store for ORW waste in an established disposal chain, *i.e.* there exists a final disposal solution and the waste is supplied, but also withdrawn from the storage and transported to disposal sites.

4 TASK ANALYSIS

4.1 INTRODUCTION

As emphasized in section 1.2, the term “storage concept” has been interpreted as the combination of an actual technical storage solution and the building containing the storage solution. Thus the actual technical storage concept and the building concept have been treated as fairly independent components in the proposed overall storage concept. Some interdependencies are further pointed out in section 5.5.

4.2 STORAGE CONCEPTS

4.2.1 Pool storage

Pool storage or wet storage is the initial storage solution for almost any nuclear fuel because of the initially high residual heat which requires efficient cooling. The pool water functions as part of an efficient heat removal system, as well as providing radiation shielding. The technical solutions fulfilling the primary functions are summarized in Table 4-1.

Table 4-1. Summary of primary functions and corresponding technical solution for pool storage.

Function	Technical solution
Containment	Protection of pool floors and walls, control of pool water, maintenance of pool heat removal systems and ventilation systems
Criticality control	Separation between fuel assemblies, separators of borronated steel
Shielding	Maintenance of water level
Heat transfer	Maintenance of pool heat removal systems
Structural integrity	Concrete walls, steel lining
Operations support	Overhead crane

Schematic layouts describing the storage concepts are shown in Figure 4-1 and Figure 4-2.

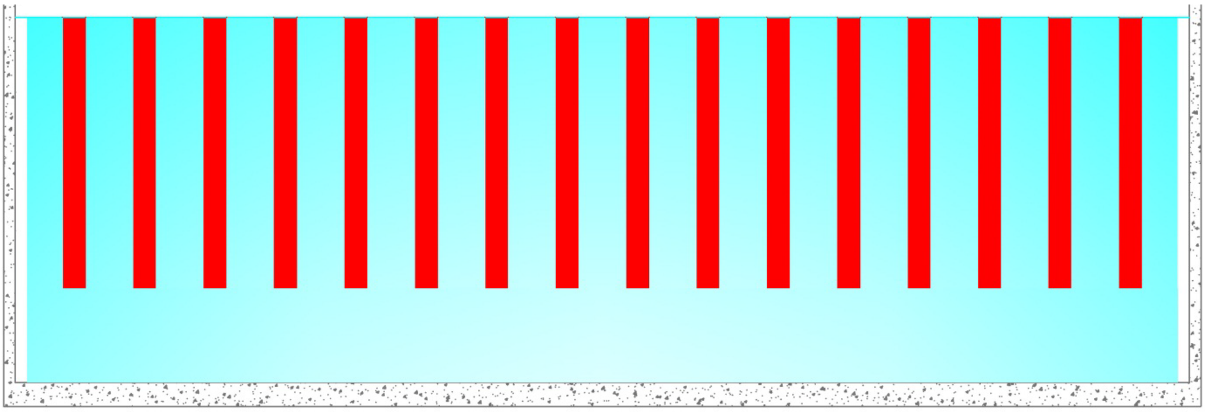

Figure 4-1. Side view of fuel storage in a pool contained within an industry building. The red bars represent the spent fuel and the accompanying structure.

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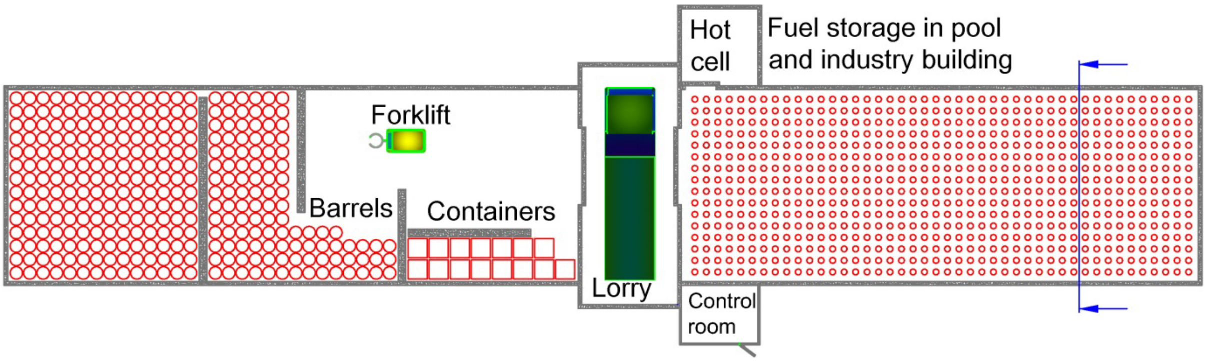

Figure 4-2. Plan view of fuel storage in a pool contained in an industry building.

Wet storage solutions have higher operating costs than dry storage solutions, because in wet stores there is a lower degree of passive safety and more personnel are required for operation and maintenance. Throughout the operation of a wet storage facility secondary waste will be produced in the form of ion exchange resins and filters. Since the barrier lining the pool is common for all fuel assemblies, any breach of the barrier will affect the entire inventory. The pool storage plan normally assumes intact fuel assemblies. Since some of the fuel rods comprising the spent fuel in Norway are detached from their assemblies, additional storage structures, e.g. baskets would be needed. Because of the poor cladding of some of the Norwegian fuel, additional containers would also be needed.

The water depths required to provide radiation shielding for fuel from power reactors are typically about 4 m. However in order to be able to move the fuel assemblies an additional depth of at least twice the fuel length is needed. Considering the lengths of fuel rods from the Norwegian research reactors, the depth of a pool would need to be in the order of 8 m. The storage hall height must again be at least twice the fuel length. The pool dimensions will heavily depend on the number of fuel rods that actually qualify for renewed wet storage and the selected type of fuel basket. The pool dimensions would be in the order of 100-200 m^2 in order to accommodate the Norwegian inventory of spent fuel of today. Assuming a production rate of approximately 190 fuel rods/year (*i.e.* 6 fuel boxes/year), additional 35-70 m^2 or 70-140 m^2 would be required for 50 or 100 years of continuous operation respectively.

The total residual heat is notably low so only a moderate cooling circuit would be needed. It is however very uncommon to put dry stored fuel back to a wet storage due to practical as well as potential corrosion issues. Moreover, since the fuel rods have been disassembled from the fuel box additional supporting structures or fuel boxes would be needed.

4.2.2 Vault

A vault, here interpreted as being storage cavities embedded in a concrete structure, is a fairly straightforward storage solution which is employed for spent fuel at both the Halden and Kjeller sites. The storage cavities can contain additional storage tubes or storage baskets in order to facilitate the storage of fuel of various dimensions. Depending on the anticipated lifetime of the store a storage cavity can be rendered inert by using an inert gas such as helium, in order to reduce corrosion rates of metal components, including the fuel (where this has not been conditioned to produce UO_2) and/or storage tubes / baskets. However, use of inert gases such as helium puts higher demands on the sealing method of the cavity and the long-term monitoring required. The technical solutions fulfilling the primary functions are summarized in Table 4-2.

Table 4-2. Summary of required primary functions and corresponding technical solutions for a vault-based storage concept.

Function	**Technical solution**
Containment	Lining of storage cavities
Criticality control	Separation of storage cavities, record keeping and control of storage density
Shielding	Concrete walls of sufficient thickness
Heat transfer	Natural convection, filtered ventilation
Structural integrity	Concrete block
Operations support	Overhead crane

Schematic layouts describing the storage concepts are shown in Figure 4-3 and Figure 4-4.

