Review study on direct disposal of Transport and Storage Casks in Norway

Technical Note – BGE Technology GmbH

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1 OVERVIEW OVER DIRECT DISPOSAL OF TSCS IN GERMANY

Casks for transport and storage of spent nuclear fuel have been designed and built in Germany for interim storage of spent fuel elements and their transport between nuclear power station, interim storage sites and a site for final underground disposal. In programs for final disposal of nuclear waste, it is generally planned to design waste containers specifically for the purpose of disposal. Spent fuel would then be removed from the Transport and Storage Casks (TSCs) and inserted into the waste containers for disposal. This process would take place in a nuclear encapsulation plant and would usually include the dismantling of spent fuel elements so that only the spent fuel rods will enter the disposal container. This ensures easier demonstration of sub-criticality and a compact storage of rods. Remaining structural elements from the dismantled spent fuel elements will be disposed of in separate containers.

Direct disposal of TSCs, or dual-purpose containers as they are usually called internationally, is based on the idea that the fuel elements from nuclear reactors are not dismantled. Instead, the idea is to not only use TSCs for transport and interim storage but also for final disposal in an underground repository. This creates challenges with regard to handling very heavy waste casks in shafts/ramps and in the underground. In addition, sub-criticality of the spent fuel has to be ensured in the post-closure phase of a repository for which the TSCs have not been designed.

1.1. Transport and Storage Casks

In the case of direct disposal of TSCs in Germany, different existing types of casks have to be taken into account:

- CASTOR® V/19 for spent fuel elements from Pressure-Water Reactors (PWR)
- CASTOR® V/52 for spent fuel elements from Boiling-Water Reactors (BWR)
- CASTOR® 440/84 for spent fuel elements from Water-Water-Energy Reactors (WWER)
- HLW from reprocessing (CSD-V, CSD-B, CSD-C) in CASTOR® HAW 20/28 CG, CASTOR® HAW 28 M, TN 23 E, TS 28 V and TGC 27

The transport and storage casks consist of a ductile cast iron body in the form of a hollow cylinder closed at one end. Axial holes are filled with polyethylene (PE) rods as moderators that provide shielding in collaboration with neutron-absorbing elements made of boron. Inside of each cask, a basket holds the fuel elements. The casks are closed by a double-lid sealing system from stainless steel. On the outside, the hull is equipped with cooling fins to regulate the temperature of a cask. Currently, TSCs are used for interim storage. Suitability for final disposal still has to be demonstrated should that idea be further developed. Detailed product information on CASTOR® casks can be found on the website of the German TSC manufacturer (Website of GNS Gesellschaft für Nuklear-Service mbH). Figure 1 shows the conceptual structure of two CASTOR® casks for spent fuel and HLW from reprocessing.

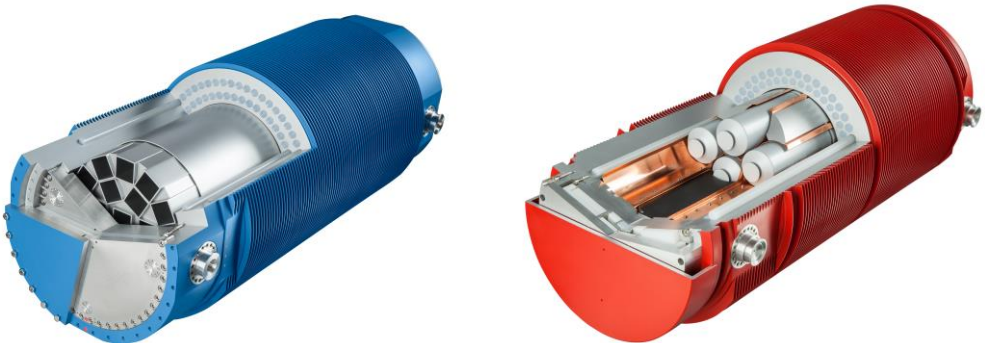

Figure 1: Representation of a CASTOR® V/19 TSC (left) and a CASTOR® HAW 28 M (right) from GNS Gesellschaft für Nuklear-Service mbH.

