Robustness, A Design Principle for the Operation of a Repository for Heat-Generating Waste? - 10011

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ABSTRACT

The common goal of all repository concepts is the safety in the post closure phase of a repository. But by this the safety of the operational staff and the today public should not take a back seat. This must be an emancipated goal beside the safety in the post closure phase. A keyword in the frame post closure safety is the robustness of the repository concept. The same keyword could be used in context of operational safety of a repository. Robustness in this sense include in particular:

- Conceptional reduction of nuclear risks;
- Conceptional reduction of radiation exposure for the operational staff and the public and
- Conceptional reduction of generating secondary waste.

The question is how the goal of a robust operational repository concept could be achieved on the basis of existing operational experience.

INTRODUCTION

With the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" [1] brought into force by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety in July 2009, the requirement for robust operation of a repository for heat-generating radioactive waste (internationally HAW) is raised for repository planning in Germany.

Based on the disposal concepts of drift emplacement and borehole emplacement discussed in Germany and with an additional comparative consideration of a ramp and shaft as accesses to a geological repository mine, the present analysis tries to provide an answer by way of example to the question of how the requirement for robustness can be conceived. In this context, the engineering notion that the operational safety and the availability of a system do not also necessarily increase with growing complexity of a technical system plays an essential role.

If one takes the primacy of safety as a basis, simple technical systems may prove advantageous for operational safety. Within this context, the question should be asked in the planning of handling and transport processes for high-active waste as to whether certain processes may possibly be avoidable. The best measure for avoiding an anomaly or incident during operational processes may perhaps consist in completely avoiding a specific operational process. For example: If a waste package is not lifted, it cannot be dropped, either. Technical design measures for systems are tried and trusted means of avoiding anomalies. However, the best way of avoiding anomalies may also consist in refraining from technical operations.

The planning of a repository and disposal concept for waste packages containing high-active waste is determined by a large number of boundary conditions, such as the geological events of the site and the waste management prior to final disposal. These boundary conditions may have a lasting influence on the planning of repository operation. The question of the robustness of repository planning may in this respect only be answered in a holistic and balanced manner, taking account of all boundary conditions.

GENERAL OUTLINE

Concepts for Drift and Borehole Emplacement

The first concrete planning measures for a German repository concept for heat-generating waste date back to the end of the 1980s. Following the decision that irradiated fuel elements may be directly disposed of in a repository, the so-called reference concept was developed according to which irradiated fuel elements in POLLUX repository casks may be finally disposed of by emplacement in drifts and POLLUX canisters may be finally disposed of by emplacement in boreholes. It was possible to prove the technical feasibility of the repository concept through analyses and inactive demonstration trials. The concept referred to the final disposal of the heat-generating radioactive waste in rock salt.

Since the 1980s, the regulatory, conceptual and technical notions concerning final disposal of heat-generating waste (and on an international level concerning high-active waste) have further developed. For example:

- The reprocessing of irradiated fuel elements was completely discontinued on 30th June 2005, with cessation of transports abroad of irradiated fuel elements. Irradiated fuel elements have since been stored in transport casks and interim storage casks, which have been put in dry storage.
- From a regulatory point of view, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) published the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" [1] in July 2009.
- The idea of investigating host rock formations alternative to rock salt (Gorleben) has established itself.
- From a technical point of view, the concept of direct final disposal of irradiated fuel elements in so-called fuel rod canisters (BSK 3) has been developed. These involve thin-walled repository containers (canisters) made of stainless steel with a loading capacity for the fuel rods from three PWR and nine BWR fuel assemblies. The BSK 3 would be sunk in boreholes up to 300 m deep, bored from a drift in the repository mine. The final disposal of CSD-C [1] and CSD-V [2] canisters (specific canisters from French reprocessing plants) from reprocessing abroad would be performed analogously.

In addition to the requirement for analysis and description of the robustness of the repository system in [1], other stipulations contained in safety requirements refer to the fact that:

- The holing through of the isolating rock zone[3] with shafts, drifts or boreholes is to be kept to a minimum;
- Manipulability of the waste packages in case of any possible recovery from the decommissioned and closed repository must still be possible after 500 years; and

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1 CSD-C (Colis Standard de Déchets-Compactés) are canisters containing compacted structure components of spent fuel elements

2 CSD-V (Colis Standard de Déchets-Vitrifié) are canisters containing a vitrified waste block

3 The isolating rock zone (IRZ) is the portion of the repository system (host rock) which, in interaction with the technical plugs (shaft plugs, vault containment structures, dam structures, backfill …) guarantees containment of the waste.

