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EXTENDED STORAGE AFTER LONG-TERM STORAGE

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ABSTRACT

Existing spent nuclear fuel (SF) and high active waste (HAW) management policies and practices worldwide are the result of past presumptions that sufficient reprocessing and/or disposal capacity would be available in the near term. Consequently, in the past many countries have developed specific solutions for different periods of time due to their individual national nuclear policies.
In Germany the concept of dry interim storage in dual purpose metal casks before disposal is being pursued for SF and HAW management and transport and storage licenses have been issued accordingly. The current operation licenses for existing storage facilities have been granted for a storage period of up to 40 years. This concept has demonstrated its suitability for over 20 years so far. Relevant safety requirements have been assessed for the short-term as well as for the long-term for site-specific operational and accidental storage conditions. But in the meantime significant delays in the national repository siting procedure occurred which will make extended storage periods necessary in the future.

This paper describes the current situation in Germany with regard to dry cask storage and focuses on current perspectives considering regulatory, technical, and scientific aspects for storage license renewal. Since there is one case of a storage license limitation to only 20 years due to administrative reasons, first experience is currently gathered in case of an expiring storage license. Subsequent license options have been pursued intensively including the extension of the initial storage license as well as shipping all casks to another storage facility considering an extended storage period at that storage facility as well. All safety relevant aspects have to be reviewed on basis of the current state-of-the-art which might be different from the initial safety demonstrations. That includes new safety assessment standards as well as improved knowledge base. Major issues are e.g. improved accident scenario analyses, assessment methods, and consideration of aging effects from previous operation periods. Inspection programs with respect, e.g. to bolts and seals to verify leak-tightness and lid screw pre-stress have been initiated to

demonstrate proper cask conditions for extended storage as well as transportation to another storage facility.

INTRODUCTION

The safe storage of spent nuclear fuel (SF) until a repository is finally available is one of the major issues with regard to the fuel cycle. In the past many countries have developed specific solutions for different periods of time due to their individual national nuclear policies. In Germany, spent nuclear fuel and high active vitrified radioactive waste (HLW) from SF reprocessing are stored in thick-walled metal dual purpose casks (DPC) with a double lid system which are approved for transportation and storage. With this concept SF can be removed from nuclear power plants flexibly during operation or later decommissioning and can be stored on-site or elsewhere, e.g. in centralized storage facilities.

Initially, dry storage of SF in Germany was performed in two central storage facilities in Ahaus and Gorleben starting in the 1980’s. This concept was applied for BWR-, PWR- and THTR (thorium high temperature)-SF from commercial nuclear power plants. HLW from reprocessing of SF in France is already stored in Gorleben. Public discussion about transportation of SF and HLW in Germany and possible contamination of casks during transportation lead to the construction of on-site storage facilities, which are located adjacent to the power plants. For these on-site storage facilities three different designs were chosen: two different types of storage buildings (Figure 1) and a tunnel-design. In a few cases SF DPC were stored in small concrete shelters (short-term interim storage limited to 5 years) prior to completion of licensing and construction of the main interim storage facility.
In addition to the two central storage facilities in Ahaus and Gorleben and 12 on-site storage facilities at nuclear power plants (which are shut-down or in operation) also two storage facilities for dry cask storage are in operation at decommissioned reactors, the Interim Storage North (ZLN) in Rubenow and the AVR Cask Storage Facility (FZJ) in Jülich.
So far, about 1000 dual purpose metal casks have been assembled and stored in German interim storage facilities since 1993 when the first cask was loaded and stored.

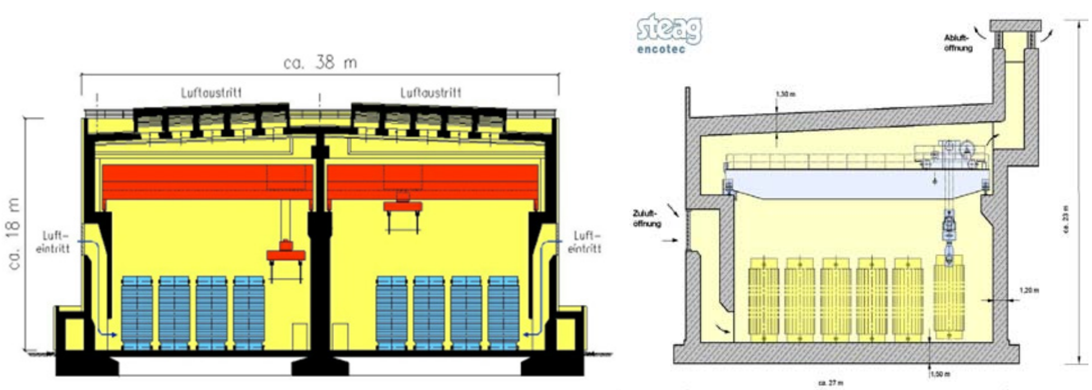

Figure 1. Storage buildings for interim storage of dual purpose casks (left: WTI concept, right: STEAG concept)

