3.2.1 HLW and SNF Containers; Domain Insight

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Overview

A safety concept for a repository for high-level waste (HLW) and Spent Nuclear Fuel (SNF) relies on the capabilities of the entire repository system to contain and retard the disposed radioactive inventory. A repository system consists of natural barriers (host rock, overburden) and engineered barriers like geotechnical barriers (borehole, drift and shaft seals) and technical barriers (waste form and containers). In some national waste management programmes there may be the possibility of selecting host rocks of different characteristics for the repository. Since the Engineered Barrier System (EBS) should be tailored to the characteristics of the waste and be compatible with the natural (geological) barrier, there will be a significant number of different options and combinations of engineered barriers. In this context containers have to provide several safety functions (containment, shielding, sub-criticality and sufficient decay heat dissipation of the radioactive inventory) during all handling procedures until disposal is completed. Subsequently, containers have to provide these safety functions depending on the geologic boundary conditions and on the design criteria, as well as during possible future retrieval and recovery operations.

The majority of the internationally considered waste container concepts for HLW and SNF consist of containers that are mechanically robust but nevertheless in most cases not sufficiently shielded for handling and transport. Together with the waste form, either vitrified HLW or SNF, they form the waste package but depend usually on additional transfer casks for handling operations during transport and storage inside the repository. As no repository for HLW and SNF is in operation today, but the first ones are expected for the next time, only a few a container designs and prototypes exist so far; but many concepts and designs have been developed so far on a generic or concept stage.

Keywords

Safety Concept, repository system, engineered barrier system, natural, geotechnical, and technical barriers, waste container, design requirements

Key Acronyms

HLW, SNF, DGR, EBS

1. Typical overall goals and activities in the domain of HLW and SNF disposal containers

Disposal containers are essential parts of the EBS of any DGR repository for SNF and HLW. Thus, the containers have to provide several safety functions: containment, shielding, sub-criticality, and sufficient decay heat dissipation of the radioactive inventory during the operational period of the repository as well as for the long-term. HLW and SNF containers have to provide these safety functions depending on the geologic boundary conditions, the selected repository concept, as well as on additional design requirements for possible future retrieval and recovery operations.

This section provides the overall goal for the domain HLW and SNF disposal containers, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to the phase of implementation, needed to achieve the domain goal. Typical activities are generic and are common to most geological disposal programmes.

Domain Goal	
3.2 Identify container materials and designs for each waste form under storage and disposal conditions and confirm properties, behaviour and evolution under storage and disposal conditions (Waste packages, for disposal)	
Domain Activities	
Phase 1: Programme Initiation	Starting point for the waste container development process is, on the one hand, a clear understanding of the type and amount of HLW and SNF to be disposed of. On the other hand, a safety and safety demonstration concept is needed for a selected repository system for the host rock(s) available in the country. Thus, the waste container requirements have to be derived in a general approach and adequate container concepts must be developed. The set of requirements has to include requirements derived from possible container retrieval and recovery as well.
Phase 2: DGR Site Identification	During the phase of site selection, the stipulated geosphere's properties become more and more evident. Accordingly, the set of container requirements has to be adjusted, and material selection for the waste container to be launched. First ideas of an adequate quality management programme for container development, manufacturing and operation are requested. Eventually alternative container concepts should be considered concerning different host rock options and for optimisation purposes.