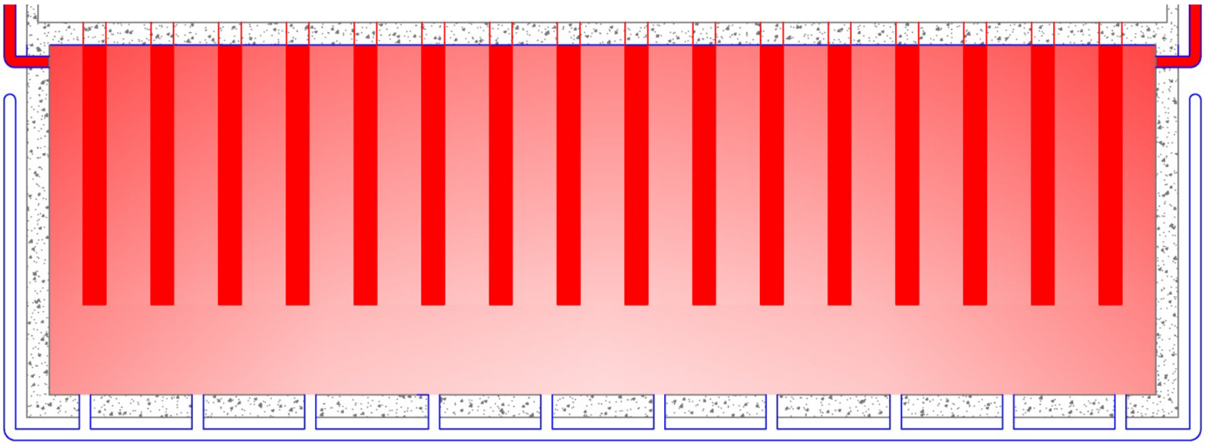

Figure 4-3. Side view for fuel storage in vaults, industry building. The red bars represents the storage cavities containg the spent fuel.

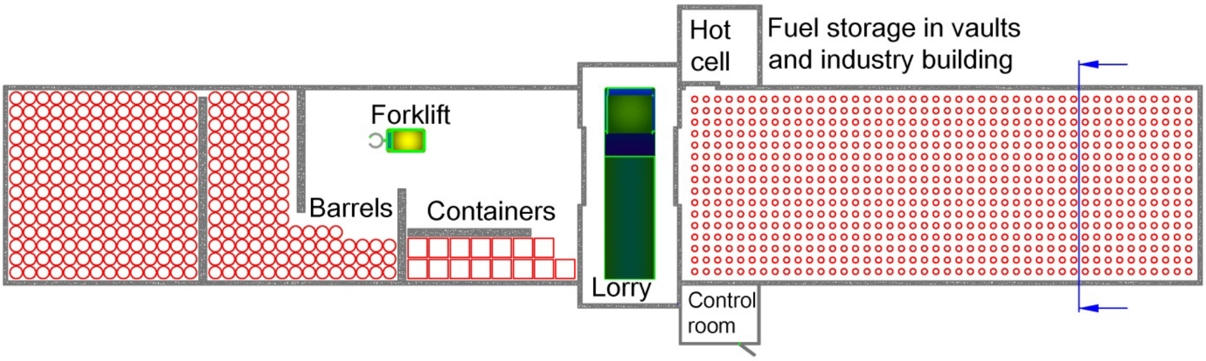

Figure 4-4. Plan view for fuel storage in vaults, industry building.

A vault-based storage solution has a relative low investment cost as well as relatively low costs associated with operation and maintenance. Unlike storage in casks, additional transport casks are needed.

The storage capacity is not flexible and difficult to expand once constructed. Although the fuel rods can be inspected, the actual storage cavities are harder to inspect and require remote monitoring. As for pool storage, any breach of the barrier will affect the entire inventory.

The storage cavities for the spent fuel need to have the same dimensions as the present storage cavities in Halden and Kjeller. The height of the storage hall needs to be at least 3 m, in order to be able to safely move the spent fuel. Assuming additional margins of 1 m, this gives a total height of the storage hall of 7 m, of which 3 m is below the floor level.

The storage area would depend on the type of storage tubes and the treatment options for the unstable metallic spent fuel or damaged fuel. Based on the present storage density and number of storage tubes a floor area of 200 m^2 would be sufficient to accommodate today's inventory of spent fuel. Assuming the current production rate of approximately 190 fuel rods/year (*i.e.* 6 fuel boxes/year), 50 or 100 years of normal operation would require additional 70 m^2 or 140 m^2 of floor area.

4.2.3 Silos

Silos are to some extent intermediate between stationary vaults and transportable storage casks. Instead of stationary vaults arranged in an air filled building, the storage cavities are located within a massive concrete block which may or may not be partially movable within the site or storage hall by using a heavy-weight forklift, crane or air cushions. The storage solution is thereby slightly more flexible than a vault and the storage capacity may be expanded by adding additional storage blocks as long as there is sufficient space in the storage hall. The loading of the storage cavity can in principle be made horizontally or vertically, though in terms of handling there are advantages of using overhead cranes. However, the actual handling depends on the degree of protection and radiation shielding provided by the overpack for the storage tubes. In extreme cases, as for Arevas NUHOMS concept, the storage tube itself serves as a certified transport cask. If a more basic storage tube is used, the silo concept would be similar to the vault-based storage solution in so far as it would require additional transport casks. Depending on the type of storage tubes and the dimensions of the silos it can be assumed that approximately 50 to 250 fuel assemblies could be assumed to be stored in a single silo, implying that 3-15 silos would be sufficient for accommodating the current inventory of spent fuel. Assuming a production rate of approximately 190 fuel rods/year (*i.e.* 6 fuel boxes/year), additional 5-25 silos or 10-50 silos would be required for 50 or 100 years of continuous operation respectively.

The technical solutions fulfilling the primary functions are summarized in Table 4-3.

Table 4-3. Summary of required primary functions and corresponding technical solutions for a silo-based storage concept.

Function	**Technical solution**
Containment	Lining of storage cavities
Criticality control	Separation of storage cavities, record keeping and control of storage density
Shielding	Concrete walls of sufficient thickness
Heat transfer	Natural convection
Structural integrity	Concrete block
Operations support	Overhead crane

Schematic layouts describing the storage concept are shown in Figure 4-5 and Figure 4-6.

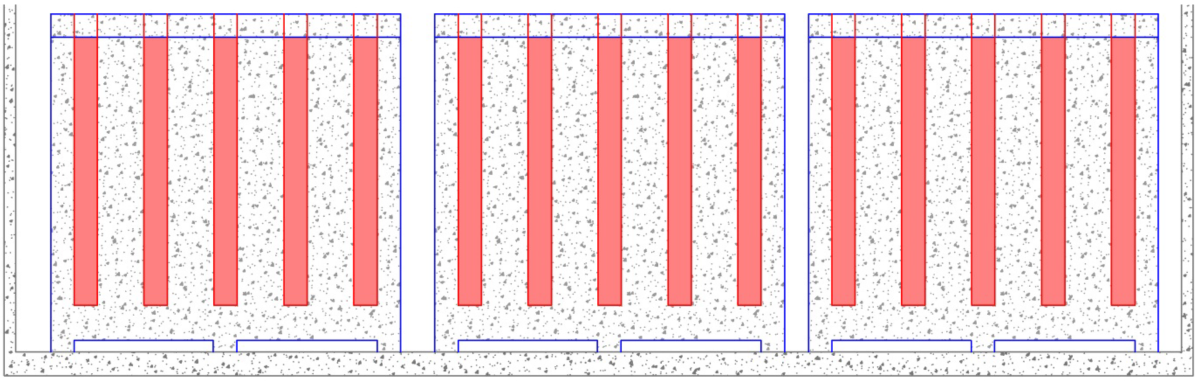

Figure 4-5. Side view for fuel storage in a silo contained in an industry building. The red bars represent the storage cavities containing the spent fuel.

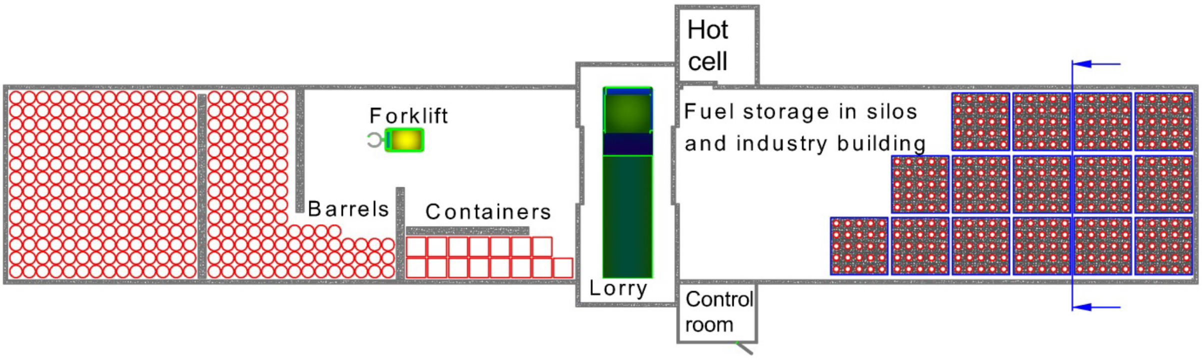

Figure 4-6. Plan view for fuel storage in a silo contained in an industry building.