- Within the operating phase until closure of the shafts or ramps, recovery of the deposited waste packages must be possible in case of an assumed inflow of solutions into the emplacement areas.

These requirements have a direct relationship to the setup and operation of a repository for heat-generating waste.

Both the existing German reference concept for final disposal of irradiated fuel assemblies in POLLUX casks and the newer conceptual and technical developments concerning the final disposal of heat-generating radioactive waste must fulfil the requirements of [1].

Drift Emplacement

The German reference concept for final disposal of POLLUX repository casks makes provision for loading of the waste packages outside the repository. The reference concept was developed for final disposal in rock salt. The largest and heaviest POLLUX cask is capable of receiving the fuel rods from up to ten PWR fuel assemblies. The repository cask weighing approx. 65 Mg is self-shielding. An additional shielded cask for the actual emplacement operation is not required. For internal transport operations in the repository, the POLLUX cask is loaded onto a flat-top trolley weighing approx. 20 Mg. At the emplacement location, the POLLUX cask is raised from the flat-top trolley using an emplacement machine and is deposited directly on the drift floor. After the emplacement machine has been removed from the emplacement site, the deposited repository cask is backfilled with salt. The feasibility of internal transport within the repository (including shaft transport) was demonstrated for weights of up to 85 Mg in corresponding trials [2] and [3]. The internal processes extending to the actual final disposal may be automated and remote controlled. Insofar as operational anomalies require personal intervention, this is possible owing to the shielding of the repository casks. The reference concept is characterised by the fact that:

- Feasibility of final disposal has been successfully demonstrated; and
- Only a small number of simple handling operations are required for final disposal of the waste packages.

The operational processes for emplacement refer to the raising/lowering and horizontal displacement of the waste packages. The possible loads affecting the cask in case of an incident, which cannot be ruled out, would not result in a release of a radioactive source term from the waste packages owing to the design of the casks and the assumed design loads. There are no fundamental doubts about the presentability of a recovery of the waste packages over a period of 500 years following completion of emplacement according to the requirements arising from [1].

The repository concept of drift emplacement developed for final disposal in rock salt may basically also be used for final disposal in clay. Lower limit values exist for permissible heating of clay for rock salt. This circumstance would be encountered by reduced loading of the casks. For example, final disposal of POLLUX 3 casks with fuel rods from up to three PWR or alternatively nine BWR fuel elements would be conceivable.

The demonstration of the feasibility of direct final disposal of irradiated fuel assemblies in Switzerland [4] is likewise based on the drift emplacement of waste packages in an argillite formation. The repository casks intended for use there are lighter and have thinner walls in comparison to the POLLUX casks. Until they reach their emplacement destination, these casks are placed in another shielding container for safe handling.

In summary, drift emplacement of heavy self-shielding repository casks presents itself as simple and robust from the point of view of specified normal repository operation and to possible anomalies and incidents. For the concept of drift emplacement in rock salt as the host rock, it is useful to verify whether the existing transport and interim storage casks may be directly emplaced, if necessary following modification. If the irradiated fuel were not to require repacking in new casks, the number of handling processes with the heat-generating and high-active waste would be further reduced. A reduction in operational radiation exposure and the nuclear risks would be associated with the reduction in handling operations.

Borehole Emplacement

The German concepts concerning borehole emplacement exclusively make provision for final disposal in vertical boreholes. The concept of final disposal in horizontal boreholes, as for example provided for by the French feasibility study [5] for final disposal of the high-active waste in clay [5], is not pursued in Germany. The borehole depths discussed for final disposal in Germany lie within a range between 100 and 300 m for a borehole diameter of approximately 60 cm [6]. The boreholes are directly loaded, i.e. without piping installation. Final disposal in clay is only difficult to represent with the aforementioned borehole depths, since a uniform clay structure (IRZ) that is in line with the borehole depths must be available.