Phase 3: DGR Site Characterisation	After site selection and comprehensive exploration detailed information about the respective host rock formation will be available. On this basis, the container design should be launched in a stepwise approach. In a first step, a decision on the disposal concept is needed. In a second step, the set of container design requirements should be accomplished and finalised. Different technical solutions for an adequate or most suitable container concept should be considered. A comparative analysis of different potential container concepts should demonstrate the compliance with the respective set of design requirements. Finally, the most suited container concept should be chosen and realised. This includes an elaborated and adequate quality management (QM) system and programme for container development, manufacturing and operation including handling and loading procedures filling in a conditioning plant including a hot cell. In addition, it is recommended, that procedures for further optimisation of container design, materials, manufacturing, and operation is enabled.
Phase 4: DGR Construction	Parallel to the repository construction, the container manufacturing has to be launched in compliance with the appropriate QM programme. All steps of the entire manufacturing process must be approved in advance and documented in the approved way. This includes results of all defined verification tests of containers, all their components and material properties. The schedule of container manufacturing, delivery, loading in the hot cell and emplacement in the repository has to be adjusted to the schedule for repository operation.
Phase 5: DGR Operation and Closure	During DGR operation, the required number of approved waste containers has to be loaded with the appropriate waste type (HLW or SNF) and sealed in a conditioning plant with a hot cell following the respective QM programme. Subsequently, the loaded containers are transferred to the repository site and disposed of in the emplacement chamber following the emplacement regime of the repository. If the waste conditioning plant is at a different location than the repository, the transfer includes a public transport and the container has to fulfil all respective requirements for the transportation of dangerous goods including safe enclosure of the radioactive inventory and subcriticality even under Type B(U) test conditions and sufficient shielding by self-shielding or an additional transfer cask. If no public transport is necessary, only the safety requirements of the repository site are valid.

2. Contribution to generic safety functions and implementation goals of HLW and SNF disposal containers

This section describes how HLW and SNF containers and their associated information, data, and knowledge contribute to high-level disposal system requirements using EURAD Roadmap Generic Safety and Implementation Goals (see, Domain 7.1.1 Safety Requirements). It further illustrates, in a generic way, how such safety functions and implementation goals are fulfilled. It is recognised that the various national disposal programmes adopt different approaches to how disposal system requirements are specified and prioritised. Each programme must establish its own specific requirements, to suit national boundary conditions (national regulations, different spent fuel types, different packaging concept options, different host rock environment, etc.). The generic safety functions and implementation goals developed by EURAD and used below are therefore a guide to programmes on the broad types of requirements that are considered, and are not specific or derived from one programme, or for one specific disposal concept.

2.1 Features, characteristics, and properties of HLW and SNF disposal containers that contribute to achieving requested safety functions as well as long-term safety of the disposal system.

HLW and SNF containers are exposed to a variety of mechanical, thermal, radiological, chemical, and biological impacts and effects in a repository for high-level radioactive waste. Depending on the safety demonstration concept of the DGR, the waste container, if necessary in combination with geotechnical barriers (e.g., buffers), must provide safety-functions under these impacts for a long period of time. The reference time period varies in national programmes, e. g. 100.000 years in Sweden and Finland, and 1 Mio. years in Germany. The site-specific and repository concept-specific impacts on the container and the respective loads result from the boundary conditions of the repository site, its host rock formation, and the selected repository concept. On the one hand, there are invariable boundary conditions that provide stationary impacts on the waste container over long periods of time, e.g., the host rock geology at the repository site and the corresponding mechanical, hydraulic, chemical, and thermal rock properties at the emplacement level some hundred meters below the surface. In some countries, as long as no site decision is taken, the (potential) properties of different host rock formations have to be considered in parallel: e.g. in Germany currently properties of rock salt, claystone, and crystalline rock. The second major boundary condition with impact on the safety function of the disposal containers is the type and amount of radioactive waste to be disposed of; either spent fuel assemblies from nuclear power reactors, spent fuel assemblies from prototype and research reactors, or waste from the reprocessing of spent fuel assemblies. On the other hand, some impacts are variable and can be adjusted in a safety-oriented manner within the disposal container and repository design phases. Such impacts are for example the envisaged depth of the repository mine, the mechanical impacts from transport and emplacement procedures, the retrieval technology as well as operational disturbances or accident scenarios to be considered. However, there are also boundary conditions and actions that can be influenced by the waste container itself, such as the container materials selected, which influences the geochemical environment in the near field. Thus, the relevant boundary conditions and impacts at the repository site in a country have to be taken into account when developing the waste container concept and design.