Within a few centuries after disposal in a repository, it is expected that contact with ground water will corrode the hull of the TSCs and enter the interior structure. This will then result in corrosion of the internal elements like the heat-conducting plates and absorber rods. This will have two effects that are detrimental to criticality:

On the one hand, since the heat-conducting plates are to a large part made of aluminium, their corrosion will enrich the groundwater solution with aluminium hydroxide, $Al(OH)_3$, which is unfavourable for ensuring sub-criticality. On the other hand, by corrosion boron is removed from the heat-conducting plates and the absorber rods. Thus, the neutron-absorbing function of the plates and the rods that relies on boron will be fulfilled in a less effective way or not at all. Both effects can be counteracted by filling the voids in the TSCs with a suitable material before disposal. This can prevent spreading of corrosion products like $Al(OH)_3$, and, if the correct material is chosen, can compensate the boron loss in the heat-conducting plates and the absorber rods.

Criticality analyses have shown that several different materials may be suitable as filling material to ensure sub-criticality. Besides magnetite, titan(IV)-oxide, depleted triuranium octoxide and boron carbide have been considered. The success of ensuring sub-criticality is highly dependent on the practical challenge to fill as much of the voids in the, probably vertical, TSCs with the granular filling material. In addition, material may not unfavourably accumulate in certain parts of a TSC while it is lying horizontally during transport and after emplacement. Technical aspects regarding the filling of the TSCs have not yet been developed.

Approximately 1,400 transport and emplacement operations are expected in disposing of TSC in Germany. A total of 160 Mg[1] is assumed as the covering cask mass of a TSC after filling the voids to ensure sub-criticality. Of all TSCs in Germany, the CASTOR V/19 containing 19 fuel elements from PWR has the highest thermal output. The basic data for TSCs is shown in Table 1.

Table 1: Overview over basic data (ranges) for TSCs with spent fuel.

Length/Height [mm]	**Diameter [mm]**	**Weight [Mg]**	**Max. weight after filling [Mg]**	**Max. thermal output after 60 years of interim storage [W]**
4,080 – 6,200	2,430 – 2,660	110 – 126	160	10,000

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[1] megagrams or metric tons

In German repository concepts that rely on direct disposal of TSCs in salt rock, the cask itself is not a relevant barrier for the long term containment of SNF/HLW. The function of long term isolation and containment is entirely based on the host rock and the closure concept of the repository (Chapter 2). However, waste containers have to stay intact for a period of 500 years after repository closure. This timeframe is supposed to sufficiently cover future scenarios that might lead to a decision for waste retrieval. The integrity of the waste containers is the central requirement that ensures feasibility to realise such a decision. Whether it can be demonstrated that TSCs can meet this requirement remains to be investigated.

1.2. Hoisting technology for very large loads

For direct disposal of TSCs in a geological repository, the means of transportation from the surface to the underground are a critical issue. A single cask can weigh up to 160 Mg. The weight is even higher if there is a need for a shaft transportation cart, which weighs around 15 Mg. The total payload to be transported by a shaft hoisting system is thus 175 Mg, which is unusually high for shaft hoisting. Therefore, BGE TEC developed a hoisting system (Figure 2) for that purpose, basing the design on the regulatory requirements for shaft hoists in Germany (TAS)[2]. The development was performed with the Gorleben salt dome in mind, which was the designated site for an SNF/HLW repository at the time. Hence, a specific repository depth of 870 m was used for all calculations.

A friction hoist (also called Koepe hoist), tower mounted, was chosen and equipped with six steel ropes (66 mm in diameter), resulting in a sufficient safety factor of 6.77 with regard to their tensile strength. In one regard, however, the design did not follow the safety requirements from TAS. The contact pressure between ropes and their respective groove surface on the winder exceeded the allowable (340 N/mm² vs. 200 N/mm²). However, this was accepted due to the very slow hoisting velocity of 1 m/s on the one hand and, on the other hand, after comparison with equally high pressures accepted in the design of funiculars in Switzerland. In a peer review by an independent expert employed in the technical verification and licensing of shaft hoisting systems in Germany, it was agreed that this was a reasonable and safe approach.