In comparison to drift emplacement, final disposal in deep vertical boreholes requires light and slender final repository casks. The fuel rod canister developed for the purpose of borehole emplacement fulfils this prerequisite. Its weight when filled (fuel rods from 3 PWR or 9 BWR fuel assemblies) is approximately 5 Mg. The diameter of the canister is just under 45 cm and its height is approximately 5 m. The CSD-C and CSD-V canisters containing medium- and high-active waste are of similar diameter. The heights of these canisters are approximately 1.3 m and the weight of the canisters is markedly less than one tonne.

These canisters are not self-shielding and may only be handled with a shielded cask outside the borehole. The weight of a shielded cask loaded with a BSK 3 is approximately 45 Mg [7]. Consequently, borehole emplacement requires handling stages which, depending on the implementation of the repository design, refer to above-ground inward transfer of the canisters into the shielded cask in the repository, but particularly the underground outward transfer of the canisters at and in the borehole. Individual CSD-C and CSD-V canisters can be transferred with their shielded cask upright on a flat-top trolley from above ground to below ground into the borehole for final disposal. The transfer casks with the BSK 3 canisters can only be transported on their sides owing to their length. The design of the transfer casks ensures that they are able to withstand operational anomalies without release of a source term.

Handling of the canisters in the repository from delivery to preparation for final disposal at the borehole has a large number of technical analogies resulting from manufacture of the canisters and from storage. There are no doubts about the feasibility of the handling processes; they correspond to the state of the art.

New technical territory is entered, however, in pivoting transport casks containing BSK 3 canisters from a horizontal into a vertical position above the borehole, in grabbing the canisters inside the transfer cask, which has the function of an airlock during this phase, and in lowering the canister into the well unequipped with piping. Against this background, a 1:1 scale test rig was set up by the German company DBETEC as part of the international ESDRED[4] concept. Using this test rig, it was possible to successfully demonstrate the feasibility of lifting a transfer cask loaded with a BSK 3 from a flat-top trolley, pivoting the transfer cask from its horizontal position into a vertical unloading position, and setting it down precisely on the borehole head in addition to grabbing and lowering the canister into a simulated borehole [7]. Furthermore, in this test rig, it was possible to demonstrate the feasibility of lowering a so-called triple pack, consisting of three superimposed CSD-V and CSD-C canisters, into the borehole like a BSK 3

[4] ESDRED: "**E**ngineering **S**tudies and **D**emonstration of **Re**pository **D**esigns" Project in the frame of the sixth Euratom Framework Programme for Nuclear Research and Training (2002-2006)

canister and backfilling the borehole with crushed salt. The demonstration trials provided significant results for a possible future licensing process.

From the point of view of nuclear safety, there is still need for clarification concerning borehole emplacement. This particularly concerns the nuclear design of the emplacement machine, since the possibility of a canister plunging into a borehole must be safely ruled out. Operating experience with refuelling machines in nuclear power plants should be assessed and taken into account in this connection. Need for clarification also exists with regard to the operational loads acting on the canisters, which are subject to mechanical loads in addition to static loads following the setting-down process during lowering into the borehole. Regardless of the safety requirements of [1], the requirement is imposed from the standpoint of repository operation that the integrity of the stored canisters must be maintained beyond the operating phase of the repository.

A need for a safety demonstration for the emplacement of canisters in boreholes will result from the safety requirements of BMU [1], specifically referring to:

- The analysis and representation of the robustness of the repository systems; and
- The manipulability of the waste packages in case of a possible recovery from the decommissioned and closed repository even after 500 years in conjunction with probable developments in the repository system, taking the avoidance of releases of radioactive aerosols into consideration.

There are no fundamental doubts about the presentability of the feasibility of borehole emplacement. Nevertheless, for want of operating experience, proof will have to be provided at least partly only through demonstration trials and model calculations. As repository casks, the canisters furthermore only offer limited reserves in the face of operational and accidental loads owing to their thin-walled and lightweight construction. Both factors, i.e. uncertainties in the evidential methodology and only limited safety reserves owing to design, are not beneficial from an operational standpoint for proof of a robust repository system.

The requirement from [1] that subsequent generations must be capable of recovering emplaced waste packages over a period of 500 years raises specific questions in connection with borehole emplacement. The manipulability of the waste packages must be guaranteed during this period such that a release of radioactive aerosols is avoided. The requirement is linked to the boundary condition that the repository has adopted up to this point in time an evolution from the spectrum of likely evolutions. In this case also, the necessary proof can only ultimately be provided through model approaches, though as explained above, the cask design does not possess particular safety reserves. The corresponding proof will still have to be provided in the future.