Together, the cask and building assure the compliance with the safety requirements. Safe enclosure of the radioactive material as well as the subcriticality is ensured by the cask design.

The building protects casks from harmful weather conditions, external effects or man-made hazards. Safe heat removal and shielding is conducted by interaction of cask and building structure. Therefore it is possible to apply only passive systems on the basis of natural convection, which are almost maintenance free and can ensure their function for a long time without intervention.

LICENSING OF DRY STORAGE FACILITIES

Depending on the regulatory requirements of the individual countries it is required either to have a general license for storage of spent nuclear fuel in the DPC or an individual license for each storage facility that contains DPC. Since the management of SF using DPC involves storage of SF as well as on-site and off-site transportation before and/or after storage, some countries require package design approval for the DPC as well. Therefore, demonstration of compliance of the DPC with national and international transport regulations as well as with the national storage requirements is necessary.

In Germany, the management of spent nuclear fuel and high active vitrified radioactive waste from reprocessing is defined by the German Atomic Energy Act (AtG) [1]. Since July 1st, 2005, it is prohibited to deliver SF for reprocessing. SF and already generated HAW have to be stored in interim storage facilities until disposal in a geological repository. Such storage facilities are licensed on the basis of § 6 AtG [1]. The storage license is granted by the competent authority, the Federal Office for Radiation Protection (BfS) on basis of safety assessments by the applicants which are usually the utilities of the NPPs and not the transport license holder. An overview of the interim storage licensing procedure in comparison to the Type B(U) package approval in Germany is given in Figure 2. The storage license is specific to the applied interim storage site considering certain cask designs and inventories. There is no general cask design storage license issued.

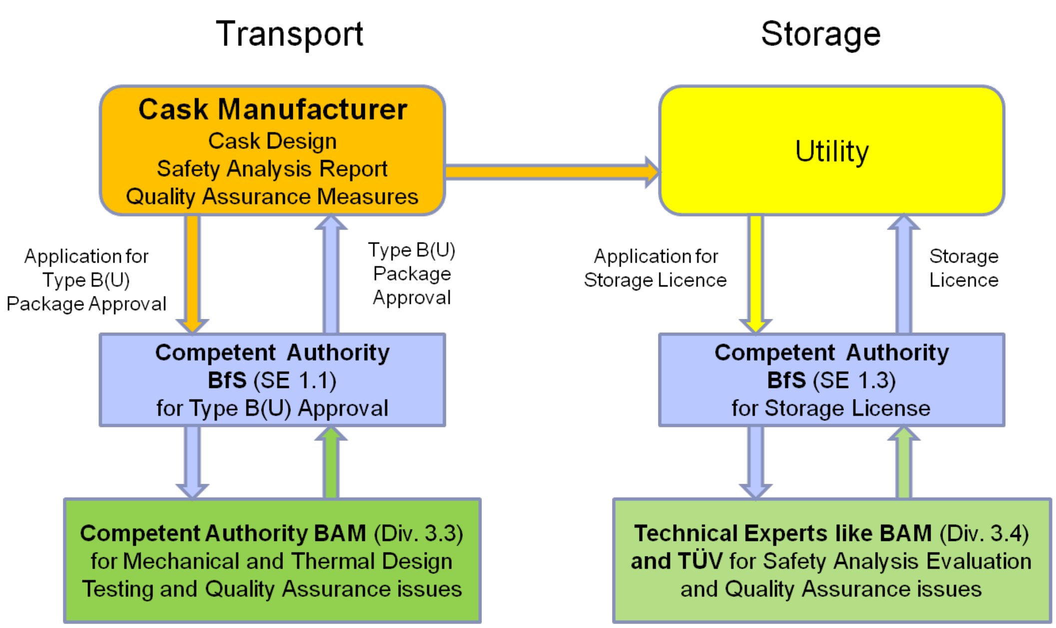

Figure 2. Type B(U) package approval and interim storage licensing procedure in Germany

The storage period was generally limited to 40 years (beginning with the first cask emplacement) for administrative reasons because it was expected to have a final repository available after that time. In the meantime Germany has passed a law to establish a completely new site selection procedure for a repository for SF and HLW. This procedure and the subsequent siting and exploration procedure will take at least three decades and therefore extended interim storage periods are inevitable in the future.

