Radiological aspects and behaviour of spent fuel considering long-term interim storage

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Abstract:
For spent nuclear fuel management in Germany, the concept of dry interim storage in dual purpose casks before direct disposal is applied. Currently operation licenses for storage facilities have been granted for a storage time of 40 years associated with the first emplacement of a cask. Operation licenses are based on safety demonstrations for all relevant safety issues as safe enclosure, shielding, sub-criticality and decay heat removal under consideration of operation conditions. In addition, transportability of the casks for the whole storage period has to be provided. Due to current delay in site selection and exploration of a disposal site, an extension of the storage time beyond 40 years seems inevitable. Relevant aspects for licensing of extended storage time will be discussed. Furthermore, an overview about current national and international activities on the safety of long-term interim storage will be given.

1 INTRODUCTION - CURRENT SITUATION OF SPENT FUEL STORAGE IN GERMANY

For spent nuclear fuel management in Germany, the concept of dry interim storage in dual purpose casks before direct disposal is being pursued. According to an amendment of the *Atomic Energy Act* (AtG) in April 2002, spent nuclear fuel from power reactors, which has not been shipped to the reprocessing facilities in France or the UK until 30 June 2005, has to be stored at the NPP sites in dry storage and transport casks. Beginning from the year 2002, dry cask storage facilities were commissioned and started operation stepwise at twelve NPP sites. In addition, the earlier commissioned centralised storage facilities at Ahaus and Gorleben are used for the interim storage of spent fuel from different types of reactors (light water reactors, THTR Thorium High Temperature Reactor, Rossendorf research reactor) and vitrified high level waste returned from reprocessing abroad. The interim storage facility Zwischenlager Nord (ZLN) near Greifswald is used for the storage of spent fuel from the Greifswald and Rheinsberg nuclear power plants of Soviet design. On the site of the Jülich research center, a storage facility is used to contain spent fuel from the AVR. **Table 1** provides an overview of the current dry storage facilities in Germany.

Due to pending site selection process for a spent fuel disposal facility, the probability increases that an extension of the licensed storage period beyond 40 years will be needed. For extended storage periods all relevant safety demonstrations have to be in line with the intended extension time and the current state of science and technology. On behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) currently GRS is in cooperation with the Federal Institute for Materials Research and Testing (BAM) and Oeko-Institut e. V. preparing a state of the art report on dry storage of spent nuclear fuel, considering in particular the conditions and needs with regard to the German policy of spent fuel management. In the following sections an overview of the state of science and technology, national and international activities towards long-term interim storage of spent fuel will be presented.

Table 1. Status of the on-site and central storage facilities in Germany at the end of 2012

Nuclear Power Plant Site	In Operation since	No. of emplaced casks
On-site storage facilities of NPPs		
Biblis	2006	51
Brokdorf	2007	16
Brunsbüttel	2006	9
Grafenrheinfeld	2006	20
Grohnde	2006	18
Gundremmingen	2006	41
Isar	2007	25
Krümmel	2006	19
Lingen	2002	32
Neckarwestheim	2006	41
Philipsburg	2007	36
Unterweser	2007	8
On-site storage facilities		
Research Center Jülich	1993	152 (AVR)
Central storage facilities		
Ahaus (TBL-A)	1997	329
Gorleben (TBL-G)	1995	113
Greifswald (ZLN)	1999	74
Sum:		984

2 REGULATORY ASPECTS

The storage of spent fuel and radioactive waste with significant contents of fissile materials requires a license under § 6 of the *Atomic Energy Act*. This refers to the on-site interim storage facilities at the nuclear power plants and the central storage facilities for spent fuel containers at Gorleben, Ahaus and Greifswald. Superior preconditions for licensing are, for example, a need for storage, adequate precautions to prevent damage resulting from the stored fuel, adequate provisions for covering the legal liability to pay compensation for damage, protection against disruptive action, etc. The licensing authority in this instance is the Federal Office for Radiation Protection (BfS), whilst supervision is performed by the competent authority of the respective Land.