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[2] Technical Requirements for Shaft Hoisting Installations and Inclined Hoisting Installations (TAS – Technische Anforderungen für Schacht- und Schrägförderanlagen) from December 2005, generally referred to as “TAS“

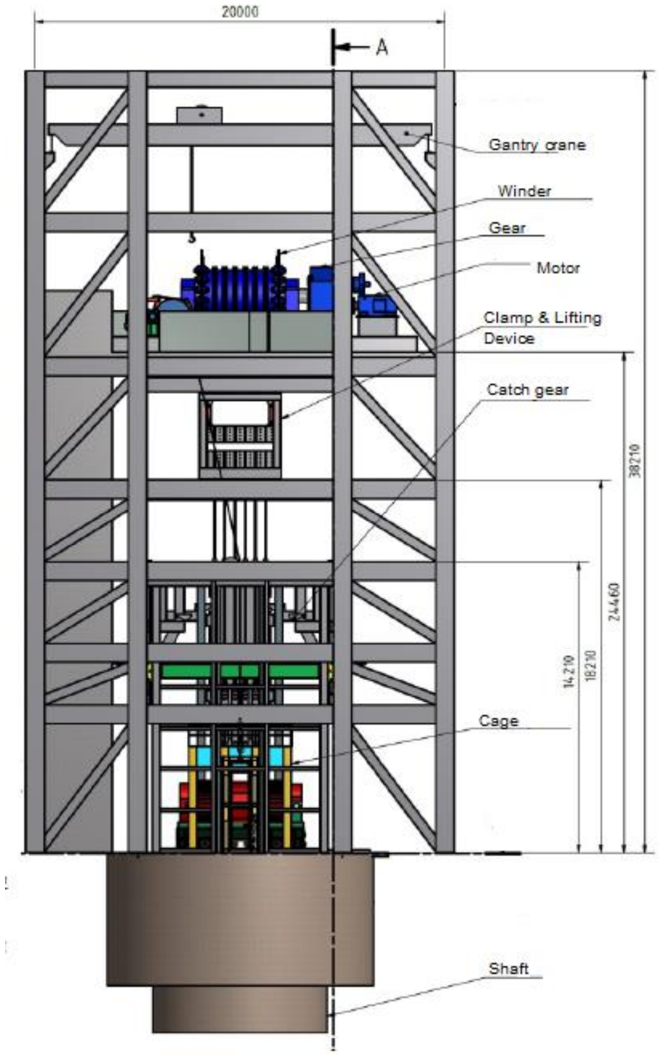

Figure 2: Model of the shaft tower with hoisting system for 175 Mg payload. Dimensions are in [mm].

The casks are conveyed from the surface to the disposal level in a specially designed hoist cage. The hoist cage features a waste transport platform that is free to move vertically within the cage framework. At both the surface shaft station and landing station, cage-latch systems are used to grasp and immobilize the platform. The framework of the cage then detaches from the platform and hangs freely from the hoist ropes. With this “false bottom” transport platform immobilized and detached, the ropes are protected against dynamic stresses resulting from the loading or unloading operations with the very heavy loads.

The hoisting system, as a whole, was judged to be feasible and safe by the peer review mentioned above. BGE TEC wrote a comprehensive report on this hoisting system for Sandia National Repositories in 2017: “Hoisting of 175 Mg payloads for a generic waste repository for used nuclear fuel” (TEC-08-2017).

The transport of such payloads in ramps has not been investigated by BGE TEC. But the general state of the art of funiculars strongly suggests its feasibility.

1.3. Underground transportation and emplacement technology for TSCs

In contrast to other German disposal concepts that rely on waste casks of lesser weight, direct disposal of TSCs involves reloading at the shaft landing station. First, the shaft transportation cart loaded with a TSC is removed from the cage by a sub-floor push-on and pull-off device. With a gantry crane or similar means, the TSC is reloaded onto the Drift Transport and Emplacement Device (STEV). The loaded STEV is then brought to the emplacement location with the help of two electric locomotives. At the emplacement location, the superstructure of the STEV, on which the TSC lies on a sliding carriage, is rotated by 90°. Thus, the TSC is brought into the emplacement position. The TSC on top of a sliding carriage is then hydraulically pushed into a horizontal short borehole (Figure 3). The sliding carriage remains in the borehole.

