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Technical Note

Dry storage of spent nuclear fuel and high active waste in Germany—Current situation and technical aspects on inventories integrity for a prolonged storage time

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ABSTRACT

Licenses for the storage of spent nuclear fuel (SNF) and vitrified highly active waste in casks under dry conditions are limited to 40 years and have to be renewed for prolonged storage periods. If such a license renewal has to be expected since as in accordance with the new site selection procedure a final repository for spent fuel in Germany will not be available before the year 2050. For transport and possible unloading and loading in new casks for final storage, the integrity and the maintenance of the geometry of the cask's inventory is essential because the SNF rod cladding and the cladding of the vitrified highly active waste are stipulated as a barrier in the storage concept. For SNF, the cladding integrity is ensured currently by limiting the hoop stress and hoop strain as well as the maximum temperature to certain values for a 40-year storage period. For a prolonged storage period, other cladding degradation mechanisms such as inner and outer oxide layer formation, hydrogen pick up, irradiation damages in cladding material crystal structure, helium production from alpha decay, and long-term fission gas release may become leading effects driving degradation mechanisms that have to be discussed.

1. Introduction

In Germany, the dry storage of spent nuclear fuel (SNF) in casks was implemented in 1995 with the admission of the first cask in the independent interim storage facility at Gorleben. The first casks with vitrified highly active waste (HAW) from spent fuel reprocessing arrived in Gorleben in 1996. With the amendment of the German Atomic Energy Act [1] in 2002, which ruled out the reprocessing of SNF that took effect from 2005, the dry storage is the only SNF treatment option or a so-called "temporary" disposal option in Germany. For the interim storage of SNF in casks under dry conditions, 16 storage facilities are available. Twelve of them are on sites of nuclear power plants and operated by the utility companies. The remaining four—located in Ahaus, Gorleben, Jülich, and Lubmin—are operated by companies in contract with the federal government. Casks with HAW are stored in Gorleben and Lubmin. Besides SNF casks, 113 casks with HAW are currently stored in Gorleben and Lubmin. Germany still has the obligation to take back some casks with HAW and moderately active waste from fuel reprocessing abroad. The expected amount of radioactive waste for a final repository in Germany is approximately 1100 casks with SNF from the LWRs (light water reactors) and more than 200 casks with HAW and moderately active waste from reprocessing. In addition, approximately 300,000 m^3 of low active waste will go into the final repository in Konrad, and approximately 220,000 m^3 of waste is expected from retrieval of low active waste from the first nuclear research repository in Germany, the salt mine ASSE II.

From 1973 to 1979, a site selection procedure for a deep geological final repository was carried out. The selected sites at that time were part of a controversial public discussion. In 1977, the government of the state of Lower Saxony, where most of the possible sites were located, selected the Gorleben salt dome as the location for a deep geological final repository and Gorleben for a nuclear waste–processing center. In Gorleben, a pilot conditioning plant for SNF was built but was never used until today; an interim storage facility was built, and the salt dome was explored for its suitability as a final repository. These developments were accompanied by further controversial public discussion and violent protests. The lack of political consensus led to several breaks in the geological exploration of the salt dome with the last break in 2012, lasting until now.

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A new understanding of the public participation in the political decisions in nuclear issues after the Fukushima accident caused a restart of the process of finding and exploring a final repository site in Germany; this was from a technical point of view in works already done in the 1980s at the Gorleben site. With the amendment of the Site Selection Act [2] in 2013, discussion about a final repository for nuclear and other radioactive waste started from scratch again. According to this act, the site selection procedure should be finished in 2031. Based on the experience with nuclear installations in Germany, one can assume a time delay of more than a decade for finishing this process and another decade for commissioning. Therefore, 2050 or even later may be a more likely date for realizing and operating a final repository for SNF and HAW in Germany.

At present, the storage time for SNF and HAW is limited to 40 years by cask licenses, starting with the loading date. The same time span applies to the storage facility starting with the first stored cask. Having a date later than 2050 in mind, the storage period has to be extended to more than 60 more years; meanwhile, a period of one hundred years is under discussion. As a consequence, licenses have to be renewed for both the casks and the storage facilities. The storage facilities and their installations can be maintained as every other building and technical installation, even if the requirements for the storage facilities are higher than those for other installations. If the requirements of the facilities are not met in future, a new facility can be built, and the casks can be transported to the new site. The situation is quite different for the casks and their inventory. After the phaseout of nuclear power production in Germany [1] in 2022, the nuclear power plants will be decommissioned, which means that further maintenance of the casks and their inventory is no longer possible at the nuclear power plants. There are concepts available to restore cask tightness after detection of a leaking seal, but repacking the inventory of SNF and HAW in a new cask is not possible with the available facilities. Therefore, for transporting to the repository site and conditioning for later final disposal, the integrity and the maintenance of the geometry of the cask inventories are essential. Especially, the integrity of the SNF rod cladding and the cladding of the vitrified HAW are stipulated as barriers in the storage concept and are necessary to secure the specified geometry.