Detailed safety requirements for dry interim storage are written down in "Guidelines for dry cask storage of spent fuel and heat-generating waste" originally issued in 2001 and now available in the revised and amended version of 2013 [1]. Basic safety issues of the German approach are:

- The main safety goals, in particular safe enclosure of the radioactive inventory, sub-criticality, radiation shielding and decay heat removal, are provided by the casks.
- The current operation licenses have been granted for a storage period of 40 years.
- According to current practice, the approval of type B(U) for public transport of the casks must remain valid for the whole storage period, license partially takes credit of the approval.
- The casks are monitored for gas leakage of the double lid system.
- Safety-related installations of the storage facility are subject to in-service inspections whose frequency is to be stipulated in accordance with the safety significance of the components to be tested. No inspection or monitoring of the stored inventory and the inside of the casks are foreseen.

- The casks have to be placed in storage buildings, which provide additional radiation and weather protection and as well withstand civilian aircrafts and sabotage attacks.
- Transportability of the casks and manageability of the fuel elements has to be assured at the end of storage period.

Safe enclosure and manageability of fuel elements require that systematic failure of the fuel rods should not occur during the storage period and that the fuel assemblies have to keep their geometric arrangement. To exclude fuel rod failure, hoop stress and hoop strain of the cladding are limited to 120 MPa and 1 %. Evidence for compliance of these values as well as appropriate heat removal (limited temperatures of cask components, e.g. neutron moderator), sub-criticality and shielding (surface dose rate) are provided by computational analysis from the licensee.

In order to sustain a continuous high safety level over the whole period of storage and also to be in line with international requirements and practices, the procedure of periodic safety review was included into the regulatory system for interim storage facilities. In November 2010, the Nuclear Waste Management Commission (ESK) handed the BMU a recommendation of guidelines for the implementation of a periodic safety review (PSR) for interim storage facilities [2]. The main objectives are to demonstrate the fulfilment of the basic protection goals listed above and the resulting requirements with regard to

- summarised documentation and evaluation of all events and findings within the review period with regard to the safety level and operating reliability of the interim storage facility, and minimisation of the radiation exposure due to ALARA.
- up-to-date safety assessment in accordance with the state of the art in science and technology with regard to
  - the safe and reliable continued operation of the interim storage facility,
  - the impacts of ageing mechanisms on the condition of the interim storage facility and its installations and on the transport and storage casks and their inventories,
  - the compliance with the safety requirements for the handling and later removal of the transport and storage casks, and
- derivation of findings and measures for further operation.

The result of the PSR should demonstrate the fulfilment of the basic protection goals for the remaining licensed operation time. A PSR for storage facilities has to be performed every ten years.

3 NEED FOR EXTENDED STORAGE

On the 27 July 2013 the *Repository Site Selection Act (Standortauswahlgesetz-StandAG)* [3] became effective in Germany. It regulates the course of actions in order to find a final disposal for heat generating waste in the Federal Republic of Germany. It is foreseen to establish a commission in 2013 whose task it is to provide the German Parliament with recommended actions and necessary elements of evidence for taking its decision. A final report about the results should be available in the end of 2015. Afterwards selection of above-ground exploration sites has to be performed. Exploration and safety analysis results should lead to recommendation of two underground exploration sites at the end of 2023. Based on the findings a final recommendation for the underground repository will be made in form of a bill by the government and pass into federal law after approval of the parliament. This is expected to happen at the end of 2031. Based on experience, the following application, licensing and legal actions by the public may take up to 15 years until construction work may begin. With an estimated construction time of the same order, commissioning could take place around 2060. For the central storage facility Gorleben licence expires in 2034. First on-site storage facility reaching expiry date will be Lingen in 2042. Hence, an extension of the licensed storage period will be needed.