2.1.1 Primary goal – long-term safety

Safety demonstration periods up to 100.000 years or even up to 1 Mio years for a DGR require container features and properties depending on the overall repository safety concept under consideration of geological barrier functions and EBS including the disposal containers. In this context, the role of the container as part of the EBS is of importance with regard to the required timeframe for container-specific safety functions. Either the selected container material itself provides corrosion resistance or an adequate overpack or coating may provide this long-term protection function. In addition, backfill and buffer material like clay can support the long-term container resistance. However, the interaction between the elements of the EBS have to be understood and compiled in a way that the long-term material and container behaviour is reliably predictable to ensure the containers' safety functions as long as requested. The basic safety functions contain the safe enclosure of the radioactive waste, sufficient shielding, ensuring sub-criticality and appropriate decay heat dissipation depending on the phases of repository operation like emplacement, potential retrieval or recovery phases, and the post closure phase.

2.1.2 Secondary goal – operational safety during the emplacement phase

The capabilities of the disposal containers to safely enclose the radioactive inventory during all operational processes in the repository, sufficient shielding, sub-criticality, decay heat dissipation are of relevance to ensure operational safety even in case of operational disturbances and potential incidents during all transport and handling procedures of the containers. Sufficient shielding can be managed either by separate shielding overpacks for the transport and handling or by means of a shielding system as part of the container itself. Technical equipment for transportation and handling of the containers has to be adjusted to the dimensions and mass of the containers, which might have different designs and dimensions depending on the types of SNF or HLW to be disposed of. Ideally, handling and operational procedures are standardised as much as possible, also concerning economical aspects. In any case, full-scale demonstration tests with inactive prototype containers could be helpful to demonstrate proper functioning of all technical equipment under field conditions and to improve whenever necessary. However, demonstration test with active material should follow.

2.1.3 Secondary goal – operational safety during retrieval and recovery phase

In many countries, retrievability (during the ongoing emplacement phase) and recovery (after closure of the repository) of the emplaced disposal containers are additional design requirements or at least the feasibility has to be demonstrated. This means that the retrieval and recovery measures must be assessed for the proper and safe functioning of all elements of the EBS, including the backfilling and sealing measures. At least a technical concept for retrieval and recovery measures is needed, in some countries the appropriate technical and operational measures have to be demonstrated prior to the application for repository construction and/or operation licenses.

2.2 Features, characteristics, and properties of HLW and SNF containers that contribute to achieving long-term interim storage safety and subsequent potential implementation of geological disposal

Because of the globally pending establishment of deep geological repositories for high-level radioactive waste, interim storage of SNF and HLW, whether under wet or dry conditions, is the necessary pre-disposal step as part of safe nuclear waste management. In case of wet storage, SNF is stored in pools waiting for later conditioning and/or packaging into disposal containers. In case of dry storage, SNF and HLW are transferred to containers for long-term dry interim storage. Such containers are often also qualified for prior and/or subsequent transportation. Usually, interim storage periods are calculated and licensed for 40 or 60 years with optional extension of the interim storage period to the needs until a DGR is available.

Safety goals and safety functions of interim storage containers are basically the same as for disposal but under the different boundary conditions of an on-surface storage facility. As the requirements for disposal containers have not been available so far, containers developed and designed for interim storage do not consider design features for deep geological final disposal. This means, they can be considered as potential disposal containers as well, but in this case their compliance with the disposal requirements and necessary design improvements have to be carefully analysed and evaluated. In contrast, specifically designed disposal containers are optimised for final disposal and with that usually have significant advantages (e. g. in selection of materials) under deep geological disposal conditions. On the other hand, a potential direct disposal of interim storage containers avoids transfer and conditioning of SNF assemblies in an elaborated conditioning plant and also lots of secondary wastes as e. g. the emptied interim storage containers.

3. International examples of HLW and SNF containers

The status of the international HLW and SF container development processes varies largely and is exemplarily shown in the table below. Depending on the host rock considered in the country, different technical concepts have been selected and developed. One example is the Swedish-Finnish KBS-3 container concept for a repository in crystalline rock. The container consists of an inner cast-iron structure accommodating the entire spent nuclear fuel assemblies and an outer 50 mm thick copper shell. This container type for crystalline rock is designed ensuring all long-term safety functions like the safe enclosure of the radioactive inventory throughout a very long period of time, up to the entire country-specific reference period of 100,000 years in this case. The design premises for the container are based on regulatory requirements, operational requirements, of the KBS-3 repository design, the design basis cases of the long-term safety assessment, the design basis events of operational safety assessment, and the technical and production feasibility.

