Safety Aspects of Dry Spent Fuel Storage and Spent Fuel Management – 13559

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ABSTRACT

Dry storage systems are characterized by passive and inherent safety systems ensuring safety even in case of severe incidents or accidents. After the events of Fukushima, the advantages of such passively and inherently safe dry storage systems have become more and more obvious. As with the storage of all radioactive materials, the storage of spent nuclear fuel (SF) and high-level radioactive waste (HLW) must conform to safety requirements.

Following safety aspects must be achieved throughout the storage period:

- safe enclosure of radioactive materials,
- safe removal of decay heat,
- securing nuclear criticality safety,
- avoidance of unnecessary radiation exposure.

The implementation of these safety requirements can be achieved by dry storage of SF and HLW in casks as well as in other systems such as dry vault storage systems or spent fuel pools, where the latter is neither a dry nor a passive system. Furthermore, transport capability must be guaranteed during and after storage as well as limitation and control of radiation exposure. The safe enclosure of radioactive materials in dry storage casks can be achieved by a double-lid sealing system with surveillance of the sealing system. The safe removal of decay heat must be ensured by the design of the storage containers and the storage facility.

The safe confinement of radioactive inventory has to be ensured by mechanical integrity of fuel assembly structures. This is guaranteed, e.g. by maintaining the mechanical integrity of the fuel rods or by additional safety measures for defective fuel rods. In order to ensure nuclear critically safety, possible effects of accidents have also to be taken into consideration. In case of dry storage it might be necessary to exclude the re-positioning of fissile material inside the container

and/or neutron moderator exclusion might be taken into account. Unnecessary radiation exposure can be avoided by the cask or canister vault system itself.

In Germany dry storage of SF in casks fulfills both transport and storage requirements. Mostly, storage facilities are designed as concrete buildings above the ground, but due to regional constraints, one storage facility has also been built as a rock tunnel. The decay heat is always removed by natural air flow; further technical equipment is not needed. The removal of decay heat and shielding had been modeled and calculated by state-of-the-art computer codes before such a facility has been built.

TÜV and BAM present their long experience in the licensing process for sites and casks and inform about spent nuclear fuel management and issues concerning dry storage of spent nuclear fuel. Different storage systems and facilities in Germany, Europe and world-wide are compared with respect to the safety aspects mentioned above. Initial points are the safety issues of wet storage of SF, and it is shown how dry storage systems can ensure the compliance with the mentioned safety criteria over a long storage period. The German storage concept for dry storage of SF and HLW is presented and discussed. Exemplarily, the process of licensing, erection and operation of selected German dry storage facilities is presented.

INTRODUCTION

During the production of electricity by nuclear power plants spent nuclear fuel is obtained, while due to reprocessing of this spent nuclear fuel, high level wastes (HLW) accrue, both of which have to be stored in a safe way until their final disposal. For their long-term interim storage different technical concepts have been established ranging from wet storage in pools to dry storage in transport and storage casks. The events of Fukushima in March 2011 had different effects on these options emphasizing their specific advantages and disadvantages [3]. Anyhow, dry cask storage proved to be a concept with inherent safety margins to prevent activity release.

Consequently, dry storage of SF and HLW gains more and more importance, especially because it features advantages in safety as well as in logistics. This paper describes different systems for dry storage of SF and HLW and explains their specific advantages in comparison to other storage systems based on BAM and TÜV experience.

SAFETY REGULATIONS AND REQUIREMENTS

Following safety aspects must be achieved throughout the whole storage period of SF and HLW:

- All unnecessary radiation exposure and contamination of man and nature must be avoided, and
- All radiation exposure or contamination of man or nature must be kept as low as reasonably achievable (ALARA)

These goals are achieved by

- Secure encapsulation of the activity,
- Safe discharge of the decay heat,
- Subcriticality,
- Shielding of gamma and neutron radiation.

Basic requirements are defined in "Guidelines for dry interim storage of irradiated fuel assemblies and heat-generating radioactive waste in casks" edited by the German Waste Management Commission [2]. Since the ability to ship the casks for their further treatment after interim storage must be ensured, additional requirements may arise from the transport regulations. Therefore dual purpose casks which are suited and approved for transportation and storage similarly are utilized in many countries.