Related to this subject, the "Guidelines for dry cask storage of spent fuel and heat-generating waste" [1] stipulates that if the licensed storage period seems likely insufficient, further appropriate safety assessments, concerning e.g. long-term behaviour of fuel elements and cask components, have to be provided by the licensee.

4 LONG-TERM STORAGE CONSIDERATIONS

It is important to know that the temporary licenses of 40 years are based on administrative reasons and not on limiting physical or technical parameters. Nonetheless, it has to be shown that safety functions will be fullfilled during the envisaged timeframe beyond 40 years. Accordingly, additional knowledge and data about material and component performance are necessary to generate sufficient safety assessments by the applicants and safety evaluations by the competent authority and its technical experts. In addition to the state of the art in science and technology, further lessons learned and information have to be gathered in the future from periodic safety inspections and ageing management programmes at all storage sites. Regarding safe operation of interim storage facilities during this long time, non-technical aspects like knowledge management and provision of human resources have to be considered.

In the following, potential long-term aspects regarding the cask and the fuel will be discussed.

4.1 Corrosion

Corrosion inside the cask will still be prevented by inert cask atmosphere and limited residual moisture. On the outer side of the casks, a coating protects the metal against corrosion. Additionally, the condition of coating can be visually inspected, allowing initiation of countermeasures if any abnormality is discovered.

4.2 Cask related aspects

With the cask fulfilling the main safety functions, the time-dependent behaviour and possible degradation effects of its respective components have to be considered for long-term storage. Under the influence of gamma radiation, the polymer neutron shielding inside the cask may undergo structural changes. The effect depends on the accumulated gamma dose and could gradually lead to a reduction of the shielding capability. Since dual purpose casks are equipped with a double-barrier lid system, the proper function of the metallic barrier seal is essential. Leak-tightness could suffer from a decrease of pressure force and resilience due to relaxation in the metal gaskets and bolts for the lids. Transportability of the casks is required during and at the end of the extended storage period to ensure the possibility of an instant transfer whenever necessary. Main components ensuring transportability are the trunnions and their connection bolts which may as well undergo relaxation and corrosion [4].

4.3 Fuel related aspects

Continious increase of discharge burn-up and application of new cladding materials for UO_2 and MOX fuels in combination with extended storage periods may require a new or additional proof of safety because related effects represent knowledge gaps and lack in sufficient data for these fuel types.

Increased burn-up leads to more fission gas production and beyond 55 GWd/tHM to accelerated fisson gas release as well as increased fuel swelling, resulting in higher mechanical loads on the cladding due to less free volume and possible pellet-cladding interaction. Furthermore, alpha decays in spent nuclear fuel generate radiation damage and helium, which could be responsible for additional lattice and volume swelling of the fuel during long-term storage, posing a potential threat for the integrity of the cladding [5]. This effect applies especially for MOX fuel with its higher alpha activity.

Another important aspect concerning the integrity of the fuel assemblies is the influence of hydrogen on the cladding. During reactor operation, hydrogen is absorbed by the cladding and will dissolute as zirconium hydrides when exceeding temperature dependent solubility limit. The hydrides dissolute alongside thermal and stress gradients with the thermal gradient being dominant during reactor operation, leading to circumferential orientation of the hydrides (**Fig. 1a**). When the fuel is transferred from wet into dry storage, the drying of the casks and decay heat result in cladding temperatures of about 370 °C, allowing around 200 ppm of hydrogen to go into solution. The amount of hydrogen will dissolute again during dry storage period but by then, stress gradient having originated from the fuel rod inner pressure will be dominant, favouring orientation of the formed hydrides in radial direction (**Fig. 1b**). The effect is called hydride reorientation and investigating its behaviour is complex as there is a multitude of influencing variables, e.g initial hydrogen concentration, cooling rate, hoop stress and different cladding materials. Significant fractions of radial hydrides cause an embrittlement of the cladding and could result in a complete loss of ductility below the ductile-to-brittle-transition temperature (DBTT). The DBTT is in the range between 120 and 220 °C [6,7] and is also determined by a variety of parameters. As it can be seen in **Fig. 2,** the respective temperatures will be reached around 40 years after discharge. Regarding dry cask storage, the importance of this issue appears to be low. However, one should consider it in terms of transport scenarios when casks will be moved and additional loads act on the cladding.