Another example is the Belgian so called Super-Container for a DGR in a clay formation. The container consists of a steel cask containing the SNF or the HLW and a concrete shielding. The EBS of the selected repository system is adjusted to the materials of the Super-Container.

In Germany a container concept for a DGR in rock salt, the so-called POLLUX® container has been developed and tested in the past. The concept relies on a self-shielded double-hull container (steel and cast-iron) for disassembled fuel rods or HLW canisters. For transport and handling processes, no further shielding is needed. A single prototype has been manufactured and full-scale transport and handling experiments have been successfully performed in the early 1990ies. Since the restart of the HLW repository siting process has been launched in 2017, container concepts for all three different kinds of host rock (rock salt, claystone, crystalline rock) are going to be developed in the next years before the final site selection will be made including the entire repository concept and the disposal container design.

Host rock	Container concept (Developers)	Description	Status of development
Crystalline Rock	**KBS-3** (SKB/Posiva Oy, Sweden, Finland)	unshielded double-hull cask (cast-iron cask with solid copper cladding) for fuel assemblies	well advanced in the licensing procedure (tests for production, loading, sealing, transport, storage)
	UOS (Škoda, Czech Rep.)	unshielded double-hull cask made of different steels for fuel assemblies	concept study derived from KBS-3 ("KBS-3 made of steel")
	UFC II (NWMO, Canada)	unshielded steel container with thin copper coating for (CANDU) fuel assemblies	advanced concept (material, production and container tests)
Claystone	**Category C Container** (Andra, France)	unshielded steel canisters or fuel assemblies	advanced concept (material, production and container tests)
	Supercontainer (ONDRAF/NIRAS, Belgium)	steel cask for fuel assemblies or HLW canisters enclosed in concrete	Material tests
	Reference container (Nagra, Switzerland)	unshielded, robust steel container for fuel assemblies or HLW canisters	generic design for fuel assemblies and canisters
Rock salt			considered by RWM as a possible reference concept for final disposal containers in salt
	BSK-3 (GNS, Germany)	unshielded steel canisters for the borehole storage of drawn fuel rods or HLW canisters	Concept developed in R&D reports; emplace-ment technology tested on dummy
	POLLUX®-10 (GNS, Germany)	shielded double-hull cask (steel and cast iron) for drawn fuel rods or HLW canisters	advanced concept (POLLUX®-8 manufactured as prototype; storage technology tested)
--	**Transport and Storage Casks, e.g. CASTOR®** (GNS, Germany)	shielded transport and interim storage casks made of cast iron or forged steel for fuel assemblies or HLW canisters	Existing containers; suitability for final disposal not yet considered

Figure 3-1: Compilation of HLW and SNF container types for different host rocks in several countries (Bollingerfehr et al., 2021)

4. Critical background information

This section highlights specific components, key information, processes, data or challenges that have a high impact or are considered as critical for implementing geological disposal, with respect to the domain of HLW and SNF containers.

4.1 Pre-disposal

With regard to the disposal container design for SNF and HLW, detailed knowledge of the nuclear and physical properties and status of the SNF and the HLW is essential prior to the development of specific container designs. As long as these relevant data are not available, assumptions have to be made which can be gradually improved according to the availability of results from further suitable RD&D activities. These RD&D activities have to be started at least in parallel with the container development process. In particular, the long-term performance, mechanical stability and integrity of SNF is an essential prerequisite for later handling options during the conditioning and container loading process for final disposal.

4.2 Repository layout and design

As mentioned before, disposal containers are essential components of any EBS of a DGR for HLWSNF. In this context, the disposal containers have to provide several safety functions: containment, shielding, sub-criticality, and sufficient decay heat dissipation of the radioactive inventory during the operational period of the repository as well as for the long-term. Prior to the container concept development and planning process, the role of the container as part of the EBS has to be defined in an early planning phase of the repository concept. This means that sets of requirements have to be derived for each EBS element considering regulatory requirements, operational requirements and requested safety functions with regard to the role of the container in the EBS. These requirements need to be transferred to design criteria for the container and its components considering the safety demonstration period (e. g. 100,000 years or 1 Mio. years): sub-criticality, corrosion resistance, chemical stability, thermal stability and heat transfer capacity, mechanical stability, shielding, etc.