The storage in silos requires in principle the same dimensions of the storage hall as for vault storage, *i.e.* a height of 7 m and approximately 200 m^2 of floor area based on today's inventory of spent fuel. The significant weight of each silo would require an enforced concrete pad. The weights of commercially available silos are substantial, but also oversized with respect to radiation shielding and heat removal considering the low burnup of the Norwegian spent fuel.

4.2.4 Casks

A storage solution based on casks represents the most flexible solution in terms of facilitating possible later expansion and re-localization. The storage capacity can be expanded as long as there is sufficient storage in the storage hall. The casks can be designed for storage or both storage and transportation, *i.e.* dual-purpose casks. The casks are easy to inspect and can easily be moved within the storage hall with a forklift or overhead crane. Since cask-based storage solutions have the highest capital costs, it may be economically favourable to employ dual-purposed casks in order to avoid costs for additional transport containers and infra-structure associated with repackaging of the fuel. Once put in storage the casks are characterized by low maintenance. However, it will in any case be necessary to finally repackage the fuel for disposal. Depending on the storage density and the potential repackaging from the present storage types to optimized storage baskets a single cask could contain 5 to 50 fuel elements.

The technical solutions fulfilling the primary functions are summarized in Table 4-4.

Table 4-4. Summary of primary functions and corresponding technical solutions for a cask based storage concept.

Function	**Technical solution**
Containment	Lining of storage cavities
Criticality control	Separation of fuel rods from internal grid
Shielding	Walls of cask
Heat transfer	Natural convection
Structural integrity	Cask wall
Operations support	Overhead crane, fork lift

Schematic layouts describing the storage concepts are shown in Figure 4-7 and Figure 4-8.

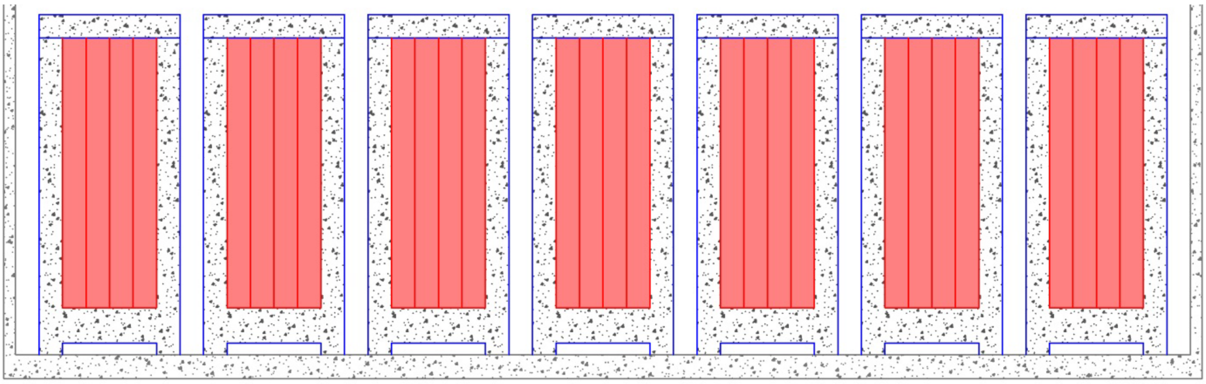

Figure 4-7. Side view for fuel storage in casks, industry building. The red bars represent the spent fuel.

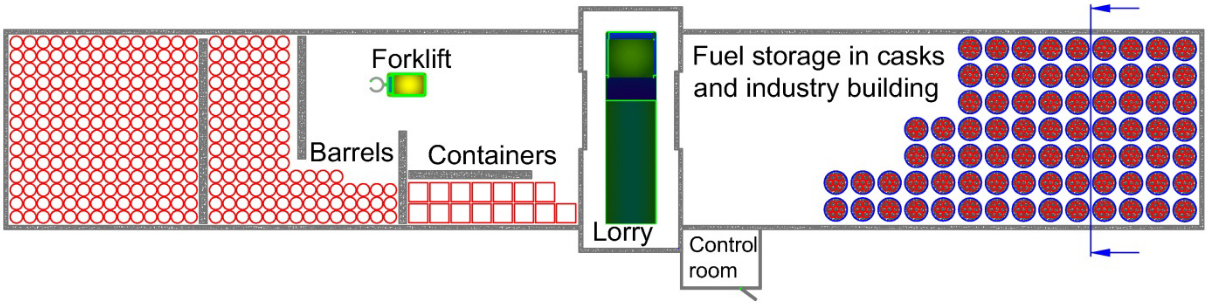

Figure 4-8. Plan view for fuel storage in casks, industry building

The heights of commercially available dual-purpose casks are 3-6 m depending on cask model and configuration. These casks require a similar height for the storage hall plus at least additional 2 m for an overhead crane or for a vehicle transporting the casks. The number of casks required will hence depend on the selected vendor, interior structure and the packaging strategy; however considering the present inventory and multiplicity of fuel types approximately 10-25 casks are needed. Assuming a production rate of approximately 190 fuel rods/year additional 15-35 casks or 27-68 cask would be required for 50 or 100 years of continuous operation respectively.

The number casks require a floor area of approximately 200 m^2, depending on cask type and interspacing between casks. The height of the storage hall could in principle be lower than for other concepts since there is no need to lift the spent fuel from a cask within the storage hall. Any repackaging can instead be performed in another designated area or in a hot cell.

4.2.5 Concluding remarks - storage concepts

The required floor area can for all storage concepts be estimated to be in the order of 200 m^2, based on the present inventory and storage density. The corresponding total storage volume would be around 1500 m^3 for all dry storage concepts, whereas for a wet store at least an additional 1000 m^3 would be needed. Future production of spent fuel would increase the required storage area to some extent, but any of the overall concepts could be used. An additional storage area of 50-100 m^2 would increase the construction costs, but the construction cost increase would be subordinate to the annual operation cost and the investment costs associated with new casks or overhead cranes etc.

All storage concepts fulfil the primary technical functions and any evaluation aimed at ranking the storage concepts needs to consider additional evaluation criteria associated with economy, safety, flexibility etc.

4.3 BUILDING CONCEPTS

A building concept for interim storage of spent nuclear fuel and long-lived intermediation level waste consists of both controlled and uncontrolled areas, where the controlled area comprises all facilities associated with radioactivity and where the uncontrolled area is a conventional industry building that houses functions that are not associated with radioactivity.

The controlled area consists of the actual storage space, receipt room, hot cell and control room. Each room will be heated with controlled humidity. Ventilation shall be designed for staff and also to mitigate unexpected radioactive emissions and will hence require filters and a chimney. Showers and dressing rooms shall be provided for staff. A schematic layout illustrating the storage concept is shown in Figure 4-9.

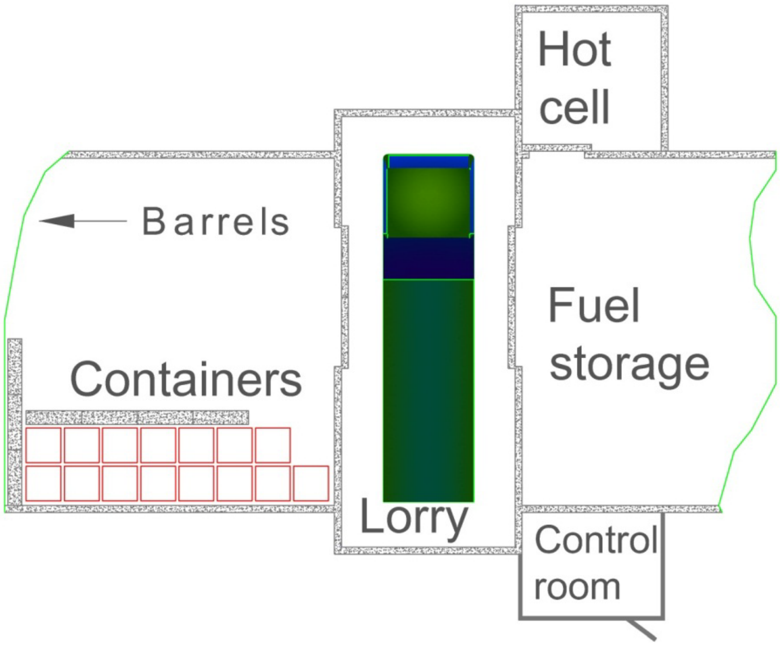

Figure 4-9. Controlled areas

The uncontrolled area typically comprises facilities such as a dining room, rest rooms, toilet, guard house and fence round the area.