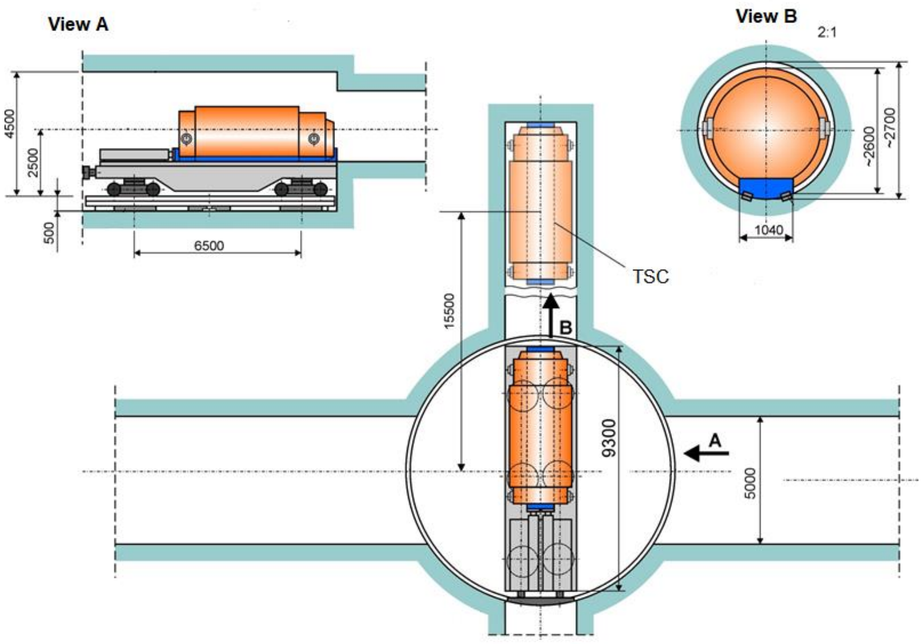

Figure 3: STEV operation during emplacement.

The STEV consists of several elements:

- Sliding carriage

When on the STEV, the TSC rests on a sliding carriage. The carriage is pushed into the borehole during emplacement and remains there. It is built as a steel framework. Underneath, coupling points for the claw of the hydraulic main cylinder of the STEV are attached. The carriage is pushed into the borehole on sliding blocks or on heavy duty rollers. In case of sliding blocks, low-friction coating is applied on these to limit the necessary thrust forces.

- Understructure

The STEV is equipped with two bogies. These are each equipped with 2 axles and are used to move the STEV on the rails. The STEV has no drive and no brakes. Driving and braking is done by the battery locomotives.

- Superstructure

For positioning the TSC in the emplacement holes, the STEV is equipped with a rotatable superstructure. The superstructure and understructure are connected by a ball bearing slewing ring. The rotation of the superstructure is made possible by a motor, which engages in a toothing on the ball bearing slewing ring via a worm drive.

- Push-in device

A hydraulic cylinder is used to push in the sliding carriage loaded with the TSC. It is mounted centrally on the superstructure below the carriage. This hydraulic cylinder is single-stage and of standard design. A gripper is attached to the end of the piston rod, which is coupled to the carriage. The main cylinder is designed with a length of approx. 6 meters. However, a stroke distance of approx. 14 meters is required for emplacement operation. To start the insertion process, the main cylinder with the gripper is attached to a coupling point at the front of the carriage and a stroke is executed over the full length of the cylinder. The gripper is then disengaged via the adjustment cylinder and retracted to the stop point for the second stroke. Here, it is recoupled and the second stroke is executed. The cylinder is then decoupled, retracted again, coupled to the last stop point at the end of the carriage, and the remaining stroke is executed.

- Hydraulic system

The necessary hydraulic unit is mounted at the end of the STEV above a bogie. It consists of a pump station and a hydraulic tank with a volume of approx. 1,500 litres. Fire resistant HFC fluid is used as the hydraulic fluid. The power supply to the unit is provided by the battery locomotive.

The complete current design (without hydraulic unit) of the STEV is shown in Figure 4.