2. Verification concept for inventory integrity during dry storage

2.1. Regulatory framework

The verification concept for the dry storage of SNF and HAW in casks is—besides the scientific and technical knowledge—based on legal provisions and the derived regulations and technical rules for nuclear issues in Germany. This regulatory framework is the basis for safety assessments in the handling of radioactive substances, the operation of nuclear facilities, and the storage of radioactive substances. Only a condensed overview is given here to classify the activities of the technical expert in this framework. The rule set is structured like a pyramid in its level of detail. If one approaches the base from the top, the requirements become more and more detailed, up to the specification of concrete embodiments in the standards and technical rules.

The Table 1 will give an overview of the regulatory hierarchy of the German national regulations:

For the technical assessment of the protection objectives, concrete requirements are already set up in the ordinances, which must be taken as concrete evaluation criteria for the technical expert. For the dry interim storage of SNF and HAW, the guidelines on dry interim storage of spent fuel and heat-generating radioactive waste in casks [3], issued by the Nuclear Waste Management Commission (ESK) in 2013, are an important set of rules for the technical evaluation. They can be seen as an important part of the implementation of the generic requirements of the IAEA (International Atomic Energy Agency) Safety Standard on Storage of Spent Nuclear Fuel [4] in the German national regulatory framework for the assessment of the dry storage capabilities and are comparable to the interim staff guidance for spent fuel storage and transportation of US NRC Regulations, Title 10.

2.2. Verification for a safe dry storage period of 40 years

The ESK guidelines [3] apply to the dry storage of spent fuel and heat-generating radioactive waste in tightly sealed metal canisters for a storage period of 40 years. It is already stated in these guidelines that for a period exceeding 40 years, additional and appropriate verification of the long-term behavior of the casks and their inventory have to be provided. With these verifications, the available experience of the 40-year storage period can be considered.

The guidelines of the ESK are found on the requirements of the German Radiation Protection Ordinance [5], which states that any unnecessary radiation exposure or contamination of humans and the environment shall be avoided and any necessary radiation exposure or contamination of humans and the environment shall be minimized, even below the respective limit, by taking into consideration the state of the art and all circumstances of individual cases. From these basic safety objectives, fundamental safety objectives of “confinement of radioactive material”, “safe decay heat removal”, “maintenance of sub criticality”, “avoidance of unnecessary radiation exposure,” and “limitation and control of radiation

Table 1
Regulatory framework for nuclear issues in Germany.

Issuer	Law, provision, standard, or rule	Legally binding nature
Federal legislator	German Basic Constitutional Law Atomic Energy Act	Generally
Federal government and federal council	Ordinances (e.g., Radiation Protection Ordinance) General administrative provisions	For authorities
Federal government and state authorities	Safety requirements for nuclear power plants Regulatory guidelines by the BMUB (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety)	By specification in the license or by supervisory measures in the individual case
Guidelines and recommendations from advisory bodies	Reactor Safety Commission (RSK) The German Commission on Radiological Protection (SSK) Nuclear Waste Management Commission (ESK)	
Standards from the Nuclear Safety Standard Commission	KTA safety standards (rules of the Nuclear Committee)	
Standards and rules from the industry and utility operators	Technical specifications for systems and components, rules for organization and operation (e.g., quality management systems), and other rules and standards	

exposure of the operating personnel and the general public" were derived. These fundamental requirements led to the requirement for the inventory that the confinement of radioactive material is to be ensured by the casks and, where required, additional barriers such as the fuel matrix, the cladding tubes in the case of intact fuel assemblies, and an encapsulation in the case of defective fuel assemblies. During storage, handling, transport, and unloading of inventories, the structure of the components that surround the radioactive material contained in the inventory and specify its geometry must be maintained. For this purpose, corrosive damage is to be ruled out with sufficient certainty. To this end, appropriate measures are the limitation of residual moisture and corrosive material in combination with an inert cask atmosphere.

2.2.1. *Cladding integrity during dry storage*

For irradiated fuel rods from LWRs, the occurrence of systematic cladding tube failure is to be excluded for the entire storage period by the limitation of cladding corrosion and compliance with the material-specific maximum tangential stress/strain. The applicability of the stress/strain criteria has been proven in several experiments initiated by the fuel vendors and the utilities. Some results of this work have been published [6–9], but all have been assessed in the licensing procedures by the authority and its Technical Support Organization (TSO).