In addition to the storage license a building permission for the erection of the storage hall is required which is granted by local authorities pursuant to the legislation of the Federal State in which the facility is located. Local authorities of the Federal State in which the facility is located are also the competent supervisory authorities of the licensed storage facility.

For the safety assessment evaluation of the storage license application documents, BfS contracts technical expert organizations according to § 20 AtG. Amongst others the Federal Institute for Materials Research and Testing (BAM) is contracted in order to evaluate all cask related safety issues including all quality assurance measures for cask fabrication and operation according to the state-of-the-art in science and technology. Other technical expert organizations like TÜV are contracted by BfS for facility and inventory specific issues. For this safety evaluation the recommendations of the German Nuclear Waste Management Commission (ESK) "Guidelines for dry cask storage of spent fuel and heat-generating waste" [2] have to be taken into consideration. Accordingly, the storage facility contains all technical and safety infrastructure for operation, casks with the radioactive contents under dry and inert conditions and a building containing the casks and all handling, maintenance and monitoring equipment.

Safety goals for dry interim storage casks are the same as for transport packages: Safe enclosure of the radioactive inventory, subcriticality, shielding, and decay heat removal in a way that safe enclosure, subcriticality and shielding are not affected. The main safety goals are guaranteed by the dual purpose casks and only shielding is additionally supported by the storage building which also protects casks from environmental conditions. Furthermore, the storage license holders have to demonstrate spent fuel element integrity before loading and fuel rod integrity during interim storage (no systematic fuel rod failure). The casks are thick-walled and made of forged steel or ductile cast iron containing a permanently monitored double barrier lid system with long-term resistant metal seals. The cask inventory is carefully vacuum dried and filled with inert gas after loading to avoid corrosion effects and ensure effective heat removal.

As it was mentioned before, transportation after storage is essential to all casks stored in interim storage facilities whether they are centralized or at-site. Permanent demonstration of transportability is required by all issued licenses for all casks being in storage. So far it is common understanding of all stakeholders in German interim storage business that valid Type B package design approvals for all cask designs during storage and not only at the beginning is a necessary prerequisite. On the other hand it is quite clear that the transport license for any cask needs the individual demonstration of compliance with the transport package design approval [3]. Ruling on this issue does need a close link and cooperation between interim storage licensing and transportation approval procedures because important safety relevant properties of the dual purpose casks are influenced by both areas of use.
Because accident safe Type B casks have demonstrated their safety level within the transport package design approval procedure all these safety assessments can be used by applicants for storage licenses as well if appropriate (for details on the transport package design approval procedure (as shown e.g. in Figure 2) in accordance with the international transport regulations and background see [3]). Additionally, different operation conditions inside the storage facility

require adapted or additional safety assessments. Especially mechanical accident scenarios are significantly different in comparison to Type B test conditions due to cask handling without impact limiters and different drop orientations, drop heights and target stiffness. Another difference is the long-term performance of all cask components which has to be assessed and evaluated for the entire applied storage period. Because of the dry and inert storage conditions and the only use of passive safety relevant systems, maintenance and inspections procedures are very limited during storage operation which is under permanent supervision by the operator, responsible state authorities and their technical experts.

It should be mentioned that since many countries operate spent fuel storage in dual purpose casks, also international activities are underway to propose an integrated safety assessment and a harmonized approved/licensing approach. Initiated by IAEA a "Joint Working Group on Guidance for an Integrated Transport and Storage Safety Case for Dual-Purpose Casks for Spent Nuclear Fuel" was established and a draft of a technical guidance document (IAEA-TECDOC) titled "Guidance for preparation of a safety case for a Dual Purpose Cask containing spent fuel" was developed. This TECDOC shall be finished until end of 2013 and shall contain guidance in dual purpose cask safety assessment criteria and methods for pre-storage transport, interim storage and post-storage transport [4].