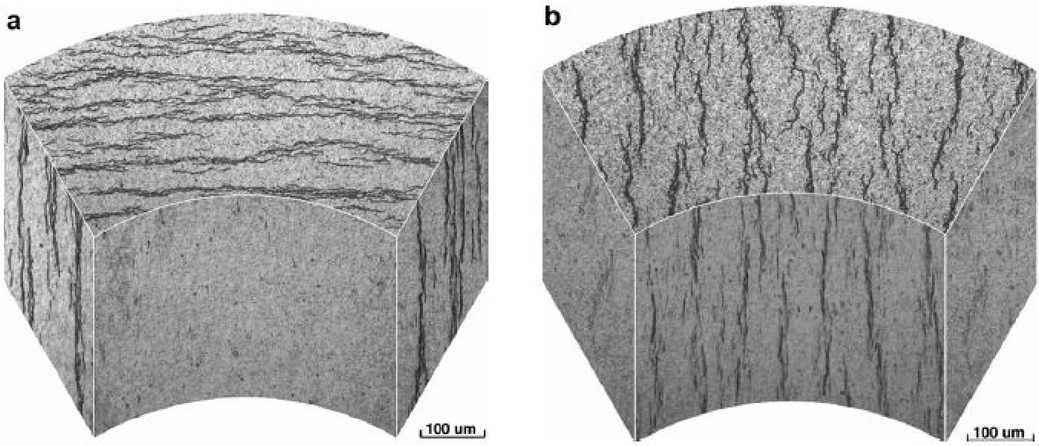

Fig. 1 a) Circumferential hydrides b) Radial hydrides in Zry-4 cladding [8]