Regarding the repository design, there is a need for a few decisions necessary to start with realistic impacts on the container. This includes on the one hand a comprehensive compilation of geological data at a future repository site and on the other hand a decision on the repository concept itself. It makes e. g. a significant difference if an unshielded container will be disposed of in vertical or horizontal small boreholes or if a self-shielding container will be disposed of on the floor of large emplacement rooms.

Consequently, a decision on the transport and handling system, either with or without additional shielding overpacks for the operational period has to be taken as well.

In addition, information about the retrieval and recovery measures and procedures – if required by the country – are needed to take their potential impacts on the container design into account.

4.3 Post closure

With regard to the disposal container design, the set of requirements from all relevant areas should be as complete and precise as possible to enable the development of a safe and efficient container design for the entire disposal period including the post closure phase. In this context, the long-term performance of the container including all materials and components under the expected or assumed boundary conditions of the geological formation in combination with the EBS have to be understood and assessed. This means, properties and characteristics of the finally fabricated series containers should comply with those used during the design process. Thus, it is recommended to exchange information and data with the group performing long-term repository performance assessments on a regular basis to ensure consistency of data.

4.4 Integrated information, data or knowledge (from other domains) that impacts understanding of HLW and SNF containers.

In particular, information and data of SNF and HLW evolution (nuclear decay, ageing) prior to disposal provide relevant input for proper disposal container design. Whereas HLW ageing after reprocessing is of minor relevance due to the stable waste form (glass matrix in stainless steel canisters), SNF alteration during dry interim storage in containers over several decades might have a relevant impact on the later conditioning and container loading process for final disposal. Thus, data on the expected properties and status of SNF and HLW after interim storage are of significant relevance for disposal container development and design.

5. Maturity of knowledge and technology

This section provides an indication of the relative maturity of information, data and knowledge of HLW and SNF disposal containers as well as past and ongoing (RD&D) projects. It includes the latest developments for the most promising advances, including innovations at lower levels of technical maturity where ongoing RD&D and industrialisation activities continue.

5.1 Past and ongoing (RD&D) projects

The development of containers for SNF and HLW has so far been considered internationally more or less as a design activity of the WMOs or the waste producers in close correlation to the development of the repository design. Since there are only two countries worldwide that have received a license to construct a repository from their national authorities recently, past RD&D projects dealt solely with the development of SNF and HLW disposal concepts. At least one RD&D project funded by the European Commission, acronym ESDRED, dealt with the development of transport and handling processes and technologies for SNF and HLW disposal containers on an industrial scale (https://igdtp.eu/activity/esdred-engineering-studies-and-demonstrations-of-repository-designs/).

A few years ago, a R&D project in Germany, acronym KoBrA, focussed on the systematic derivation of design requirements for SNF and HLW containers. The final report includes a status report on waste container development worldwide as well as a collection of regulatory and technical requirements with regard to protection goals and the level of safety. Under consideration of mechanical, thermal, radiological, chemical and biological impact factors during all phases of repository operation and after its closure, a methodological approach was derived to determine container requirements in a systematic way. Based on this the container design can be developed by identification of the necessary container functions to fulfil all requirements under the relevant impact factors during all phases. The report closes with principal ideas of different potential container design for different host rocks (Bollingerfehr et al., 2020).

Most ongoing RD&D Projects on the development of container designs for SNF and HLW are subject of WMO-internal activities. Some of the results were published recently. For a more detailed view in this domain, the SoK document on HLW and SF containers is available. The DI 3.2.3 "Containers using advanced materials (Novel Containers)" describes the consideration of different materials for container production. EURAD WP15 about the optimisation and evaluation of the behaviour of materials for disposal containers in view of their long-term barrier performance also published different documents on the EURAD website.