SITE SPECIFIC SAFETY ASSESSMENT

Any application for SF and HLW interim storage has to assess safety under consideration of relevant safety requirements, taking into account all site-specific aspects including cask handling and possible severe incidents or accident scenarios like fire or cask drop from a crane [2]. All safety assessments have to be reviewed and evaluated by the competent authority and their experts. Because of similar or identical technical solutions like buildings, casks, operational procedures, many aspects are equally relevant for several sites and safety demonstrations might be transferred from one site to another to reduce effort. Some common aspects are explained in the following:

<u>Heat removal:</u> All storage facilities are designed in such a way that the decay heat removal is ensured by natural convection without active systems, even under accident conditions and without the need of intervention by working personnel. The cooling air enters the storage building at the sides of the hall, flows around the casks and is released at the roof. In the case of the rock tunnel design, which is used at the Neckarwestheim storage facility due to the specific geography of the site location, decay heat removal is ensured by natural convection from the rock tunnel to the surface by additional shafts.

<u>Shielding:</u> The thick concrete walls of the storage buildings and the chosen thick-walled cask design reduce the dose rate outside the storage buildings effectively to acceptable levels where no further measures for the protection of the workers on the site or the public outside the storage facility need to be established. In the case of the Neckarwestheim rock tunnel design, the surrounding rock effectively reduces the dose rate on site. The casks themselves reduce the dose rate within the storage buildings to a level where handling, emplacement and displacement of casks as well as service operation can take place whenever necessary.

<u>Safe enclosure:</u> The German concept of dry storage of SF and HLW gives a maximum level of safety for design basis accidents and even beyond design basis events. This includes on one hand external hazards such as fire, earthquakes, flooding, landslip, shockwave, lightning strike or airplane crash and pressure blast wave from outside the storage facility and on the other hand

internal effects such as handling failures or casks drop. The casks and the storage building provide effective protection of the enclosed activity and guarantee the compliance with the safety requirements. Even after a collapse of the storage building, caused by a beyond design basis accident (e.g. aircraft crash), the casks remain intact and no activity will be released. This high level of safety is established by using passive safety systems and a matching combination of cask and storage building. In the case of the Neckarwestheim rock tunnel design, additional protection against external hazards like aircraft crashes is given by the tunnel.

<u>Subcriticality:</u> Nuclear criticality safety has to be ensure during storage for all normal operational conditions, cask handling procedures and all possible effects of design basis accidents as well as for beyond design basis events. In case of dry storage, e.g. re-positioning of fissile material inside the cask is excluded by the cask design including spent fuel basket. In addition, in contrast to the transport regulations, moderator exclusion may be taken into consideration for dry interim storage.

CASK SPECIFIC SAFETY ASSESSMENT

BAM is the competent authority in design testing and evaluation of all quality assurance measures within the transport license approval procedure and BAM is also involved in the storage licensing procedures by the competent authority for the same cask related aspects (see Figure 2). This enables high efficiency and comparative evaluation methods for the same technical and scientific aspects (see also [3]). A major aspect of BAM design testing for interim storage are safety demonstrations for design basis accidents such as a cask drop onto the ground of the storage building without shock absorbers and in the most severe drop orientation. This requires a systematic study of all handling procedures within the storage facility to determine from which positions a cask drop has to be considered and which are the most severe scenarios with regard e.g. to drop orientation, drop height and target. Subsequently, safety demonstration for selected most severe drop scenarios can be performed by experiments and/or numerical calculations. BAM operates state of the art equipment in both fields with a large drop test facility for cask gross masses up to 200 metric tons and a 2.400 metric tons unyielding concrete foundation in compliance with IAEA requirements and with capable computer systems and different finite element codes such as ABAQUS®, LS-DYNA® and ANSYS®. The analysis of hard cask drop scenarios needs demanding dynamic measurements and/or calculations including specific material data and sophisticated stress and strain evaluation procedures (see e.g. [5]). Verification of numerical models and calculation results by full-scale, model or component tests is usually necessary and also adequate modeling of the foundation or impact limiting structures is essential.