The corresponding proof of these criteria must take into account the operating history of the fuel assemblies specifically or in a covering manner. With the present limitation of the storage period of 40 years, the requirements for an exclusion of systematic cladding failure during dry storage in casks are formulated in Table 2.

The fulfillment of these and other requirements has to be shown by the utility and is assessed by the authority and its TSO. The proof of the cladding hoop stress considers the irradiation history of the fuel, especially the fuel rod inner pressure and the accumulated outer oxide layer. The hoop strain criterion is calculated by material-specific correlations for the time span of 40 years. Thereby, the falling temperature slope due to the decreasing decay heat during storage time is considered. As the driving force for the strain, the hoop stress of the individual fuel rods is used or the covering value of 120 N/mm^2 are used. The author uses the fuel rod performance code TRANSURANUS [10] and a conservative approach in data and model selection for the assessment of the in-pile performance of the fuel and its behavior during the dry storage period. In this way, he uses specifications and drawings to obtain appropriate input data for the fuel rod and the individual power histories obtained from the utility. Both are confirmed during the fuel manufacture and the in-pile life of the fuel in the surveillance process by the TSO.

The compliance of the maximum fuel rod temperature to 370 °C is confirmed during the licensing process of the casks and the storage facility, which are technically accompanied by the TSO. There are temperature measurements on the cask surfaces performed after the loading process with the SNF to check whether the boundary conditions of the calculations performed in the licensing process are fulfilled. Similar temperature measurements are performed on casks containing vitrified HAW. The purpose of these measurements is to check the maximum allowed temperature of the cask internal moderator instead of the inventory temperatures.

The limitation of cladding corrosion during the storage period is ensured by the limitation of the residual water content after drying the cask interior. The drying process and the fulfillment of the drying criterion are accompanied by a TSO authority in his third-party field inspections during the cask-loading process. As this is a conservative approach, it is assumed in this case that all residual water will react with the hot fuel rod cladding over the storage time period. This results in an increase of the outer cladding oxide layer of a few microns, even when only 30% of the cladding surface is considered in these calculations of the zirconium water reaction. This process can result in a nonnegligible hydrogen content in the cask's inner atmosphere, which might lead to the risk of an ignitable gas mixture on possible air ingress if the casks are opened for some reasons. Hidden and nondryable water can be assumed in defective fuel rods if these defects occurred in pile or under wet storage conditions. Therefore, the integrity of the fuel rods is proved by sipping tests or by monitoring specific isotopes during the last in-pile cycle of the fuel before loading it into a cask.

2.2.2. *Integrity of vitrified HAW during dry storage*

In this chapter, a brief description of some tasks involved in proving the cladding integrity during 40-year dry-storage concept performed by a TSO authority is given. More details on these assessments can be found in the references [11,12]. Up to this point, SNF and especially the cladding integrity of the LWR fuel were in focus. The vitrified and canned HAW has some properties comparable with those of SNF, such as decay heat and radiation, but it has a different geometry and other thermal and mechanical loads during dry storage. The cask design is or can be very similar to SNF. In addition, the barrier concept is comparable: fuel matrix–glass matrix, fuel rod cladding tubes–coquilles cladding, and SNF cask–HAW casks. The fuel matrix and the glass matrix can be seen as the first retention barrier for fission products. Under dry storage conditions, the mechanical load on the fuel rod cladding can be very high, especially at the beginning of the storage period. The cladding of the coquilles has the same function as a tight first barrier, but the mechanical load during storage is not that high. For these coquilles, no limitations during the 40-year dry storage period apply. Known degradation mechanisms of the glass matrix, such as crystallization and glass corrosion, that may have negative effects on the retention function are not of importance for the 40-year dry storage period but may become more important in the prolonged dry storage.

3. Prolonged dry storage period—A need for new verification

As mentioned before, a prolonged dry storage period of SNF and HAW is under discussion in Germany. The time span varies from 60 years to 100 years, and in some scenarios, the retrievability of SNF

Table 2
Regulatory framework for nuclear issues in Germany.

Requirement	Description
The cladding hoop stress should not exceed 120 N/mm^2.	With this criterion, stress corrosion cracking and hydride reorientation as failure mechanisms will be excluded.
The cladding hoop strain should not exceed 1%.	With this criterion, an increase of the hoop stress at higher strain levels and the failure caused by strain should be excluded.
The cladding temperature should not exceed 370 °C.	Within this temperature range, the annealing of irradiation hardening and the dissolution of the hydrogen precipitates in the cladding will be excluded. This criterion is an outcome of strain experiments on dry storage performed with irradiated cladding material.
Cladding corrosion during the storage period should be limited.	This requirement will be fulfilled by the limitation of residual water in the casks after the drying process, the use of an inert gas atmosphere in the cask, and no loading with defective fuel.