The implementation of these safety requirements depends on the specific storage system. In case of wet storage, the SF is stored in spent nuclear fuel pools with active cooling systems. The pool water has the function of heat dissipation and shielding; the activity is encapsulated as long as the fuel rods remain intact. Where necessary, additional filtration of the outgoing air must ensure that no activity is released into the environment. This concept of wet storage is used for spent nuclear fuel pools e.g. inside nuclear power plants, in a centralized storage facility like CLAB (Centralt mellanlager för använt kärnbränsle - central storage facility for spent nuclear fuel) in Oskarshamn, and at the reprocessing facilities in Sellafield and La Hague. These systems are cheaper in installation, but might be more expensive during operation compared to dry storage in casks. This aspect becomes more and more relevant with increasing storage periods.

For the dry storage of SF and HLW different concepts are in use worldwide. These include HLW storage in concrete vaults with natural air-cooling, e g. at Cogema, La Hague, or SF stainless steel canisters being stored in concrete over-packs. Other storage casks consist of various materials like concrete, forged steel or ductile cast iron.

SPENT NUCLEAR FUEL STORAGE IN GERMANY

In Germany, SF and HLW from SF reprocessing are stored in thick-walled metal dual purpose casks 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, the dry storage of SF in Germany was realized in two central storage facilities in Ahaus and Gorleben starting in the 1980's. This concept was applied to BWR/PWR-SF and THTR (thorium high temperature)-SF from commercial nuclear power plants. In addition, high active vitrified radioactive waste from reprocessing of SF in France is stored in Gorleben. Public discussion about transportation of SF and HLW in Germany and possible contamination of the cask surface 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 storage building-types (see Fig. 1 and 2) and a tunnel-design. The concept of a rock tunnel at the Neckarwestheim nuclear power plant is used due to the specific geography of the site location. In a few cases SF dual purpose casks 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.

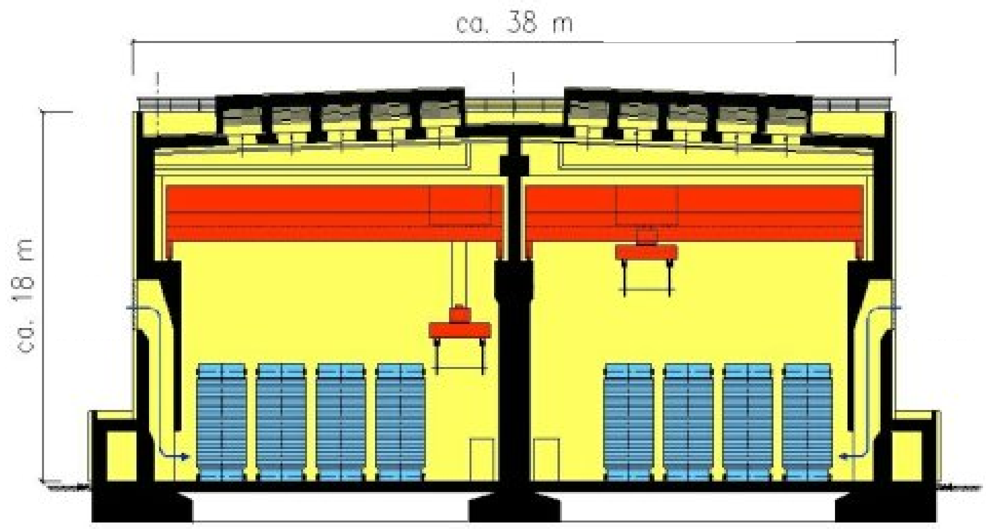

Fig. 1. Storage building WTI-type: two storage areas, air inlets at both sides, outlets on the roof

Together, casks and building assure the compliance with the safety requirements. The building protects casks from harmful weather conditions, external effects or man-made hazards. Safe and secure enclosure of the radioactive material as well as the subcriticality is ensured by the cask design. The secure heat removal and shielding is conducted by interaction of cask and building structure. Therefore it is possible to apply purely passive systems on the basis of natural convection, which are almost maintenance free and can ensure their function for a long time without intervention.