Other major issues for the interim storage safety evaluation consider the long-term performance of cask systems and components under operational conditions during the entire storage period which is 40 years in Germany so far. Because dual purpose casks are equipped with a double barrier lid system the proper function of the metallic barrier seals is essential. Not only for that reason quality assurance measures for fabrication, assembling and loading procedures and cask operation are of particular importance as well. Each cask has to be fabricated in accordance with approved manufacturing and testing plans. Finally, certificates of compliance are issued for transport as well as storage purposes and with these documents the cask can be loaded and assembled for transport and dry storage use. Cask loading under wet conditions in a spent fuel pool requires very accurate dewatering and drying procedures afterwards to prevent any relevant corrosion effect during the subsequent storage decades.

SAFETY ASPECTS BEYOND THE INITIALLY APPROVED STORAGE LICENSE – FIRST EXPERIENCE

As already mentioned, meanwhile it is quite evident that storage license periods of 40 years will not be sufficient to cover the time period until a final repository for spent nuclear fuel will be available in Germany and that extended interim storage periods will be inevitable in the future. Besides the usual storage license periods of 40 years there is one case of a storage license limitation to only 20 years due to administrative reasons. This case represents the interim storage facility at the former Jülich AVR pebble bed research reactor where 152 CASTOR® THTR/AVR casks are stored containing the remaining pebble fuel. Because the storage license expired on June 30, 2013, subsequent license options have been pursued intensively including the extension of the initial storage license as well as shipping all casks to the Ahaus storage facility considering an extended storage period there as well. Transportation to the United States is currently under discussion as another option due to the fact of dealing with research reactor fuel. Besides very complicated politically interests there are certain technical aspects to be considered with regard to extended storage periods.

At first a license extension has to consider all safety aspects representing the current state-of-the-art which is more or less different to the initial safety demonstrations. That includes new safety assessment standards as well as improved knowledge bases. Major issues are improved accident scenario analyses, assessment methods, and the consideration of aging effects from previous operation periods. All these aspects are general and not dependent on the particular initially licensed storage period, whether the license was issued for 20 or 40 years.

If not only the extended storage period is requested but also a transportation to move stored casks to another facility, specific requirements from the transport regulations have to be considered as well. That means, it has to be ensured before transport that the package complies with the specifications of the design approval certificate [3]. In case of the expiring 20 year license the following aspects have been considered exemplarily with respect to transportation and subsequent storage:

- Valid Type B(U) cask design approval,
- Documentation of periodic inspections,
- Declaration of barrier lid system for transportation and demonstration of its sufficient leak-tightness, sufficient tightening torques of the lid screws,
- Successful loading tests of trunnions,
- No cask contamination at outer surfaces,
- Sufficient shielding and heat removal,
- Subcriticality,
- Safety in accident scenarios,
- Sufficient leak-tightness of primary and secondary barrier lid systems after transportation and prior to interim storage.

The inspections towards transportability after long-term storage started in September 2012 and the casks investigated until now cover nearly the entire loading period that lasted from 1993 to 2009. The main test results until the end of June 2013, after preparation of 45 casks, are discussed in detail in [3]. It turned out that there is no relevant influence of up to 20 years storage time on the cask condition.

In general, the operation regime of the interim storage facility guarantees a proper quality of casks and components during their operation. Inspection and maintenance measures are on a minimum level due to the robust and reliable design features but are performed as necessary and required by the issued license and the supervising state authority.

With regard to bolted lids, inspections of a representative number of screws have been performed by removing them to identify potential plastic deformations. Therefore metallographic methods and high precision length measurements were used. Results have shown no relevant plastic deformations due to the applied torques during dry storage.

To demonstrate sufficient leak-tightness of the bolted barrier lids, measurements were performed at several primary lid systems. A challenge in this case was a potential helium contamination of the auxiliary elastomer seals from the previous interim storage periods when the space between primary and secondary lid is filled with helium overpressure for leak-tightness monitoring purposes. The results of several measurements have shown that the demonstration of the leakage rate of 10^{-8} $Pa \cdot m^3 \cdot s^{-1}$, which is required for SF interim storage in Germany, is achievable, but measurement times needed reached up to 70 hours.

AGING MANAGEMENT ISSUES

Details with respect to aging management fundamentals were described in [6]. The main issues with respect to dual purpose casks are also addressed in [4].

During long-term interim storage the main driving forces of aging effects are:

- Gamma radiation,
- Neutron radiation,
- Decay heat,
- Outer corrosion effects (e. g. moisture and air pollution),
- Relaxation, creeping, corrosion of screwed and sealed lid systems, basket, and fuel rods.