The building/buildings need to be adequately designed with respect to anticipated weather conditions, provided with drainage and isolated from the ground to prevent moisture from entering the building. Heating and cooling systems shall be designed to be capable of maintaining temperatures within specified limits required to ensure the adequate functioning of the facilities.

4.3.1 Industry building

A basic industrial building above ground requires the lowest investment cost. The outer cover would only protect against climatic influences. Additional security measures are required, such as fencing and vehicle barriers, in order to protect the building against accidental damage or intentional damage, for example by terrorist attacks. Schematic layouts describing the building and storage concepts are shown in Figure 4-10. The operating costs show some dependency on the storage concepts. Casks are inherently robust and don’t require controls on the temperature and atmosphere within the surrounding building. In the cases of other storage concepts the internal temperature and atmosphere within the building would need to be controlled in order to reduce corrosion rates and other potential degradation mechanisms.

Decommissioning costs for the building *per se* will be fairly low, but will depend to some extent on the actual storage concept. For cask-based storage the decommissioning of the building would be almost identical to decommissioning of a conventional industry building that is not used to house radioactive materials.

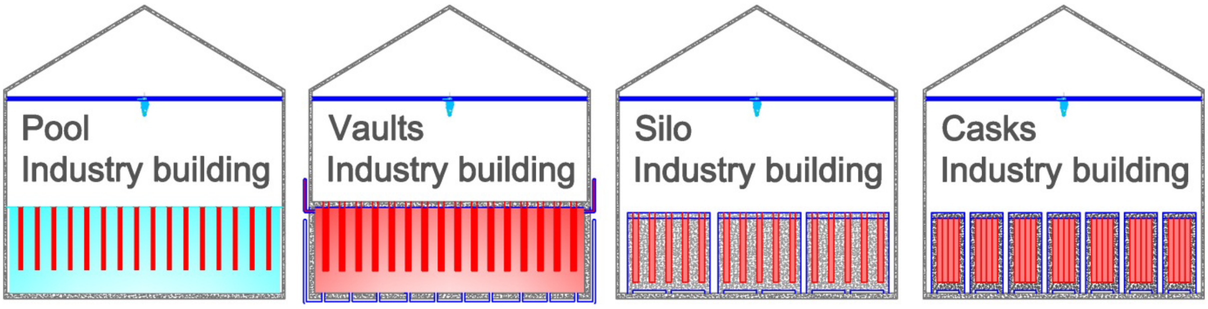

Figure 4-10. Industry building above ground

4.3.2 Concrete bunker

The controlled areas of an above ground facility can be designed with sufficiently thick concrete walls be to withstand intentional damage. The investment cost, maintenance and the decommissioning cost will be higher than for a basic industry building.

Schematic layouts describing the building and storage concepts are shown in Figure 4-11.

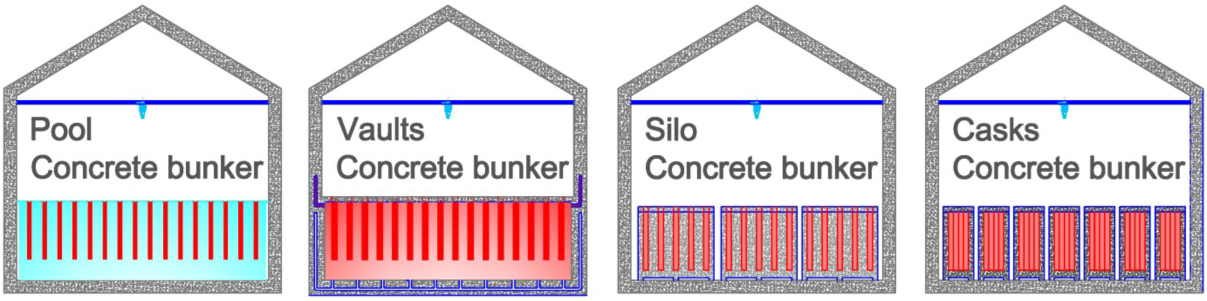

Figure 4-11. Concrete bunker above ground

4.3.3 Rock cavern

By locating the controlled areas of the storage in a rock cavern the capital costs increases, but also the passive safety and the ability to withstand external assaults are enhanced compared to an above ground facility. The access to the cavern can in principle be arranged through horizontal, inclined tunnels or through shafts. However, shafts are a much more complicated way to transport heavy transport containers.

Schematic layouts describing the building and storage concepts are shown in Figure 4-12.

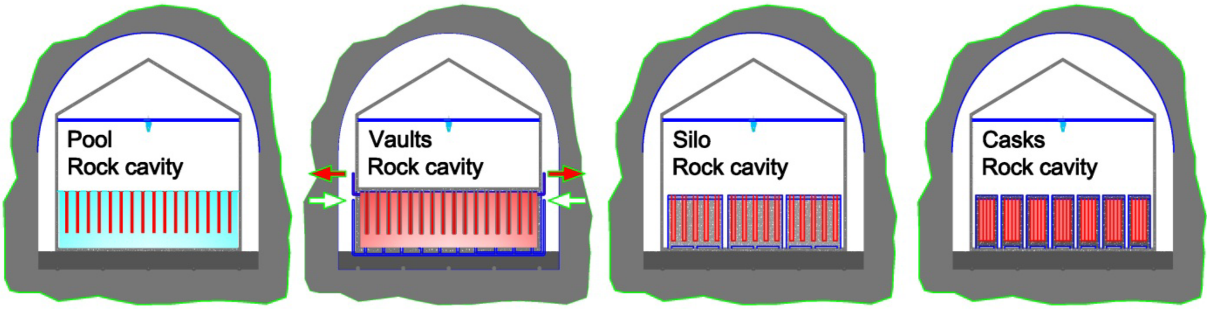

Figure 4-12. Rock cavern.

By localizing the facility underground, there are higher demands on drainage and ventilation. The naturally high humidity in an underground cavern will need to be reduced in order to decrease corrosion rates. Additional issues may arise from drainage of water. Even the natural composition of drainage water may contain levels of certain aqueous species (for instance fluorides) which exceed the levels allowed by environmental regulations. Thus even if the drainage water bears no traces of radioactivity derived from the storage of spent fuel or ORW, the natural composition may require additional purification before returning the water to the surface hydrosphere (rivers or lakes), or managing it by re-injecting it into the groundwater system.

4.3.4 Concluding remarks - building concepts

All storage concepts can be located in all potential building concepts, although with some interdependencies considering operating and decommissioning costs. As for the storage concepts, any evaluation aimed at ranking the building concepts needs to consider additional evaluation criteria associated with economy, safety, flexibility etc. An essential factor worth pointing out relates to the expected storage time and site localization. If localized on any of the sites currently in use, there are strong reasons for reusing available facilities as well as personnel. However, if the expected storage time significantly exceed the expected operation time of these existing facilities there may be reasons for selecting a flexible storage solution at the existing sites which would allow re-localization.

5 EVALUATION OF STORAGE CONCEPTS FOR SPENT FUEL

The requirements derived from international guidelines and national regulations merely put demands on the level of refinement of each individual concept, but do not provide specific guidance for choosing between the concepts. Thus, further evaluation criteria need to be developed in order compare the building and storage concepts in a systematic manner.

The evaluation criteria can be categorized as follows:

- *Technical aspects*
  The technical aspects have been further elaborated in section 3.1 and concern criticality,

decay heat, radiation shielding, containment, material, operation. Additional technical aspects include flexibility and consistency with the overall management strategy.

- *Economic aspects*
  Investment, operational and decommissioning costs

- *Safety and security aspects*
  These aspects are covered in more detail in the Task 4 and Task 5 reports. Safety relates generally to the protection from harm of humans, animals and plants and the wider natural environment. Safety also concerns the long-term store function of preventing the release of radioactivity, as well as the resistance to design-base accidents. Security here concerns the physical protection of the store. The major difference between safety and security events is that while events that compromise safety are usually accidental and typical unpredictable, an event that comprises physical security is usually intentional and targeted.