Against the background of a recovery of canisters from a borehole, account must also be taken of the fact that owing to the plastic behaviour of rock salt, particularly under the influence of heat, the original emplacement coordinates may change after emplacement has been performed. This circumstance may considerably complicate any planned or already initiated recovery.

In summary, this means that with regard to the concept of borehole emplacement, proof is still to be provided concerning:

- The robustness of the method;
- The stability of the repository casks; and
- The possibilities of recovery of the waste packages over a period of 500 years.

A matter also to be taken into account for the concept of borehole emplacement is that not only are the handling stages with the waste packages in the repository in part markedly more complex in comparison to drift emplacement, but also that in pursuing this emplacement concept, the number of handling stages necessary in the repository and in the waste management steps preceding emplacement will increase. Even if the handling stages are automated and remote-controlled, the handling stages in the individual case are correlated with operational radiation exposure and with the potential occurrence of operational anomalies.

Shaft Transport /Transport Via a Ramp

In connection with the questions concerning the robustness of repository systems, the matter was investigated as to whether development of an underground repository mine via a ramp as apposed to via a shaft presents any advantages with regard to the robustness of the system. The original idea behind this issue was the notion that the crash of a waste package down a hoisting shaft may best be prevented by avoidance of this way of transportation altogether.

An answer to the question as to whether a ramp suggests itself as an alternative to a shaft cannot be derived only from the analysis of possible operational anomalies and incidents. The analysis concerning this issue was performed based on the following criteria:

- Regulatory aspects;
- Aspects from conventional mining;
- Repository operation / operating safety;
- Possible occurrence of incidents; and
- Closure of the repository / long-term safety

Regulatory Aspects

The German mining regulations, e.g.[8], do not contain any regulatory requirements that fundamentally restrict construction and operation of a ramp or a shaft. Regardless of the nature of the access to the mine, § 15 of the General Mining Ordinance [8] requires:

"The contractor must ensure that

1. each underground operation is connected to the surface by at least two separate, properly established routes which are readily accessible to the employees,
2. these routes are equipped with mechanical means of conveyance if their use implies particular effort on the part of the employees".

Insofar as a repository mine is exploited by means of two shafts, this requirement can be fulfilled accordingly from a technical point of view by shaft transport installations. If access is planned by means of a shaft and a ramp, the requirement, particularly with regard to the second requirment, must also be fulfilled for the ramp. Should this prove impossible, since the ramp for example is not available as a second independent escape and rescue route owing to transports of radioactive waste or the technology installed on the ramp, a third access to the mine may be necessary. The safety requirements [1] stipulate on the other hand that holing-through of the isolating rock zone with shafts, drifts or boreholes is be kept to a minimum. According to the requirement from [1], more than two accesses to the repository are also possible; against the background of a robust repository concept, the number of accesses should however be weighed up against the need for and advantages of other variants.

Aspects from Conventional Mining

Conventional extraction mining is governed by economic interests. The aim of a permanently safe closure of the mine does not play any role in conventional extraction mining. The decision as to how access to a mine is achieved depends among other aspects on the size, extension and deepness of the valuable mineral to be mined. Other aspects for or against the construction of a ramp are the results of the geological and hydrogeological conditions encountered between the valuable mineral and the top edge of the terrain. In [9] it is described for example that from an economic point of view, the limit for construction of a ramp is reached at a depth of approx. 700 m. These are depths that are basically relevant in connection with the final disposal of radioactive waste in a mine. However, it has to be taken into account that when it comes to the nuclear safety of disposal in a mine, cost aspects are to be considered of secondary importance.

Repository Operation / Operational Safety

From the point of view of repository operation, an essential difference arises with regard to the transport times that result for waste transport via a ramp or a shaft. With a transport speed of approx. 10 km/h on a ramp and a gradient of approx. 10 %, a repository mine at a depth of 500 m is reached in around 1 hour. Using a shaft transport installation with a transport speed of 4 m/sec., a waste package could be made available in the mine for final disposal after only 2 to 3 minutes.