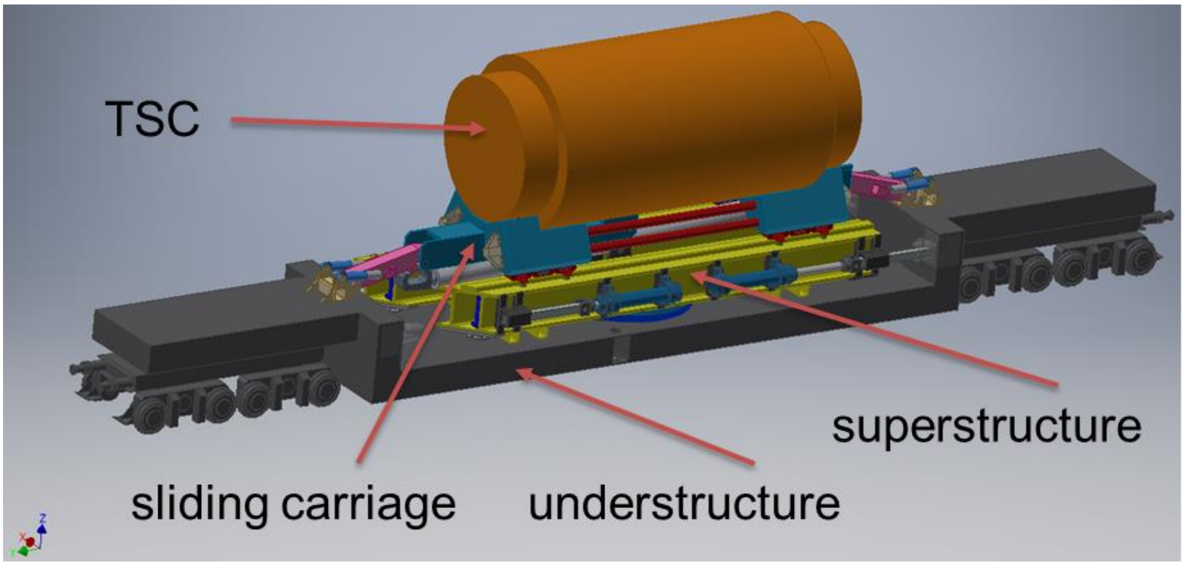

Figure 4: Current design of the transport and emplacement device for TSCs.

2 INTRODUCTION TO EXISTING REPOSITORY CONCEPTS FOR DIRECT DISPOSAL OF TSCS

2.1. Disposal in salt rock

The design of the repository layout is based on the results of numerical thermal calculations to ensure conformity with maximum allowable temperatures as well as space requirements of the transport and emplacement technology. The emplacement area is made accessible by two main drifts. An emplacement field consists of a cross cut that connects the two main drifts with each other and horizontal short boreholes that can accommodate one TSC each. The design of the cross sections of the different types of openings (main drifts, cross cuts and boreholes) is based on the necessary technical equipment in these sections. The final emplacement of transport and storage casks is carried out in short horizontal boreholes using crushed salt as backfill material.

Different types of waste are distributed in the following way: the waste with the highest heat production (PWR) will be emplaced in the emplacement fields near to the shaft, the cooler waste in the emplacement fields’ farther away from the shaft (e.g. WWER). This ensures the highest convergence of salt rock and compaction of backfill close to the shafts, sealing the pathway along drifts and the shafts for radionuclides into the biosphere soon after closure of the repository.

Due to the high thermal output of CASTOR® casks it is necessary that each short disposal hole almost fits the diameter of the individual cask. The gap between the cask and the hole, which will be backfilled with crushed salt, is therefore limited to 7.5 cm. This provides a good thermal connection to the rock. The lower thermal conductivity of crushed salt as compared to rock salt will otherwise lead to a higher temperature if the gap is increased. This assessment required a thermomechanical simulation approach for the design of the repository based on the stress-dependent behaviour of crushed salt. A maximum design temperature at the cask surface of 200 °C was ensured by this design based on the tolerance of the salt rock to withstand such a high temperature without disadvantageous alterations. The thermomechanical calculations were carried out by varying the pillar size among the emplacement drifts in the parameterized calculation model. The disposal hole spacing within a drift was set to 20 meters. This value was derived from the requirements of the emplacement technology. The hottest point on the cask is located at the lowest point of the cask hull in contact with the crushed salt. This is where the thickness of the crushed salt is greatest due to the open spaces created by the sliding carriage underneath the TSC.