5.2 Lessons learnt

Each country, i.e., each responsible WMO, which has launched a programme to develop SNF and HLW disposal containers, has its own experience of the complexity of the design process. In particular, lessons have been learned from the need for validated data sets of the type, amount, and properties of expected HLW and SNF over time, the type and characteristic of the host rock/geological environment of the proposed DGR as well of the decision/selection about the repository concept.

If a country/WMO has no design experience for SNF and HLW containers, and the repository project is more or less in an early stage, it may makes sense to develop an approach that enables a systematic derivation of qualitative and quantitative requirements for the containers. Based on such an approach, a methodology for the assessment of the transferability of existing national and international waste container concepts and for the development of generic container concepts that meet the requirements can be developed as well. In this context, it should be noted that there is a limit to take advantage of already existing disposal container concepts because usually there are lots of differences due to different regulatory frameworks, different host rock parameters, and different potential repository concepts. For instance, requirements for container retrievability vary and requirements for recoverability (after repository closure) do not exist at all. It should be also known that, apart from safe containment and the radiological requirements, thermal requirements differ from country to country. The final report of the R&D project KoBrA revealed the following main recommendations for future waste container development. Most of them are applicable for all newcomers in the domain of SNF and HLW disposal container development:

- Accomplishment of the detailed data set of the expected type and amount of SNF and HLW in the country including time dependent processes like ageing.
- Definition of the site-specific requirements for SNF and HLW containers.
- Improvement of the geological database for the host rocks and potential repository sites to determine host rock- and site-specific impacts on SNF and HLW disposal containers.
- Assessment of the impacts on the SNF and HLW disposal containers induced by operational processes.
- Development of suitable repository concepts including transport and emplacement techniques.
- Robust container concepts are recommended utilising proven materials and technologies that have already been developed and tested as far as possible and that can be manufactured reliably.
- Production of SNF and HLW disposal containers to the required quality standards must be possible in due time in the required large quantities.

Flexibility is required during the entire design process. Nothing is fixed, unless final data are available and accepted.

6. Uncertainties

As the implementation of DGRs for SNF and HLW require time periods of several decades one most relevant uncertainty is the status of SNF and HLW at the time of containerisation for final disposal. In any case, a detailed specification of the SNF and HLW is needed for appropriate waste container design. Ongoing RD&D activities might provide adequate data and information, e.g. the stability of spent fuel rod tubes over very long time of interim storage up to 100 years.

Another uncertainty is linked to the status of SNF after decades of interim storage. There is a lack of knowledge and data to which extent aging of SNF assemblies lead to adjustments of processes and techniques for disassembling entire spent fuel assemblies in a conditioning plant (hot cell) or for handling of altered fuel assemblies at the time of disposal container loading.

In many countries, site selection processes for a DGR for HLW and SNF are still in an early stage or were stopped and completely reset. Thus, reliable data and information on the host rock is not available yet. This means that the container design has to be launched with appropriate assumptions for the host rock characteristics and might be adapted at a later stage as soon as site-specific knowledge on the host rock characteristics is available.

The containers for HLW and SNF are part of the EBS of a selected repository system. In order to specify the detailed requirements for the containers, it is necessary that a decision on the repository concept and the appropriate EBS is made at the earliest possible stage of the site selection process. As long as site selection, repository concept and EBS have not been fixed, all concept and design activities for SNF and HLW disposal containers are of preliminary character.

7. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with people, focussed on the domain of HLW and SNF containers.

No explicit information for guidance, training etc. is available so far. There are few countries with advanced disposal programmes like Finland and Sweden, which do have well documented design experience for disposal containers for SNF or even have container construction facilities.

8. Further reading, external Links and references

8.1 Further Reading

- https://skb.se/upload/publications/pdf/TR-10-14.pdf
- https://www.osti.gov/etdeweb/servlets/purl/1013206
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8.2 External Links

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- https://www.posiva.fi/en/index/finaldisposal/encapsulationplant.html
- https://international.andra.fr/innovative-pre-disposal-projects-disposal-containers-and-waste-conditioning
- https://igdtp.eu/activity/esdred-engineering-studies-and-demonstrations-of-repository-designs/
- https://cordis.europa.eu/docs/projects/files/508/508851/104143971-6_en.pdf
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and see Chapter 8.1 Further reading

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