Degradation effects strongly depend on the type of material. All main cask components responsible for the safe enclosure are usually made of metal (e.g. cask body, lids, main seals, and screws). Additionally, polymer components are used for supplementary neutron shielding components and auxiliary seals. In general, damaging effects of radiation depend on dose rates, type of radiation and material structure. Metals are generally more resistant than polymers. Degradation effects may result in quantitative changes of specific material properties or modifications in material structure which may decrease the effectiveness of cask components.

With respect to possibly extended storage periods in the future and international recommendations with regard to the existing legal framework in countries of the Western European Nuclear Regulators Association (WENRA), Germany has decided to improve its existing regulations in the field of periodic safety inspections and aging management during interim storage of spent nuclear fuel. On behalf of the Federal Ministry for the Environment, Nature Protection and Nuclear Safety (BMU), the German Waste Management Commission (ESK) elaborated periodic safety inspection guidelines [7] and recommendations for aging management procedures [8] of interim storage facilities. However, the established and supervised operation regime does already consider aging management issues as well but mainly based on the license requirements and not on formal guidelines. The general periodic safety inspection period shall be 10 years. The draft documents are considered now for a two years test phase at two selected sites, the Gorleben centralized storage facility and the storage facility at the nuclear power plant Emsland as an on-site representative. The outcomes are expected to be evaluated by the end of 2013. Thereafter the final guidelines will be fixed and have to be considered by all storage facilities afterwards. Figure 3 illustrates that regulatory framework. This systematic approach allows to summarize lessons learned, technical changes and optimization measures and to share the experience with other facilities and licensing authorities. Finally, such an information pool might be a good basis for possible future lifetime extension applications.

For periodic package design approval certificate renewals during the storage period, the maintenance of the package design safety report is essential. It has to be kept up-to-date considering the assessment of aging effects on package safety compliance with the transport regulations, changes of regulations, standards and technical knowledge, experiences on that issue are reported in [14].

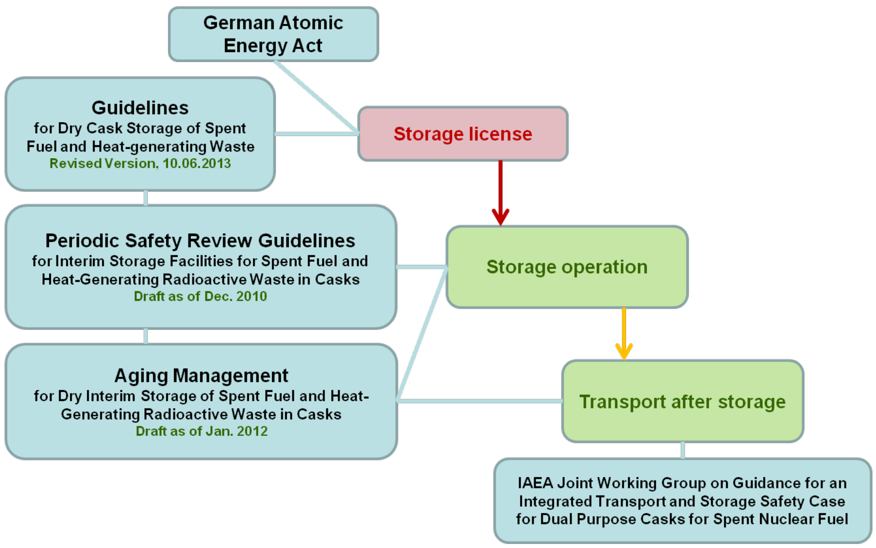

Figure 3. German regulatory framework for aging management during SF long-term interim storage

ADDITIONAL MATERIAL INVESTIGATIONS

In addition to the current state-of-the-art, lessons learned and information gathered from periodic safety inspections including aging management programs, questions concerning the long-term performance of sensitive components for cask safety have to be investigated by additional laboratory and/or field tests. Recently analyses in this field have been performed also internationally for various dry spent fuel storage systems and so called data gap reports have been published. In addition, IAEA has initiated a consultancy service concerning the “Challenges Associated with Extending SF Storage until Transport for Reprocessing or Disposal” and a coordinated research project on “Demonstrating Performance of Spent Fuel and Related Storage Systems beyond the Long Term”. BAM participates in these activities to contribute to an international exchange of information on long-term material performance issues.