The marked time difference between these options may be put into perspective if in the case of transport by means of a ramp, the waste packages can be transported directly to the emplacement site and handling processes can be saved in comparison to shaft transport. If one assumes an emplacement operation in which on average one HAW waste package is placed per emplacement shift, the transport time over a ramp also does not represent any substantial operational restriction. From the point of view of operational radiation protection, the comparison between shaft and ramp is only meaningful if transport by means of a ramp, as with shaft transport too, is automated and remote-control is possible. A trackless vehicle for the planned Swedish HAW repository that fulfils this requirement was developed and built in Germany. It was delivered to Sweden for trial operation.

In Finland, both transport routes are planned as options for the repository for HAW planned there. Whether the ramp set up in any case at the site will be used for the transport of the waste packages depends on whether the waste will be delivered in conditioned form or whether subsequent conditioning will be performed on site at the repository. If conditioning is performed on site, the option of underground waste transport via a shaft specially erected in this zone is preferred [10].

If the repository mine is to be developed by means of a ramp, the ramp must perform further functions. It has to be used to draw fresh air into the mine, or the waste air must be extracted through it. Furthermore, the ramp must fulfil the function of an escape and rescue route. These functions are only achievable with compromises in the aforementioned configuration of a ramp and a shaft. If the ramp were used for the incoming air, the fresh air would already be drawn through the control area before it reached the mine. Furthermore, the air would already be contaminated with vehicle emissions on ingress. If the ramp were to be used for the outgoing air, an airlock would have to be set up in the vehicle entrance area.

With respect to the need for a second escape and rescue route, the ramp is to be equipped for use by vehicles for the miners working underground. This may result in specific spatial requirements for the ramp, e.g. lay-bys for vehicles and a corresponding cross-section of the ramp. It is to be accepted if necessary that in an emergency, the operating personnel must pass a transport vehicle coming in the opposite direction. The conceptual boundary conditions could be avoided by construction of a third access.

With regard to operational availability and the occurrence of operational anomalies, no noteworthy advantages are to be expected with a ramp compared to a shaft transport system. Operating experience with shaft transport installations in connection with the final disposal of radioactive waste so far has demonstrated emplacement operation as planned. Transport by means of a ramp should show a similar degree of availability. In case of automated and remote-controlled transport by means of a ramp, it is not expected that this will be the case as a matter of course.

In summary, it cannot be perceived from an operational point of view that planning and construction of a ramp for the transport of radioactive waste into the repository mine will result in more robust repository operation than would be the case compared with shaft transport.

Possible Internal Incidents

The analysis of possible internal incidents in a shaft transport system refers to fires, the crash of the loaded means of transport, the falling of a waste package into the shaft without the means of transport in situ, and the so-called severe overdrawing of the means of transport. The analysis of possible internal incidents on a ramp refers to incidents with a completely different focus. Account is to be taken in this case of a collision with the walls of the ramp, with and without fire, and the complete vehicle burnout as a result of an initial fire.

The results of all safety analyses conducted to date on deterministic and probabilistic bases have shown that the occurrence of one of the aforementioned incidents in connection with the shaft conveyor system may be reliably avoided by the design of the system, e.g. [11] and [12]. Newer developments of heavy-duty shaft transport systems for final disposal, e.g. [5], also make provision for design characteristics for the shaft transport system that would markedly reduce the repercussions of an incident. These measures include isolation of the transport shaft in terms of ventilation and the installation of a shock absorber in the shaft sump. The potential risk involved in shaft transport may in this respect be classified as controllable, based on engineering design measures and existing operating experience.

In case of transport of the waste packages by means of a ramp, an analysis of possible effects on the waste packages resulting from an incident will arrive at different results. It is therefore not foreseeable that an occurrence of the aforementioned incidents (complete vehicle burnout and/or collision with the walls of the ramp) can be safely ruled out over the operating period on the basis of operating experience and appropriate vehicle and installation design. Depending on the repository and cask concept, it will have to be proven that the waste packages are designed to withstand the loads to be assumed and that a release of a radioactive source term can be ruled out. Regardless of the radiological repercussions of such an incident, the effects on repository operation would likely be substantial. The recovery of a transport vehicle from the ramp will prove very costly. Consequences for further facility operation cannot generally be ruled out.

Seen from the aspect of incidents to be considered, the transport of the waste packages into the repository mine by means of a ramp does not ultimately prove more robust in comparison to alternative shaft transport. This means that the ramp does not impose itself as an alternative in terms of possible incidents.