Meanwhile, besides the two central storage facilities, many other on-site storage facilities for dry cask storage are in operation at each nuclear power plant but also at shut-down reactors like Interim Storage North (ZLN). TÜV NORD Nuclear and BAM have been assigned as independent experts by the competent authorities in the licensing procedure due to their safety expertise within the application, erection and operation of such storage facilities. TÜV NORD Nuclear and BAM have checked and reviewed all safety assessments and documentations in the fields of cask designs and quality assurance, location, building structures and technical equipment, heat removal, shielding, subcriticality and safety under operational and accident conditions. TÜV NORD Nuclear and BAM are still in charge on behalf of the competent authorities for supervision of some of these sites during operation. New cask designs and changes in operation procedures, the building structures or the technical equipment are checked and reviewed by BAM and TÜV NORD Nuclear continuously. Furthermore TÜV NORD Nuclear and BAM developed and run a German-wide interchange-platform of experience concerning all loadings of SF into casks. Thus all relevant information is available to all involved experts organizations, competent authorities and utilities.

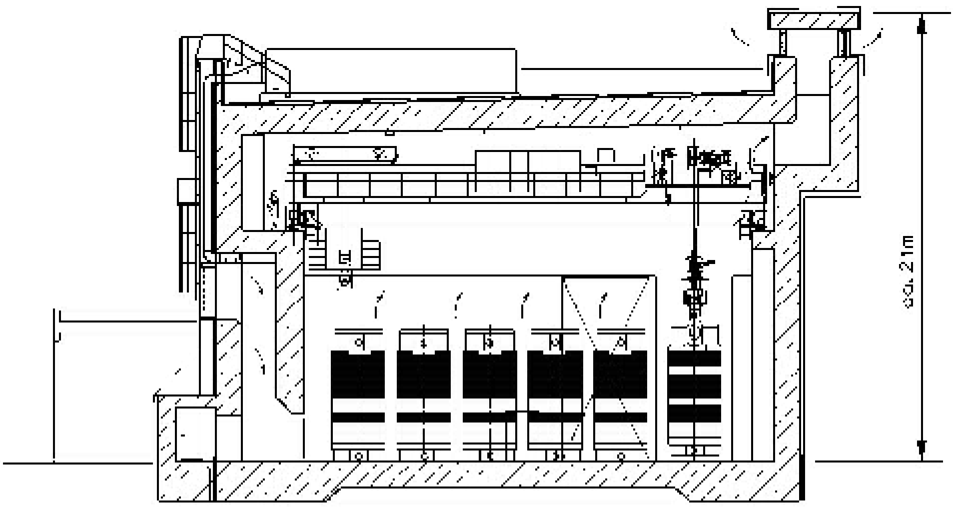

Fig. 2. Storage building STEAG-type: one storage area, air inlets at one side, outlet at the other side

Based on this long-standing and fruitful common work, BAM and TÜV NORD Nuclear have gained huge and unique knowledge and experience that can be used beneficially for similar studies or projects in other countries, especially where dry storage concepts may be considered for the safe long-term management of SF and HLW at present or in the future (http://www.tuev-nord.de/de/storage.htm).

SITE SPECIFIC SAFETY ASSESSMENT

Any application for SF and HLW interim storage has to demonstrate safety under consideration of the above mentioned safety requirements. Hereby, all site-specific aspects including cask handling and possible severe incidents or accident scenarios like fire or cask drop from a crane have to be taken into account. These safety reports have to be reviewed and evaluated by the competent authority and their experts. With regard to similar or even identical technical solutions for storage buildings, casks and operational procedures, many aspects are equally relevant for several sites. BAM and TÜV NORD Nuclear have performed these evaluations for each of the storage facility for SF and HLW in Germany.

Safe enclosure

The German concept of dry storage of SF and HLW guarantees a high degree of safety for design basis accidents and even beyond design basis accidents. The casks and the storage building provide effective protection of the encapsulated 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 (see below). This high level of safety is established by using passive safety systems and a matching combination of cask and storage building. Even in the Fukushima event, storage casks with SF were not affected significantly by the earthquake or the tsunami [3]. But the storage pools inside the nuclear power plants, which are dependent on active cooling systems, caused massive problems and release of activity after cooling failed. By using thick dual purpose casks with double lid sealing systems, the activity stays encapsulated under normal operation and even under severe accident conditions without active measures. The safe enclosure is checked by BAM during the cask design testing procedure (see below).

If casks have to be repaired, for example in the case one barrier of the double lid sealing system failed, different concepts exist. The casks can be opened and, if necessary, unloaded in the nuclear power plant or – if this option is no longer available – the double lid system can be reestablished by adding an additional third lid above the secondary lid that e.g. is welded to the cask body. It might also be possible to transport the cask to another nuclear facility where a hot cell is available.