- *Ethics*
  Ethical aspects relates in general to the burden brought forward to future generations. The general accepted interpretation is that the solution should minimize the necessary actions for future generations, but at the same time maintain freedom to improve the selected solution.

Present public acceptance is a function of the perceived physical protection to ensure security and the perceived effectiveness of the barriers to prevent harm to people, animals, plants and the wider environment in general which does not necessarily equal the degree of radiation protection. Public acceptance greatly benefits from transparency in all evaluation steps and compliance with international guidelines. Therefore, public acceptance is not a criterion in itself, consistent with best practice in such options assessments.

5.1 TECHNICAL EVALUATION CRITERIA

The primary categories of functional criteria have been summarized in Table 3-1, section 3.1.2 and section 3.1.3 and relates to fundamental technical requirements regarding criticality, heat removal, radiation shielding, containment, structural integrity and operation. The proposed storage solutions for spent fuel can, with the appropriate design, comply with the technical requirements summarized in Table 3-1. With appropriate implementation all storage concepts can avoid criticality, provide containment and radiation shielding and transfer decay heat. The provisions for inspection are however somewhat different in different concepts. Additional criteria are related to confidence in the effectiveness of the technical solutions devised to fulfil the functional criteria. Another important parameter is related to the flexibility in terms of capability to accommodate diverse types of spent fuel and ORW, but also to allow for a potential expansion of the initially designed storage capacity.

Additional requirements can be derived from a storage concept's function as an integrated part of a national waste management system. It is essential that the proposed solution for interim storage is reviewed as a component in a systematic chain of waste handling, from the initial packaging at the production site to the final disposal, with additional requirements originating from the transport, reconditioning and monitoring steps. Irrespective of the storage concept, a transport system, including transport container, is needed in order to transfer the waste to the interim store. For spent fuel, a transport container can be adjusted with different interior fuel basket boxes in order to fit both the historic spent fuel and the currently produced spent fuel.

The typical technical requirements are summarized in Table 5-1.

Table 5-1. Summary of categories of technical requirements.

Technical requirements	**Exemplifications**
Primary functions	Prevention of criticality, heat removal, radiation shielding, containment, maintenance of structural integrity and enabling of operations.
Flexibility	Expansion of storage capacity, ability to accommodate diverse types of waste
Integration in national waste management system	Requirements on infrastructure at present sites, transport casks

It is emphasized that all proposed storage and building concepts can, with sufficient resources, comply with the primary technical requirement and any grading related to technical aspect relates to the ease with which the technically requirements can be fulfilled.

5.2 ECONOMIC EVALUATION CRITERIA

The economic evaluation criteria need to include both investment costs and operating costs. The investment costs need to consider the costs and time associated with licensing of a storage concept, including the transport containers, and costs associated with infrastructure. Costs associated with decommissioning represent a capital cost, which includes both decontamination as well as conventional decommissioning of buildings, barriers and systems. Operating costs comprise the costs of personnel, including surveillance personnel, as well as those operating heating, ventilation and drainage systems. Technical operating costs include costs of heating, ventilation and drainage. Maintenance costs comprise the costs of: maintaining outer and inner surfaces, equipment such as overhead cranes, lightning, ventilation and drainage systems, monitoring systems, physical protection and safeguards. The typical cost categories are summarized in Table 5-2, which refers both to storage concepts and building concepts.

Table 5-2. Summary of cost categories.

Cost category	**Exemplifications**
Investment	Engineering and construction of building and barriers, overhead cranes, monitoring systems, surveillance system, heating, ventilation and drainage systems
Operation	Personnel, heating, ventilation and drainage systems
Maintenance	Exterior and interior surfaces, heating, ventilation and drainage systems, power cables, overhead cranes
Decommissioning	Decontamination, buildings, barriers, systems

Because of the importance of costs associated with provision of system functions, such as overhead lifting capability, waste containment, ventilation etc., the construction cost of the storage will not scale linearly with storage area. Thus, whereas the cost for provision of system functions can be considered as fixed, other costs, as construction of storage cavities or the number of casks will scale with the storage area. The costs associated with any increase of the storage area can be subordinate to the cost for the system functions. It is also emphasized that the operating costs would even for a fairly short operation period of 20 years, exceed the actual construction cost (excluding the costs for casks).

5.3 SAFETY EVALUATION CRITERIA

Safety aspects are considered in more detail in the Task 4 and Task 5 reports. Safety relates generally to the protection from harm of humans, animals and plants and the wider natural environment. Safety also concerns the long-term store function of preventing the release of radioactivity, as well as the resistance to design-base accidents. Security in this context concerns the physical protection of the store. The major difference between safety and security events is that while events that compromise safety are usually accidental and typically unpredictable, an event that compromises physical security is usually intentional and targeted. The potential security events include mere sabotages as well as attempts to steal the fuel.

A system approach is needed for assessing the general safety, radiological and non-radiological, of a storage concept, addressing the integral safety of all steps and operations, rather than the safety of each separate step. The assessment should demonstrate that doses and risks remain within established criteria both under normal operation and plausible accident conditions. The safety assessment must cover all relevant phases in the storage concept, from receipt of wastes, through waste storage to eventual waste retrieval. The assessment must also consider all plausible incidents that might compromise safety that might potentially arise from both internal processes (e.g. internal fire, dropped waste packages, failure of containment of the waste packages) or from external hazards (e.g. aircraft crashes, transport accidents, earthquakes and external fires). Whereas long-term storage benefits from passive safety functions, the transport, receipt and retrieval phase require adequate auxiliary means, devices and action procedures.

The technical requirements must be fulfilled during normal conditions, abnormal conditions and design basis accidents, where the typical conditions suggested by [D318] are summarized in Table 5-3.

Table 5-3. Design basis events for interim storage of spent fuel [D318].

Design basis accident basis events	**Design basis natural phenomena design basis events**
Cask drop	Flood
Cask tip over	Tornado
Fuel rod rupture	Earthquake
Leakage of confinement boundary	Burial under debris
Explosive overpressure	Lightning
Air flow blockage	

Additional natural phenomena of relevance for Norway could for instance be snowstorms or landslides. An additional design basis accident event for the storage period is the failure to monitor and react accordingly. The postulated initiating events in [D318] are in accordance with the events postulated in [D252]. Further guidelines for procedures regarding performing safety analysis for stores have been summarized in [D319].

The safety assessment should consider all relevant steps, from the initial packaging at the present storage site, through interim storage, to the preparation for final disposal, including repackaging, reconditioning and transport.

It is emphasized that the evaluation not only should consider radiological safety, but also include conventional safety associated with heavy lifts, transport etc., which often constitutes the most probable hazard. The safety categories are summarized in Table 5-4.

Table 5-4. Summary of safety categories.

Safety category	**Exemplifications**
Radiological safety	Passive safety functions, number of barriers, design basis events
Conventional safety	Heavy lift, transport
Security	Air craft crash, terrorist attacks

It is emphasized that all proposed storage and building concepts can, with sufficient resources, comply with the safety requirement and any grading related to safety aspect relates to the ease with which the safety can demonstrated.

5.4 ETHICAL EVALUATION CRITERIA

Ethical aspects relates in general to the responsibility to future generations. The generally accepted interpretation is that the solution should minimize the necessary actions for future generations, but at the same time maintain freedom to improve the selected solution. The requirement can also be formulated in terms of minimizing the burden, both in terms of future actions required, as well as quantities and activities of secondary waste. A wider range of socio-economic issues are typically addressed by waste store siting/design studies but are outside the scope of the KVU.

Ethical requirements call for robust technical solutions based on passive safety and with minimum requirements for maintenance and monitoring.

5.5 INTERDEPENDENCIES BETWEEN BUILDING AND STORAGE CONCEPTS

It is in principle possible to distinguish between the actual storage solution and the building containing the storage halls. The storage solution will determine the size of the storage hall and the equipment that it contains, but not the overall layout and structure of the interim storage. Thus, the storage concept represents combination of the technical storage solution and the surrounding building. The objectives for selecting a particular storage solution may differ from the objectives for selecting the surrounding building.

The access to an underground facility, *i.e.* from horizontal or inclining tunnel does not influence selection of the actual storage solution.

The storage solution for spent fuel and the building containing the storage halls are to a large extent independent. However, there are some inter-dependencies which need to be pointed out. The need for a hot cell is less pronounced if the fuel is stored in casks that are licensed for use throughout the assumed lifetime of the interim storage. Moreover, dual-purpose casks that are used for transport and storage are inherently robust and a side effect of their construction is passive protection against external threats to their integrity, such as terrorist attacks.