Table 3
Cladding degradation effects with importance to a prolonged dry storage.

Degradation effect	Description
Reorientation of hydrogen precipitates	The reorientation of hydrogen precipitates may cause embrittlement and lower stress-bearing capability of the claddings.
Extended fission gas release	An extended fission gas release, especially from the high burnup structure and/or from alpha decay, increases the inner fuel rod pressure with consequences on cladding stress and strain state.
Chemical interactions of the fuel with the cladding	Chemical interactions of the fuel with the cladding, especially the chemical impact of fission products (e.g., halogenides), may increase the risk of stress corrosion cracking.
Annealing of irradiation damages	The annealing of irradiation damages in the cladding material may have consequences on the cladding ductility and creep that may lead to cladding failure by overstrain or to increasing stress states with the effects on hydride reorientation and stress corrosion cracking.
Cladding embrittlement processes	The hydrogen dissolved in the cladding and the precipitation of hydrogen at lower temperatures may cause cladding embrittlement processes with the consequences of this for handling and transport.

and HAW from a future final repository is discussed for a time span of 500 years. The latter can be seen as a correction option for the final disposal options that are under development and will not further be discussed here. What consequences on present verifications for the 40-year storage period may these prolonged storage times have? At first, it should be mentioned that exceeding the 40-year time span fixed in the license does not imply that the technical storage period is exceeded. When the storage period laid down by the approval is reached, the legal situation is considered to have changed, but the storage itself will not become less safe from one day to another. In addition, the time available until the first authorization expires for the first cask stored will be sufficiently long to provide further evidence and assessments for an extended storage. From the author's point of view, the following aspects result from the assessment of the inventory behavior with respect to the exclusion of a systematic cladding failure:

1. It has to be evaluated whether the requirements for 40 years are still valid and applicable for a longer time span.
2. In the long term, other effects of degradation may take leading parts in the assessment of cladding integrity.
3. High burnup fuel and mixed oxide fuel are identified as fuels with the highest loads and with the highest potential for systematic cladding failure (see also IAEA Standard on Storage of Spent Nuclear Fuel [4]).

Answers to the before mentioned aspects of extended interim storage will be given according to the considerations and analyses carried out until then. In addition to a safe prolonged interim storage, the fact that the storage casks must be transported to the final storage location after the interim storage period must also be taken into account. This implies the need for new verification.

To find out the most important effects and parameters, an international gap analysis [13] was started some years ago in the United States and is still in progress. This gap analysis will be considered in the German discussion of the most important parameters for a prolonged interim storage. From the authors point of view for the German licensing and surveillance procedure, the degradation effects listed in Table 3 are highly relevant and should be addressed in future R&D programs.

Some of these degradation effects were already discussed by the author [11,12]. Recently two new R&D projects in Germany have been started. TÜV NORD will support these projects with the technical knowledge accumulated among other sources in the licensing and surveillance processes of the dry storage projects and will participate in the model development for hydrogen uptake, dissolving, and precipitation to calculate the reorientation of hydrogen precipitates with fuel rod performance codes. In the first step, it will be investigated whether the fuel rod performance codes are able to predict the 40-year interim storage period with the requirements mentioned in chapter II. Furthermore, it will be investigated which data from manufacturing, in-pile life, and storage of the fuel are needed to predict the present requirements and what might be needed for future investigations when new models for new requirements are available. The latter is very important in Germany because it can be expected that after the nuclear phaseout in 2022 and the decommissioning of the nuclear power plants, there will be a potential risk of losing data and knowledge about the fuel that will be kept in interim storage.

4. Summary and conclusions

An overview of the situation of the dry storage of spent fuel and HAW in casks in Germany was given with respect to the cladding integrity. Some possibly important effects of cladding degradation during dry interim storages for a longer period were addressed. The assessment of these effects may make some experimental examinations of spent fuel after a longer storage time necessary in future. These examinations should be used for the development of models to be used for the forecast of fuel performance during longer storage times. It is planned to implement new models in available fuel performance codes to perform full-fuel lifetime calculations, including the interim storage period, and also to take benefit from the methods of sensitivity analyses and probabilistic methods. Data and knowledge management aspects are identified as being as important as technical considerations.

Conflict of interest

There is no conflict of interest within the contend of the paper and its publication.

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