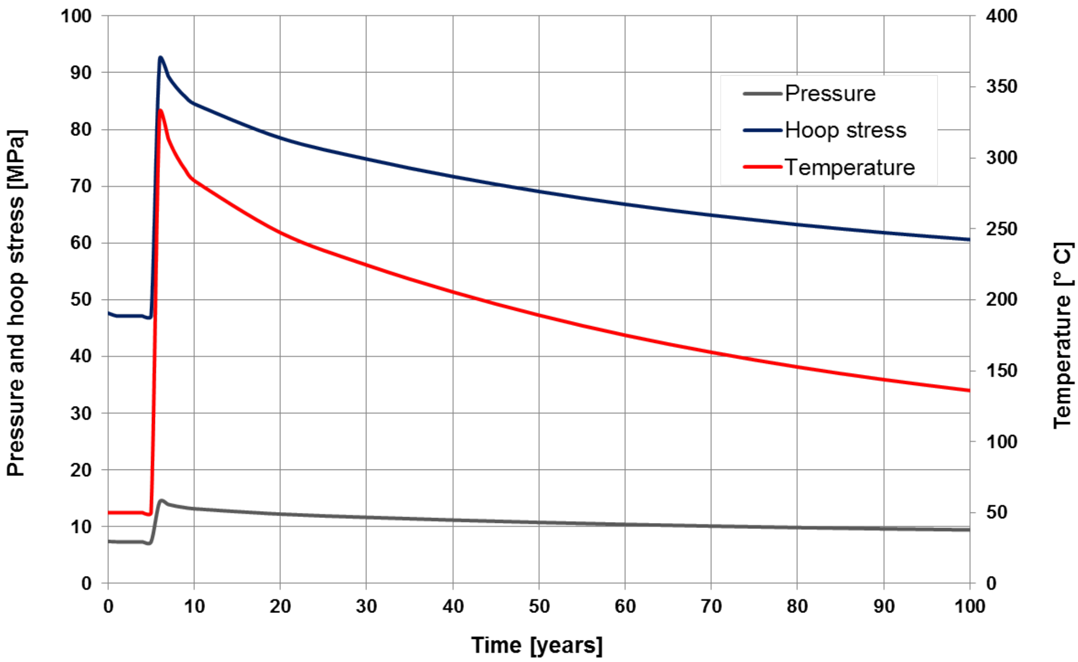

Fig. 2 Hoop stress, temperature and pressure vs. time of a UO2 fuel rod with 55 GWd/tHM

5 CURRENT ACTIVITIES TOWARDS LONG-TERM STORAGE IN GERMANY

GRS is performing a project funded by BMU on safety issues of long-term interim storage of spent fuel and vitrified high level waste. Participating partners in this project collaboration are the Oeko-Institut e.V. and BAM. BAM is internationally acknowledged for its technical expertise and experience in the field of safety evaluation for the long-term performance of interim storage containers and all associated components under storage-specific operational conditions. By evaluating relevant publications, an overview of the state of the art in science and technology will be provided, followed by an analysis and discussion of technical aspects like e.g. the long-term behaviour of spent fuel elements, casks and storage systems.

Currently, the first PSR for the central storage facility Gorleben is under way. GRS is carrying the process in terms of technical assistance for the BMU. This approach should allow identifying problems and uncertainties regarding the implementation of the guidelines. As a result a report about the lessons learned and recommendations for an optimisation of the process and the guidelines is intended.

In Germany, research on the mentioned long-term storage issues is performed by various institutions and companies. AREVA, Gesellschaft für Nuklear Service (GNS) and the Institute for Transuranium Elements (ITU) in Kalrsruhe are investigating fuel and fuel rod behaviour, whereas studies on polymer neutron shielding under radiation and heat are conducted by BAM [9]. Further, BAM started different long-term performance tests under ambient operating conditions for metal gaskets supported by the cask vendor GNS, which are expected to deliver useful information [10].

6 INTERNATIONAL ACTIVITIES AND COOPERATION

Long-term interim storage internationally gained increasing attention due to the pending site selection process for a disposal facility in numerous countries. Consequently, several research and development projects as well as working groups were initiated, e.g. by US DOE and US NRC, Electric Power Research Institute (EPRI), IAEA and OECD/NEA, aiming at a better understanding of degradation processes and at identifying and closing knowledge gaps. Furthermore, practical experience was gained by the re-opening of a CASTOR V/21 cask in 1999, which has been stored for 15 years in the USA [11]. In addition, at the beginning of 2013, the Japanese TEPCO investigated three dry storage casks which were located at Fukushima site and flooded by the tsunami in 2011 [12].

7 CONCLUSIONS

A fundamental part within the German concept for spent fuel management is dry interim storage in transport and storage casks until it can be disposed of in a deep geologic repository. Discharged spent fuel from power and reseach reactors as well as high active vitrified waste from reprocessing abroad is to be stored in suitably designed dry interim storage facilities. The current licenses for storage are valid for 40 years after the first cask was emplaced, with its limitation not being based on limiting physical or technical parameters. Due to the delay of the site selection for a geological repository a necessary extension of the period for interim storage might be occuring. Consequently, long-term storage is in the focus in many countries. The legislative and technical base for an extension of the interim storage needs to be provided. This requires the demonstration and justification for safe storage in accordance with the state of the art in science and technology for a time period beyond the currently licensed period. Besides the fulfilment of the basic safety goals during extended storage, the requirement of transportability of the casks has to be met as well. The main challenges in the future consist of closing knowledge gaps for long-term component and fuel behaviour as well as the management of ageing, knowledge and human resources. Worldwide, there are more than 20 years of experience in dry storage and currently, many research and investigation programmes in a collaborative manner are already under way.

8 REFERENCES

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