To emplace all spent fuel created in Germany until the phasing out of nuclear energy in 2022, the resulting repository layout is 3,300 meters long. The width of the repository is 470 meters. The repository has a footprint of approximately 1.6 km². These figures are highly dependent on disposal depth and the virgin rock temperature, though. Figure 5 shows the principal layout of cross-cuts and horizontal boreholes.

Long term containment of the waste is achieved by the following strategy:

- Construction of sealing elements in the main drifts, sealing the emplacement area from the shafts
- Construction of shaft seals to separate the underground from aquifers and the biosphere
- Backfilling of the emplacement area with crushed salt directly after emplacement that will compact due to salt rock convergence until it almost matches the low permeability of salt rock
- Backfilling of infrastructural areas with porous crushed rock to serve as a retarding reservoir for incoming fluids
- Demonstration of integrity of the salt host rock so that no water bearing fissures have to be expected in the rock to connect the repository with aquifers above or below.

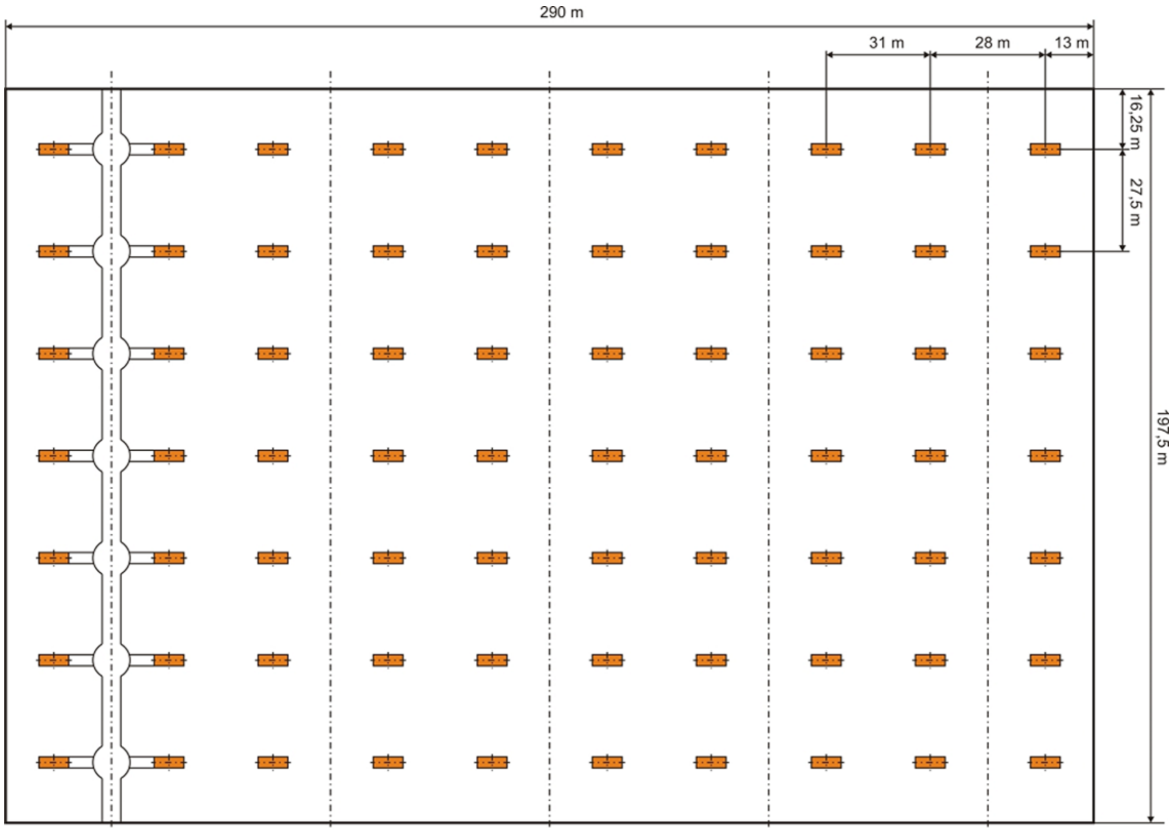

Figure 5: Principle of underground layout in the emplacement area

2.2. Disposal in clay rock

Feasibility of the direct disposal of TSCs in salt rock relies on the high thermal conductivity of salt rock and a maximum design temperature of 200 °C at the surface of the waste cask. Clay rock has much lower thermal conductivity and less tolerance to high temperatures. Therefore, the approach has to be slightly different. A maximum design temperature of 150 °C is accepted at the host rock in contrast to 200 °C at the cask surface. Waste cask and surrounding buffer may experience higher temperatures than 150 °C. The annulus around the TSC is therefore increased in order to decrease the thermal load on the host rock. That annulus, including spaces among the cooling fins of the TSCs, is backfilled with low-pH cement. The design temperature limit of 150 °C at the host rock is higher than what is accepted e.g. in Switzerland or France (less or up to 100 °C). This is based on three separate arguments:

1) It is known from various investigation programs on claystone that the thermal expansion of the rock turns into compaction above a certain temperature and depending on the consolidation ratio of the rock. The compaction results from a weakening of the friction between the clay particles, which ultimately leads to a reduction of the pore space with simultaneous displacement of pore water. Compaction irreversibly increases the strength and stiffness of the claystone. The decrease in porosity associated with thermal compaction also leads to a decrease in permeability. The swelling ability of the rock might be reduced when exposed to high temperatures, although the research is not yet conclusive. On the other hand, creeping seems to be enhanced at least up to 110 °C. In total, these processes might be positive for long-term containment.