The future disposal site and encapsulation plant as well as transport system to the interim storage and eventually to the disposal site have not been determined and are also beyond the scope of this study. However, the uncertainties concerning these aspects will nevertheless have some influence on the overall cost of waste management.

The transport system constitutes important boundary conditions for the storage solution. Since the present transport systems have insufficient capacity to reallocate the fuel from the present storage to an interim storage, additional investment in transport system is needed. The design of a new transport system is beyond the scope of this study, but the selection of the storage solution will influence the selection of transport system and containers and thereby also the total cost. If a combined transport and storage cask (dual cask) is selected there will be only minor additional cost associated with a transport system. If a silo or valve storage system is selected a transport system with a new transport cask is needed.

5.6 STORAGE CONCEPT

5.6.1 Pool storage

Although wet storage can provide a high storage density and potentially a relative low cost for a sufficiently large number of fuel assemblies, it is better suited for countries with full-scale nuclear power programmes, which generate large amounts of spent fuel of a given type. This storage solution has relatively little flexibility for the storage capacity to be expanded to accommodate experimental fuels from research reactors, where there are relatively small amounts and varied kinds of fuel, and the fuel rods are detached from their assemblies. In such cases additional containers or baskets may be needed. The high cooling capacity of pool storage represents an advantage mainly for high burnup fuel from power reactors, rather than for relatively low-burnup fuel from research reactors.

The storage concept is characterized by a high investment cost, especially if constructed in an underground facility. The high construction costs and secondary waste associated with operation as well as decommissioning probably make this concept inappropriate for countries which have only research reactors. It is also not a passive safety storage solution and will require more personnel and maintenance throughout the storage period.

The concept has a low degree of passive safety and requires active cooling and purification of the water. However, the condition of the fuel can be monitored through sampling and analysing the water.

In a wet store, the spent fuel is more at risk from an accident or attack than would be the case in dry stores. In a wet store, accidents that results in barriers being breached may jeopardize the entire inventory. The potential consequences are more severe and the recovery could be more difficult.

Several handling steps and lifts would be needed when transferring the fuel from the present storage sites to the final encapsulation unit and each step has a certain associated risk. Pool storage represents a higher burden in terms of operation, maintenance and decommissioning and the fuel requires reconditioning before transport to encapsulation unit. The evaluation of pool storage is summarized in Table 5-5.

Table 5-5. Evaluations of pool storage

Criteria	**Advantages**	**Disadvantages**
Technical	High cooling capacity	May not be suitable for all types of fuel Require additional storage container/baskets for fuel initially stored as separate fuel rods Difficult to expand storage capacity Requires long term maintenance
Economical		High cost for investment, operation and decommissioning Additional cost when constructed in underground facility
Safety	Radiation protection Monitoring the condition of the fuel through water samples	Low degree of passive safety (requires active cooling and purification) Accidents that results in barrier breach may jeopardize the entire inventory Several handling steps Generate secondary waste Hazards during decommissioning Low physical security once potential intruders reach the storage pools.
Ethical	Promote the local economy by offering job opportunities	Burden in terms of operation, maintenance and decommissioning Fuel requires reconditioning before transport to encapsulation unit.

5.6.2 Vault

Storage in a vault is a familiar storage technique in Norway. Although the storage volume in principle can be expanded, the costs associated with any expansion of the storage capacity or changes of the conceptual features make it a less flexible storage option than cask-based storage solutions.

For a storage concept based on vaults, the spent fuel and the interior walls of the storage tube can easily be inspected with a remotely controlled camera, whereas the exterior walls of the storage tubes need to be examined by a robot, which is likely to incur additional costs.

The investment and operating costs are fairly low, but the decommissioning cost is higher than for instance cask-based storage solutions.

Several handling steps and lifts would be needed when transferring the fuel from the present storage sites to the final encapsulation unit, each one being associated with a certain risk. However, the number of handling steps would depend on the location of the encapsulation unit and disposal site. The evaluation of vault storage is summarized in Table 5-6.

Table 5-6. Evaluations of vault storage

Criteria	Advantages	Disadvantages
Technical	Familiar technique in Norway	Difficult to expand storage capacity
Economical	Low investment and operation cost	Relatively high decommissioning cost
Safety	Passive safety Low amounts of secondary waste during operation	Accidents that results in barrier breach may jeopardize the entire inventory Several handling steps Low physical security once potential intruders reach the storage area.
Ethical		The fuel requires repackaging before transport to an encapsulation unit. Secondary waste from decommissioning

5.6.3 Silos

The silo concept represents a variety of storage solution that is intermediate between vaults and casks, and shares the advantages and disadvantages of the vault concept. It offers slightly more flexibility in terms of expansion of the storage capacity compared to vaults if sufficiently storage area is available.

In a storage solution based on silos, the inspection of fuel, storage cavity and structure containing the storage cavity is fairly straightforward.

Barrier breaches may not jeopardize the entire inventory, but only a single silo at a time.

Several handling steps and lifts are needed when transferring the fuel from the present storage sites to the final encapsulation unit, each activity being associated with a certain risk. However, the number of handlings steps would depend on the location of the encapsulation unit and disposal site. The evaluation of silo storage is summarized in Table 5-7.

Table 5-7. Evaluations of silo storage

Criteria	**Advantages**	**Disadvantages**
Technical	Storage capacity may be expanded	
Economical	Relatively low investment and operation cost	Relatively high decommissioning cost
Safety	Passive safety Low amounts of secondary waste during operation Accidents that results in barrier breach may only jeopardize one silo at a time	Several handling steps
Ethical		The fuel requires repackaging before transport to encapsulation unit.

5.6.4 Casks

Casks offer a high degree of flexibility, both in terms of storage capacity and the ability to accommodating diverse types of fuel. Casks may be regarded as slightly more easily integrated into a national waste management system. The inspection of the exterior of a cask is straightforward, but the inspection of the fuel may be slightly more complicated due to the cask sealing process, which involves refilling the void space in the cask with inert gas. The need for performing visual inspection is on the other hand less compelling.

The dual-purpose casks represent a mature technology and containers are available from a wide selection of vendors; however special adjustments are required in order to store fuel with non-standard dimensions. Moreover, in Norway the historic fuel is stored pin-wise, in contrast to being stored in standard integrated fuel assemblies. A cask would therefore need additional grids or baskets in order to stabilize the Norwegian fuel, which may increase the cost for each cask even further. The number of casks depends on the selected cask type, and also on the packaging strategy. The most straightforward approach, but also the most space consuming and costly one, would be to reuse the pre-existing IFE cans. A higher density configuration can probably be achieved by repackaging the fuel. The interface requirements in terms of the available infrastructure at the sites put further constraints on the transport casks. The cost for a dual-purpose cask and a transport cask is however comparable.

Available cask-based storage solutions are licensed for at least 50 years. Sealing with inert gas decreases corrosion rates and increases long-term safety. Casks divide the inventory of the spent fuel among a number of discrete robust containers which reduce the consequences of a potential failure. Moreover, the need for facilities to transfer fuel between different packages is minimized and so are also associated safety risks and costs. Various operations between different steps of the spent fuel handling are facilitated and fewer handling steps would be required in order to transfer the fuel from the present storage sites to a final encapsulation unit. However, the number of handling steps would depend on the location of the encapsulation unit and disposal site. The use of casks localizes the potential damage that could occur in design basis accidents.

Storage in dual-purpose casks appears at first glance to pose fewer problems to future generations. However, since the final disposal solution is not at hand, the fuel will still require further reconditioning/encapsulation processes before disposal. The re-conditioning can be done at the same site as the interim store, a site adjacent to the disposal site or on a third location (possibly in another country). In the two latter cases the transport will benefit from the spent fuel being stored in dual-purpose casks, otherwise the future transport system from interim storage to re-packaging/encapsulation plant will have to be supplemented with a set of transport containers. The localization of a future encapsulation plant is again beyond the scope of the present study, but it is emphasized that an encapsulation plant adjacent to the interim store may be slightly more straightforward to integrate with an above ground facility than with an underground facility.

The packaging of an ordinary transport cask or a dual-purpose cask would be performed in a similar manner and the costs related to the construction of transport and packaging systems would be comparable.