Incident and accident analyses

BAM and TÜV NORD Nuclear are leading experts in the field of identification and evaluation of possible incident and accident scenarios for storage facilities for HLW and SF. For all mentioned storage facilities in Germany such possible incidents and accidents have been identified and possible consequences have been evaluated with respect to safety functions of storage system components.

For the analyses, all possible incidents and accidents were evaluated and those with the greatest impact on the casks were selected for further evaluations. Hereby internal accidents like mechanical impacts (drop), thermal impacts (fire), handling failures, loss of electrical supply or loss of air ventilation as well as external effects like seismic events (earthquake), stress caused by wind and snow, lightning strike, flood, external fires, impact of dangerous materials, aircraft crash or blast waves were analyzed. Some of these incidents and accidents apply to each storage facility, but most are site specific.

As there are usually very little fire loads inside the storage buildings, an internal fire can only have limited impact on the casks. In Germany, only Type B(U)-casks are used, and an internal fire cannot exceed the limits of the Type B(U) fire test scenario at 800°C (full engulfment) over 30 minutes. Therefore, for any fire scenario inside a storage facility the close encapsulation of the activity is guaranteed.

Mechanical accident scenarios have to be analyzed in addition to the Type B(U) drop test scenarios because casks are handled without impact limiters and may drop onto various targets like concrete foundations or rail car structures. Because of the passive heat removal a loss of electricity will also have no effect on cask safety. Only the monitoring systems for cask leaktightness may be affected but without relevance for the safe enclosure.

Loss of ventilation as a result of blocking of the inlets or outlets could interrupt the cooling by natural air flow. But because of the mass of the concrete building this would result in a very slow increase of the temperature of the casks and the inner building structures, leaving enough time to regain the cooling by air before critical temperatures are reached.

From all external events that can affect the building structure, aircraft crash or a blast wave are the most challenging ones. Under these beyond design basis accidents the building may collapse and the casks may be buried under debris. But even in these scenarios the casks will stay mechanically intact and the activity will stay encapsulated. The loss of air ventilation will lead to a slow increase of the temperatures inside the casks, but nevertheless there will be enough time to remove the debris and reestablish the cooling by air flow, before critical temperatures are reached.

As a result, the chosen combinations of storage facilities and casks ensure that even under beyond design basis accident conditions no severe impacts on the public have to be assumed for all storage sites.

Heat removal

All storage facilities are designed in such a way that the cooling of the casks is performed passively by natural convection of air (see Fig. 3). The cooling air enters the building at the sides, flows around the casks and is released at the roof. 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. In the case of the rock tunnel at the Neckarwestheim nuclear power plant decay heat removal is ensured by natural convection from the rock tunnel to the surface by additional shafts.

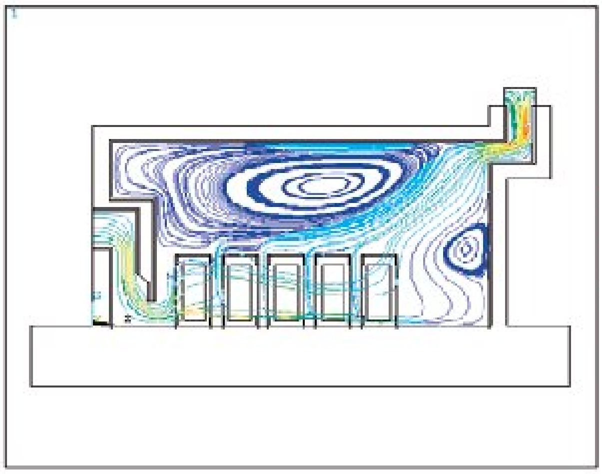

Fig. 3. Heat flow calculation inside storage building

The heat flow inside the storage building and the resulting component temperatures as well as the heat distribution inside the casks were calculated by TÜV NORD Nuclear by state-of-the-art codes like ANSYS®. Therefore, the casks and the storage building are modeled in detail.

As a result it is shown that the maximum heat levels for the fuel elements, the casks components and the building structures are not exceeded during the storage period. For these calculations also very adverse situations like hot weather conditions and heavy sunshine were taken into account.