Closure of the Repository / Long-Term Safety

Final disposal of radioactive waste in a repository mine pursues the aim of long-term isolation of the waste from the biosphere. The corresponding proof of long-term safety in the Safety Case must refer to a period of a million years according to [1]. Against the background of the required long-term safety of a repository for heat-generating and high-active waste, the stipulation is made in [1] that “holing-through of the isolating rock zone with shafts, drifts or boreholes is to be kept to a minimum”.

Adequate experience is available in connection with the working-out and presentation of closure concepts and sealing structures for shafts that represent the shortest connection between the surface of the ground and the repository mine. One technical advantage that the closure and sealing of a shaft offers in comparison to the sealing of a drift is e.g. that the sealing material introduced naturally distributes itself horizontally and consequently already contributes to radial sealing with respect to the shaft wall. Since the shaft itself represents the shortest connection with the repository mine, the holing-through of aquifers in the overburden is generally performed by the shortest route. The interface between an aquifer and the potential access to the repository is reduced to a minimum both operationally and from the point of view of long-term safety.

If a ramp is to be sealed and backfilled at the end of the operational phase of a repository, the expenditure is considerably higher in comparison to that of a shaft. This is due to the approximately tenfold greater void volume. Concepts for the construction of horizontal and almost horizontal sealing structures exist. The technical expenditure for the construction of these closure structures is, however, greater than in the case of a shaft and is fraught with greater uncertainty. Ultimately, no advantage can be perceived for the ramp with regard to robustness in terms of sealing and closure of the repository mine at the end of the operational phase.

In summary, it is to be noted that with regard to the comparison of shaft and ramp, the transport of waste packages by means of a ramp may have advantages from an operational standpoint. The essential advantage may lie in the fact that the transport vehicle can function simultaneously as an emplacement vehicle and that waste packages can be transported from reception at the repository to their emplacement area without any further intermediate technical stage. This way, a very efficient repository and emplacement concept would be presentable. This, however, needs to be weighed against other disadvantageous aspects, such as the needs for the construction of a third access to the repository mine. All in all, the assessment is that the development of the repository mine by means of a ramp does not prove any more robust than by means of a shaft and that development by means of a ramp does not impose itself as an alternative to shaft transport.

CONCLUSION

Against the background of the requirement for a robust repository system in the “Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste”, the concepts of drift and borehole emplacement in addition to the development of a repository mine by means of a ramp or a shaft were analysed. These are relevant subsystems of final disposal.

For the final disposal of waste packages in drifts, the results of the analysis have shown that from a technical point of view, this is a simple and sophisticated repository concept. The feasibility of this emplacement method was demonstrated in the 1990s in Germany by demonstration trials with casks weighing 65 Mg. Massive and, if necessary, self-shielding repository casks may be used for final disposal, which are appropriately designed against potential anomalies and incidents. The concept of drift emplacement may be optimised with regard to a reduction of waste package handling processes. Should the need arise to recover waste packages from the repository necessary during the operational phase and after closure of the repository, this would probably be presentable using comparatively simple technical means. With regard to a consideration of alternative repository locations, the concept of drift emplacement represents a more universal emplacement concept. These circumstances lead to the overall assessment that drift emplacement fundamentally involves a robust repository and emplacement concept.

With regard to final disposal of waste packages in boreholes, the results of the analysis have shown that this emplacement technology is advanced, but not yet sophisticated. Questions particularly relate to the technical design of the waste packages and the design in terms of safety engineering of the emplacement machine. The number of handling stages with the radioactive waste prior to and during disposal are comparatively numerous and complex from a technical point of view. The increase in complexity does not result in a gain in nuclear safety in this case. Should the need for a recovery of the waste packages arise, recovery of the thin-walled canisters from the boreholes will prove an ambitious task, which will hardly be presentable with the existing technology. There is still an overall need for proof with respect to the required robustness of borehole emplacement.

In Germany, the development of a repository mine has so far only been pursued by means of shaft transport systems. It was studied whether seen from the aspect of robustness of repository operation, arguments might be found in favour of development by means of a ramp. The main points of the analysis were specified normal operation of the repository, possible incidents, long-term safety of the repository, and conventional mining issues. In conclusion, from the point of view of robustness, the ramp cannot be justified as an alternative to shaft transport. Only with regard to an optimisation of a drift emplacement concept could the use of a ramp possibly offer any advantages.

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