In conclusion, unless the future encapsulation unit is localized adjacent to the interim store, dual-purpose casks reduce the delegation of responsibilities to future generations. However, the corresponding costs are expected to be higher than for silos or vaults. Cask-based storages may be regarded more easily integrated into a national waste management system than storage in silos or vaults. The evaluation of cask storage is summarized in Table 5-8.

Table 5-8. Evaluations of cask storage

Criteria	**Advantages**	**Disadvantages**
Technical	High degree of flexibility both in terms of storage capacity and accommodating different types of fuel	
Economic	Low operation and decommissioning cost	High investment cost
Safety	Accidents may only jeopardize one cask at a time Fewer steps of conditioning and handling Passive safety	Handling incidents (conventional, non-radiological, risk associated with heavy lifts etc.) Higher physical security once intruders reach the storage area
Ethical	No preparation is needed before transport to encapsulation unit	

5.6.5 Summary of the evaluation of the storage concepts

Table 5-9 summarizes the relative performance of each storage concept when measured using each evaluation criterion, where 5 denotes the best performance, 3 intermediate and 1 the lowest. It is emphasized that the figures in the table cannot be combined since each evaluation criteria is independent and the relative importance of each evaluation criteria is beyond the scope of this study. For each concept it would be possible to apply weightings to each criterion and then determine a total score, in order to reflect different values that different stakeholders will place on each criterion.

Table 5-9. Evaluation of storage concepts for interim storage.

	Technical solution	**Economic**	**Safety**	**Ethics**
Pool	2	2	3	2
Vaults	3	5	3	3
Silos	3	4	3	3
Casks	5	3	4	3

The weightings of all criteria are sensitive to the localization. If localized on an existing site, Kjeller or Halden, there would be advantages of reusing existing concepts, equipment, vehicles and storage areas. It is emphasized that auxiliary equipment will constitute a major share of the total cost.

For pools, vaults and silos, an overhead crane may not be needed to handle heavy lifts, but the requirements for remote handling and gripping calls for specific construction solutions at a significantly higher cost than ordinary standard equipment. The normal weights for fuel or dual-purpose casks exceed the specified maximum loads for standard forklifts. Both massive overhead cranes and special vehicles will result in significant contributions to the overall cost.

It is emphasized that all storage concepts are sufficiently safe from a radiological point of view during the actual storage phase, but the criteria here embrace additional aspects, as the ease with which the safety can demonstrated, risks associated with repackaging etc.

5.7 EVALUATION OF BUILDING CONCEPT

5.7.1 Basic industry building

A storage concept contained in a basic industry building can, from a purely technical standpoint, definitely comply with requirements for containment, radiation shielding and physical protection, although it may contradict the intuitive feelings of the public. There are several international examples where the spent fuel is stored in basic industry buildings. A basic industry building is also less expensive, but naturally offers less protection in terms of aircraft crashes or other types of accidents. Overall, sufficient physical protection can be achieved by appropriate selection of barriers, personnel and adoption of appropriate operating procedures. Albeit less expensive in terms of construction, additional budget may be needed to establish adequate physical protection, in terms of fencing, other barriers and intruder monitoring systems.

A basic industry building clearly needs stronger surveillance facilities and fencing, including vehicle barriers, in order to achieve the same degree of physical protection as a concrete bunker.

The required operation and the maintenance activities are comparable for the different storage concepts. A basic industry building, however, would require a larger organization for surveillance. Required maintenance during the lifetime of an interim storage facility typically involves maintenance of ventilation, power cables, and overhead cranes etc., which are similar for each building concept. However, in contrast to underground facilities, no pumps and other measures for controlling groundwater inflows would be needed. Compared to underground facilities, above ground facilities will in general require access to a larger surface area, which otherwise possibly could be used for other purposes.

In terms of the future decommissioning of the interim store, the building concepts are comparable. In any of the storage solutions, the contamination should be low and the units should be possible to free release. The overall building decommissioning cost will therefore scale with conventional decommissioning costs which scale with the size of the building. Thus, an industry building with smaller amounts of concrete will require lower costs and possibly give lower dose rates than a solid concrete bunker.

From an ethical standpoint, compared to underground facilities, above ground facilities will in general require access to a larger surface area, which otherwise possibly could be used for other purposes. In terms of the future decommissioning of the interim store, the building concepts are comparable. In any of the storage solutions, the contamination should be low and it should be possible to freely release the unit after minimal decontamination. The overall building decommissioning cost will therefore scale with conventional decommissioning costs, which scale with the size of building. Thus, an industry building with relatively small amounts of concrete will require lower costs and possibly give lower dose rates during decommissioning, than a solid concrete bunker. The evaluation of a basic industry building as a building concept is summarized in Table 5-10.

Table 5-10. Evaluations of basic industry building

Criteria	**Advantages**	**Disadvantages**
Technical	High degree of flexibility in terms of storage capacity and modifications Easy to control ventilation and drainage	
Economical	Low investment and decommissioning cost	
Safety	Lower dose rates during decommissioning than other solutions	Low numbers of barriers, passive safety and security
Ethical		Higher degree of burden in terms of maintenance

5.7.2 Concrete bunker

A concrete bunker is slightly less flexible in terms of the potential for expanding storage capacities than a basic industry building. The investment cost is higher than for a basic industry building, but there is a higher degree of security.

The overall decommissioning cost will scale with conventional decommissioning costs, which scale with the size of the building. Thus, an industry building with relatively small amounts of concrete will require lower costs and possibly give lower dose rates than a solid concrete bunker during decommissioning.

From an ethical standpoint, above ground facilities will in general require a larger accessible surface area which otherwise possibly could be used for other purposes. The evaluation of a concrete bunker as a building concept is summarized in Table 5-11.

Table 5-11. Evaluations of concrete bunker

Criteria	**Advantages**	**Disadvantages**
Technical		
Economical		Higher investment and decommissioning cost than industry building
Safety	Higher degree of security compared to basic industry building	
Ethical		

5.7.3 Underground facility

Compared to above ground facilities, an underground facility is less flexible in terms of expanding storage capacities or changing storage concepts.

In order to maintain an atmosphere which ensures low corrosion rates for internal structures and storage containers, there are strong requirements on ventilation and drainage. The operational cost associated with an underground facility will therefore be comparable with or higher than other building concepts in terms of power consumption for ventilation and pumping, drainage water management, safety overheads associated with working underground etc. However, because of the higher reliance on passive security systems, fewer operating personnel may be required for a new storage site which from the long-term storage perspective results in a lower operating cost than other building options. On the other hand, if the storage building is localized on a nuclear site, such as Halden or Kjeller, which already have sufficient security measures, the operating costs may be in the same order as for other building concepts, or higher than for these other concepts.

The costs associated with maintenance are to a large extent equivalent to other building concepts since the systems most likely to need to be replaced during the life time of the interim storage are power cables, ventilation system, and lifting cranes. However, the need for pumps and drainage systems will incur additional costs. Although an underground facility would feature less exterior surfaces exposed to the atmosphere, the internal humidity inside would likely lead to higher corrosion rates for internal structures.

The overall decommissioning cost will scale with conventional decommissioning costs, which will scale with the size of the facility. If the underground facility eventually should be considered for free release, the decommissioning costs will be higher than for a basic industry building. However, these costs will depend on the regulators requirements regarding the final state of the facility.

An underground facility benefits strongly from the inherent security provided by the surrounding rock and requires less additional engineered security measures than a facility at the surface. Underground facilities pose higher construction risks and might also result in long-term risks for operating personnel in terms of background activity from radon. Water management can also result in safety issues that need to be properly managed. Drainage water may also contain natural radioactivity, and / or non-radioactive constituents that are naturally present at concentrations in excess of permitted regulatory limits, which complicates the management of the drainage water. The evaluation of an underground facility as building concept is summarized in Table 5-12.

Table 5-12. Evaluations of underground facility

Criteria	**Advantages**	**Disadvantages**
Technical		Less flexible in terms of storage capacity than industry building Drainage issues (management of drainage water)
Economic	Operating cost (if localized on new site and requiring security personnel)	High investment and decommission cost
Safety	Passive safety and security Multi barrier	Water management Radon (background activity, operating personnel) Constructions risks
Ethical	Not occupying surface area Less burden on future generations	

5.7.4 Summary of the evaluation of the building concept

The technical requirements provide the framework for developing the technical solution/engineering work, but once the proposed technical solution fulfils the requirements, other criteria are needed in order to evaluate the options. Table 5-13 summarizes each building concept relative performance within each evaluation criteria, where 5 denote the best performance and 1 the lowest. It is emphasized that the figures in the table should not be summed to provide an overall numerical indication of suitability since each evaluation criterion is independent and different criteria need not have the same importance in the overall selection of building concepts. Furthermore, different stakeholders might assign different weights to the criteria. Thus, to assign an overall ranking to the different building concepts, it would be necessary to assess the relative importance of each one, which in turn would involve significant stakeholder engagement that was beyond the scope of this study.