2) From a chemical/mineralogical point of view, the illitization of smectites and an associated impairment of the sorption behaviour are to be considered at elevated temperatures. Typically, illitization is expected at temperatures above 350°C. Other processes such as thermochemical sulphate reduction or kerogen transformation are also assigned only minor influences at temperatures up to 150°C.
3) The last argument is about microbial processes and iron reduction. Corresponding microbes are endemic in clay rocks and can remain active up to 122°C. The gas evolution and gas pressure formation associated with biogenic metal corrosion can lead to overpressure and ultimately to cracking with corresponding damage to barriers. Other sulphate-reducing species are equally inactive at temperatures around 120°C. In the course of limiting microbial activity, a temperature increase above 122°C would significantly reduce the population and activity of sulfate-reducing or Fe(II)-reducing and methane-producing microbial species, respectively. With the temporary "sterilization" by the increased temperature in the vicinity of the containers and thus a limitation of microbial activity, microbial corrosion during the thermal phase is suppressed.

It should be noted that these findings are part of ongoing research and that no significant amount of data is available for temperatures above 150 °C. Based on a different design temperature, mechanical and thermal host rock parameters, the spacing of waste casks after disposal will be different in claystone than in rock salt and result in a larger repository footprint. The general layout can remain the same, though. In clay rock, the long-term containment of the waste is achieved by the following strategy:

- Construction of sealing elements in the main drifts, sealing the emplacement area from the shafts
- Possibly construction of alternating seals in emplacement fields
- Construction of shaft seals to separate the underground form aquifers and the biosphere
- Backfilling of the emplacement area with material based on clay minerals, possibly modified to improve swelling, sealing and mechanical properties; the backfill should over time evolve to have a very low permeability due to swelling and compaction due to rock convergence after corrosion of rock support
- Demonstration of integrity of the clay host rock so that no water-bearing fissures have to be expected in the rock to connect the repository with aquifers above or below.

3 DIRECT DISPOSAL OF TSCS IN NORWAY

3.1. Cask type

Based on the waste types and quantities in Norway, it is assumed that the general structure of a TSC in Norway follows the standard CASTOR® type design with a cast iron body and a double lid sealing system. The client provided some preliminary data that is summarised in Table 2. Compared to the TSCs considered in Germany for direct disposal, the cask types are assumed to be smaller and of less weight. It is assumed that their content produces only a fraction of the heat than a TSC in Germany. As a result, several important challenges of TSC disposal in Germany are not as much of a challenge for such a type of cask.

Table 2: Overview over basic data for realistic TSCs in Norway provided by the client.