In case of a severe accident parts of the building structures may crash or the natural convection of air may be blocked. These cases were modeled and calculated also. It was shown that even if the casks are buried under debris the maximum tolerable temperatures are not exceeded, because of the relatively slow increase in temperature of the cask inventory. There will be enough time to reestablish the natural convection by removing the debris, before critical temperatures can be reached. This shows the high safety level of the chosen concept of dry storage in casks.

Shielding

The thick concrete walls of the storage buildings and the intentionally thick-walled casks reduce the dose rate of gamma and neutron radiation 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 need to be established. The casks themselves reduce the gamma and neutron radiation dose rate within the storage building to a level where handling, emplacement and displacement of casks as well as service operation can take place whenever necessary. In the case of the rock tunnel at the Neckarwestheim nuclear power plant the surrounding rock effectively reduces the dose rate on site.

The shielding of cask and building is calculated and verified by TÜV NORD Nuclear with state-of-the-art program codes like MCNP® or QAD®. These are international accepted and validated codes which are in use worldwide. The shielding calculations are usually done in two steps. First the radiation transport from the source (the SF or HLW) to the outside of the casks is calculated. Therefore the cask is modeled in each detail and 'filled' with the corresponding radioactive material (SF or HLW). Normally, the dose rate on the outside of the cask is calculated for gamma and neutron radiation separately. In some cases this is done for each position of the fuel basket inside the cask, so every loading option is included. All storage sites have certain limits for the maximum allowed dose-rate on the surface of the cask, fixed in their acceptance criteria, normally about 0,5 mSv/h. So it is checked whether these limits are met by every allowed loading scheme of the cask. In German storage facilities mainly casks of the CASTOR®-series are used, where for HLW casks of the TN®-series are also in operation.

The calculations for the storage facility are performed likewise. The storage hall is modeled in detail and the storage positions are filled with casks. Here, the emitted particles are started on the surface of the casks with the recorded spectrum. In this process, different loading options of the storage facility are simulated; also situations like a cask in the repair area or the handling of a cask with the building crane are modeled and calculated. Effects like sky shine or scattering are accounted for in these calculations by the utilized program codes automatically.

As a result, the dose rate at every point of interest inside and outside the storage building is calculated, and the fraction of the dose rate caused by direct radiation or skyshine from the storage facility is obtained by these calculations.

Calculations have shown that inside the storage hall the radiation levels stay below the limit for an exclusion area of 3 mSv/h. On the outside of the storage building the radiation level is normally below 1 mSv/2000h and outside the storage premises below 1 mSv/year, which is the limit defined by the German radiation protection ordinance (StrSchV) [1].

Subcriticality

In order to secure nuclear criticality safety, possible effects of accidents are taken into consideration. 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 and/or neutron moderator exclusion can be taken into account.

The subciticality is checked by TÜV NORD Nuclear with special program codes like MCNP®. Therefore the cask and its internal components like the neutron absorbers, the basket and the fuel rods or the HLW are modeled in detail. To ensure subcriticality the multiplication factor must stay well below a value of one [2].

These calculations are performed for each possible distribution of fissile material inside the cask. For some considerations, e.g. transportation or unloading in a pool after storage, the cask model considers also complete water filling. .As a result, the subcriticality is guaranteed under all possible circumstances, even in beyond design base accidents. In all scenarios the position of the fuel elements stays fixed by the basket, so no critical rearrangement of the fuel elements will occur.

CASK DESIGN TESTING AND APPROVAL

As mentioned above, thick-walled dual purpose casks are the main safety component of dry interim SF and HLW storage in Germany. These casks have to demonstrate safety with regard to all relevant objectives as mentioned before. The concept implies a monolithic cask body with integrated or attached neutron shielding components, and that the cask is closed by a monitored double lid barrier system with metal gaskets. Further details are described in the recent ESK guideline [2].

BAM is the competent authority in design testing and evaluation of all quality assurance measures within the transport package license approval procedure. BAM is likewise involved in the storage licensing procedures by the competent authority with regard to all cask related aspects. The necessarily close interaction between these tasks yields high efficiency and comparative evaluation methods applicable to common technical and scientific aspects. A major aspect of BAM cask design evaluation for interim storage concerns cask drops without shock absorbers within storage buildings and in the most severe configuration. Systematic studies of handling procedures (see e.g. Fig. 4) are required to determine the most severe scenarios with regard to drop orientation, drop height and target. Subsequently, safety demonstrations for these accidents are performed by experiments and/or numerical calculations. For this purpose, BAM makes use of a large drop test facility with an unyielding foundation in compliance with IAEA requirements designed for casks having masses up to 200 metric tons. Numerical simulations are performed with state of the art computer systems and a variety of finite element codes such as ABAQUS®, LS-DYNA® and ANSYS®. The analysis of hard impact drop scenarios needs demanding dynamic measurements and/or calculations including specific material data and sophisticated stress and strain evaluation procedures. Numerical models and their results have to be validated by full-scale, small-scale and/or component tests. Apart from the cask simulation, adequate modeling of the foundation and impact limiting structure is essential. BAM has broad experience and competence in both these experimental as well as numerical test methods.