Table 5-13. Evaluation of building concepts for interim storage.

Building concept	**Technical**	**Economic**	**Safety**	**Ethics**
Basic industry building	4	4	2	2
Concrete bunker	4	3	3	2
Underground facility	3	4	4	4

It is essential to emphasize that the operating cost is sensitive to the localization and the possibility for utilizing personnel and infrastructure that are already present at the site. For a stand-alone store at a new site the annual costs for maintaining sufficient security will accumulate to significant figures in comparison with the construction costs. The same situation will also arise if the store is located at Kjeller or Halden and the current nuclear activities there subsequently close down, so that store- specific security personnel will be needed.

5.7.5 Discussion

The building and storage concepts have been evaluated in previous sections with respect to technical, economic, safety and ethical evaluation criteria. In order to determine any total scores and thereby rank the different concepts, it is essential to apply weightings to the selection of criteria in order to reflect different values that different stakeholders will place on each criterion.

The evaluation of a combined storage and building concept will be sensitive to the localization. If localized on an existing site, Kjeller or Halden, there are advantages of reusing the concepts, equipment, vehicles and storage areas as well as personnel.

It is emphasized that auxiliary equipment will constitute a major share of the total cost. For a pool, vault or silo, an overhead crane may not be needed to handle heavy lifts, but the requirements for remote handling and gripping calls for specific construction solutions at a significantly higher cost than ordinary standard equipment. The normal weights for commercially available transport containers for spent fuel or dual-purpose casks exceed the specified maximum loads for standard forklifts. Both massive overhead cranes and special vehicles will be needed and will result in significant contributions to the overall cost. Building and storage concepts have been evaluated in previous sections with respect to technical, economic, safety and ethical evaluation criteria. In order to evaluating any total scores it is essential to apply weights to the different criteria in order to reflect different values that different stakeholders will place on each criterion.

6 EVALUATION OF STORAGE CONCEPTS FOR ORW

For storage of ORW a less complex set of requirements applies than for spent fuel storage, since for ORW no provisions are required for criticality and heat removal and since the specific radioactivity in general is significant lower. Thus, a storage hall in any of the building concepts elaborated in the previous sections will suffice as storage for ORW. However, there are some intrinsic differences between storage for ORW and spent fuel which potentially impact on the storage design (see **Table 6-1**).

Table 6-1. Conceptual differences between storage for ORW and spent fuel.

	ORW	**Spent fuel**
Security measures during storage	Less stringent than for spent fuel	High
Container design	Potentially acceptable for final disposal	Not acceptable for final disposal
Container stability	Sensitive to storage conditions	Insensitive to storage conditions

The essential guiding requirement can be derived from the specific requirement that the waste packages should be acceptable for final disposal. Additionally the employed waste containers will have a limited robustness for long-term storage in sub-optimal conditions. Although the ranking matrix in **Table 5-13** still applies for storage of ORW, there are therefore reasons to consider a different time frame than for storage of spent fuel, because of the limited robustness of the containers usually employed for ORW.

7 CONCLUSIONS

7.1 SPENT FUEL

A selection of store and building concepts have been reviewed and evaluated according to their compliance with evaluation criteria comprising technical, economic, safety and ethical aspects. All proposed storage concepts fulfil technical as well as fundamental safety requirements. In order to ultimately decide appropriate concepts, additional weightings need to be applied to the evaluation criteria in order to reflect their relative importance as perceived by different stakeholders. However, it is still possible to identify four major types of combined storage solutions for spent fuel:

A. Vault storage in industry building

B. Vault storage in underground facility

C. Cask storage in industry building

D. Cask storage in underground facility

All these combinations fulfil primary technical and safety requirements. The concepts provide rather equal safety during the actual storage period and the differences between them mainly concern repackaging, transitions to new transport containers, transport and manual operations within the facility etc. These differences between the concepts mainly influence costs (long-term vs. short-term) and flexibility. It is emphasized that auxiliary equipment and operation costs will constitute a major share of the total cost. For vaults an overhead crane may not need to be able to handle heavy lifts, but the requirements for remote handling and gripping call for specific construction solutions at a significantly higher cost than ordinary standard equipment. The normal weights for commercially available transport containers for spent fuel or dual-purpose casks exceed the specified maximum loads for standard fork lifts. Both massive overhead cranes and special vehicles will result in significant contributions to the total cost. For long-term operation of the store, operation costs are mainly associated with security and will add up to significant levels. Thus, concept A features the lowest investment costs, whereas D features the highest investment costs. The total cost will strongly depend on the anticipated storage time.

The storage time will also determine the possible need for flexibility. If the anticipated storage time will be in the order of the life-time of the existing nuclear facilities, there are strong arguments for re-using the present sites and present facilities. If localized on an existing site the additional operating cost will be lower than for a store at a new location, as long as the existing facility is still in operation, mainly because of the multiple uses of security infrastructure and personnel. On the other hand, once the initial facility is closed, the store may become a burden, since it will occupy an otherwise valuable area within an urban centre (Kjeller and Halden both being urban locations). If there are uncertainties in the anticipated operation time for the existing facility as well as for the storage time of the spent fuel, there are strong arguments for selecting a flexible storage solution which permits re-localization, minimizes the need for decommissioning activities and ultimately ensures an early remediation to green-field, *i.e.* concept C.

However, if the interim storage time is certain to exceed the lifetime of the present nuclear facility there are reasons to instead develop storage with minimum operation costs and maximum passive safety, *i.e.* concept D.

Concerning the safety aspects, it is emphasized that all the storage concepts feature similar passive safety within the storage period, the differences refers mainly to radiological risk associated with any re-localization, receipt and retrieval, and repackaging and transport to a final disposal site. On the other hand, handling of casks is associated with significantly higher conventional safety risks in terms of heavy lifts etc. than the other storage concepts.

The overall evaluation of the optimum storage concept must consider the total storage time. If the anticipated storage time is shorter or within the same order of lifetime as the current nuclear facilities, the most economical and technically straightforward solution would be to utilize the conventional storage techniques at the present site, either by expanding the capacity or by re-organizing the storage.

7.2 ORW

The storage concepts for ORW are essentially a storage hall in any of the building concepts presented. For spent fuel, the casks and/or the storage tubes have an inherent robustness and resistance to corrosion and other degradation mechanisms. For ORW the packaging is in general less robust and more sensitive to corrosion. Moreover, the waste form is not supposed to be repacked before disposal. Thus, the ORW puts higher demands on the environment of storage external to the packaging and/or storage times, significantly higher than for instance fuel stored in casks which in principle does not need any additional protection. However, the radiological risks are also low during the storage period, so the overall most important requirements are related to the ability to retrieve the waste and transport it to a final disposal site. The storage time for LILW should therefore be minimized to minimise the corrosion of the waste containers.

7.3 CO-LOCALIZATION

Co-localization of stores for spent fuel and ORW minimizes the investment and operation cost, but will also introduce interdependence between waste forms. Owing to the limited waste inventory and relatively low hazard levels of Norwegian ORW, a store intended only for these wastes would require only moderate measures for security. Storage for spent fuel would on the other hand require more extensive safety measures and hence significantly higher operation costs. The differences in stability of the container and the acceptance for final disposal may establish requirements for the storage that otherwise would not be needed for a store entirely developed for spent fuel.

Establishing a final repository for spent fuel is in general significantly more costly and time-consuming process than a corresponding repository for ORW, due to the amount of long-lived activity and corresponding regulatory requirements. Because of the potentially shorter times associated with establishing final disposal and the low corrosion resistance for ORW containers there are reasons to minimize the storage time for ORW.

In conclusion, any decision process needs to carefully consider the implications of the various time frames, because of the long-term accumulation of operation costs as well as the need for flexibility (re-localization, changes in storage concepts, and development of disposal concepts).

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9 HISTORY

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