	Cask 1	**Cask 2**	**Cask 3**
Diameter (mm)	1,192	1,150	1,950
Height (mm)	2,920	3,245	6,150
Weight (Mg)	20,500	20,000	80,000
Heat Output (W)	Roughly 2,000 W		

A shaft hoisting system to transport these waste casks can operate well within the state of the art of the mining industry and easily follow all applicable safety rules. The means for underground transportation and emplacement presented in Section 1.3 could be adjusted to a smaller and lighter waste cask. Instead of emplacement in short horizontal boreholes, the technically simpler emplacement of the waste casks on the floor of emplacement drifts (drift disposal) could also be a feasible option. Containers for drift disposal like the POLLUX® containers in Germany are comparable to Cask 3 in Table 2 so that the transfer of the transport and emplacement technology to this cask would be possible.

The technical feasibility to emplace a Norwegian TSC in an underground repository in short horizontal boreholes or in drifts is therefore very likely. Further requirements on casks for final disposal still have to be researched to make a final assessment. For TSCs in Germany it seems to be very likely, that by filling the empty spaces inside of the TSCs with a suitable material, sub-criticality can be demonstrated for the post-closure phase of the repository. Whether this assessment holds true for a Norwegian TSC cannot be assessed due to lack of a detailed cask design. An important prerequisite is the technical feasibility of filling the internal voids of a TSC with the appropriate granular material.

The primary requirements with regard to the suitability of a Norwegian TSC for final disposal are assessed as follows:

- <u>Sub-criticality in the post-closure phase:</u> can likely be demonstrated for most TSCs
- <u>Long-term containment of waste:</u> In salt rock and clay rock containment does not need to be specific to the waste cask as containment is provided by the host rock and

geotechnical barriers; in fractured crystalline rock, long-term containment is unlikely since the TSCs will corrode and release radionuclides.
- Thermal requirements: A Norwegian TSC would probably have a comparatively low thermal output so a repository design in appropriate depth that respects relevant maximum design temperatures seems possible for all host rocks.
- Handling: Assumed sizes and weights of a Norwegian TSC pose no problem with regard to handling above or below ground or in a shaft or ramp.
- Retrievability: Integrity of the waste cask might be problematic after longer periods of time (probably decades) due to corrosion.

3.2. Heat development and waste quantities

The rather small assumed thermal output of a Norwegian TSC means reduced challenges for the definition of and compliance to a maximum design temperature, e.g. the maximum temperature at the cask surface or at the host rock. It is interesting to note that the assumed thermal output is in the same order of magnitude as waste containers employed in German R&D for underground repositories with drift disposal in clay rock and crystalline rock. The maximum design temperature in these repository concepts is 150 °C at the waste container's hull. The emplacement depth was around 600 to 700 meters with a host rock temperature in-situ of ca. 30 °C. Due to the lower average surface temperatures in Norway compared to Germany and the lower geothermal gradients, such a repository concept in Norway would have more margin in terms of depth for choosing appropriate geological formations for an underground repository.

However, building an underground repository mine for a maximum of 30 waste containers is a large effort. It would be necessary to excavate accesses to the underground, e.g. in the form of 2 shafts or a shaft and a ramp. Two accesses are usually required for security purposes as one access always remains available as an escape route. The underground will then be rather small and only needs to host a few drifts for emplacement and possibly smaller mine openings for infrastructural purposes.

3.3. Thoughts about the host rock and conclusion

In Norway, crystalline rock is assumed to be the dominant type of rock for the underground disposal of nuclear waste. Possibly, a repository site in clay rock could be found. Long-term containment of nuclear waste that is disposed of in cast-iron TSCs depends largely on the low permeability and integrity of the host rock as well as geotechnical barriers and backfilling material. The TSCs will corrode over time in the presence of ground water and release radionuclides. In a clay rock formation with low permeability, the radionuclides will travel only very slowly through the host rock and the backfilled former underground repository as well as be retarded by sorption at clay minerals in rock and backfill. Nuclides that reach the biosphere will be heavily diluted and decayed, posing only small doses on potentially present human beings at the surface.

Crystalline formations contain faults and hydraulically active fractures. It is unlikely to find rock masses with a low enough permeability to function as a significant barrier against radionuclide migration. Thus, repository concepts in crystalline rock rely heavily on the long-term integrity of the waste container and an engineered barrier system. Waste containers are therefore equipped with a corrosion resistant shell like copper and are often based on the KBS-3 design of SKB and Posiva. Cast-iron containers like the TSCs in question are not designed for that purpose, thus will corrode in such an environment and release radionuclides early in the post-closure phase.