Besides the current storage license extension for the Jülich facility after only 20 years all other facilities will have the need to apply for extended storage periods timely before the end of their 40 years lifetime. Therefore additional knowledge and data about the material and component performance beyond 40 years are necessary to generate sufficient safety assessments by the applicants and safety evaluations by competent authorities and their technical experts. This might be summarized under a so-called national investigation program. To close identified data gaps and to gain the needed technical data, long-term investigations have to begin early enough because they are mostly time consuming. Figure 4 shows the principle for additional data needs.

BAM has already started investigation programs with metal seals of the Helicoflex® type as major component of bolted lid closure systems which are evident for the safe enclosure of the radioactive inventory. Major outcomes of these test series show decreasing pressure forces and decreasing elastic recovery (useable resilience until the specified leakage rate of 10^{-8} $Pa\cdot m^3\cdot s^{-1}$ is exceeded) after certain holding times at different temperature levels for various seal types (aluminum, silver). But improved contact of the metal surfaces due to plastic deformation of the outer seal jacket results in proper seal function even in case of nearly complete loss of pressure force. More detailed information about that test program can be found in [9, 10]. Recent results are presented in [11].

Furthermore, since 2001, BAM is running a test program investigating Helicoflex® seals with enclosed boronated water (boron concentration 2040 ppm) in between the two metal jackets and installed in a flange system. In addition, in order to stimulate corrosive damages over relatively short periods of time, some seals were filled with water containing 10^{-3} mol of sodium chloride. Seals are stored at 20°C and 80°C. Leakage rate measurements stay well below the required value of 10^{-8} $Pa\cdot m^3\cdot s^{-1}$ until now.

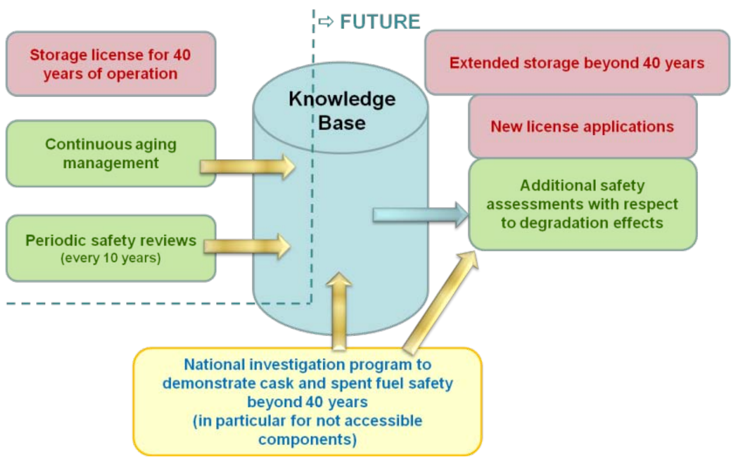

Figure 4. Data needs for storage periods beyond 40 years

Further investigations consider degradation effects by gamma radiation on polymer neutron shielding components during storage (see e.g. [12]). Also elastomer seals, which are only used as auxiliary seals in spent fuel and high active waste storage casks but may become of major interest for cask designs for other types of radioactive wastes. Recent results especially on the low temperature behavior of elastomer seals are presented in [13].

CONCLUSIONS

The German concept of dry spent fuel and high active waste interim storage in dual purpose casks has demonstrated its suitability for over 20 years so far. Relevant safety requirements have been assessed for operational and accidental conditions, for the short-term as well as for the long-term. Due to major delays of the siting and establishment of a final repository in Germany extended interim storage periods are inevitable in the future. First experience is currently gathered in case of an expiring 20 years storage license. Inspection programs with respect, e.g. to bolts and seals have been initiated to demonstrate proper cask conditions for extended storage as well as transportation after storage.

To be prepared for lifetime extensions of interim storage facilities, the systematic collection and evaluation of data and information from periodic safety inspections and aging management programs is as important as additional investigation programs to gain more data about the long-term behavior of relevant cask material and components. Even if there remain more than 15 to 20 years today until most storage licenses expire in Germany, investigation programs for reliable long-term predictions are time consuming and that necessitates starting such programs early. BAM has already commenced test series with metal seals, neutron shielding polymers and elastomer seals and contributes to international activities on extended storage issues such as material aging mechanisms. Also contributions on international regulatory development activities for extended SF storage and for a better harmonization of both, transport and storage licensing are fields of BAM activities.

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