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 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 storage use. Cask loading under wet conditions in a spent nuclear fuel pool requires very accurate dewatering and drying procedures afterwards to prevent any relevant corrosion effect during the subsequent storage decades.

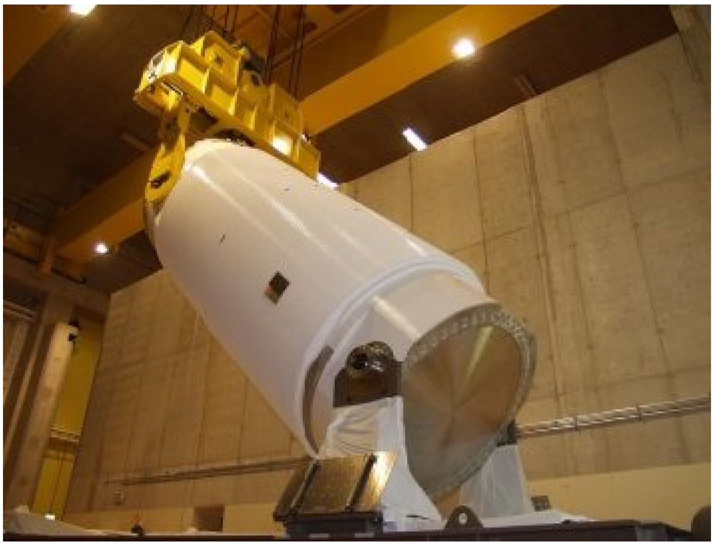

Fig. 4. Handling of dual purpose cask in storage facility

BAM safety evaluation reports on cask safety under normal operation and accident conditions in combination with TÜV NORD Nuclear safety evaluation reports on inventory and site specific safety aspects are the major basis for any storage license issued by the Federal Office for Radiation Protection (BfS) as the competent authority in Germany. Licenses have been issued for nearly all applied storage facilities so far and on that basis all storage facilities have been operated safely without any major problems.

For the future, extended storage periods are an upcoming issue due to delays in establishing a deep geological repository in Germany. With regard to that aspect and further international and European developments, guidance documents for periodic safety inspections [4] and ageing management [5] have been improved recently and are currently tested for selected storage sites. Furthermore, additional research and development is essential to gain required data on the long-term performance of materials and components like metal and elastomer seals and polymer components for neutron radiation shielding. BAM has already started such investigations by experimental and analytical methods and an additional test facility with heating and cooling chambers and specific measurement equipment is nearly completed on the BAM Test Site Technical Safety (BAM TTS, see http://www.bam.de/en).

CONCLUSIONS

Dry and wet storage of SF are established throughout the world in a safe and reliable manner. While wet storage is used in Germany at all nuclear power plants during plant operation, dry storage in dual purpose casks is the established concept for long-term interim storage of SF and HLW whether on-site or in centralized interim storage facilities. Dry storage systems are usually characterized by passive and inherent safety functions ensuring safety even in case of severe incidents or accidents. After the events of Fukushima, the advantages of such passively and inherently safe dry cask storage systems have become more obvious. Safety assessment and evaluation procedures are sometimes challenging but have been performed successfully for many interim storage facilities throughout Germany. Additional licenses are required for various new or modified cask designs and additional spent nuclear fuel configurations in the future especially under consideration of the German phase out decision. Further delays in the national site selection for a deep geological repository will lead to extended interim storage periods with significant consequences for additional long-term safety demonstrations for storage as well as subsequent transportation. BAM and TÜV NORD Nuclear have broad experience and knowledge in safety evaluation of dry SF and HLW storage systems under all relevant safety aspects defined by international and national regulations. BAM supports also national and international organizations like IAEA with its expertise and cooperates with several international institutes.

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