Considerations of Aging Mechanisms Influence on Transport Safety and Reliability of Dual Purpose Casks for Spent Nuclear Fuel or HLW

Bernhard Droste, Steffen Komann, Frank Wille,
Annette Rolle, Ulrich Probst, Sven Schubert

BAM Federal Institute for Materials Research and Testing, Berlin, Germany

Abstract: When storage of spent nuclear fuel (SNF) or high-level waste (HLW) is done in dual purpose casks (DPC), the effects of aging on safety relevant DPC functions and properties have to be managed in a way that a safe transport after the storage period of several decades is capable, and can be justified and certified permanently throughout that period. The effects of aging mechanisms (like e.g. radiation, different corrosion mechanisms, stress relaxation, creep, structural changes and degradation) on the transport package design safety assessment features have to be evaluated. The consideration of these issues in the DPC transport safety case will be addressed. Special attention is given to all cask components which cannot be directly inspected or changed without opening the cask cavity, what are the inner parts of the closure system and the cask internals, like baskets or spent fuel assemblies. The design criteria of that transport safety case have to consider the operational impacts during storage. Aging is not subject of technical aspects only, but also of "intellectual" aspects, like changing standards, scientific/ technical knowledge development and personal as well as institutional alterations. Those aspects are to be considered in the management system of the license holders and in appropriate design approval update processes. The paper addresses issues which are subject of an actual IAEA TECDOC draft "Preparation of a safety case for a dual purpose cask containing spent nuclear fuel".

Keywords: Transport and storage casks for spent nuclear fuel or high level waste, aging mechanisms, corrosion, safety assessment, metal seals, closure system

1. INTRODUCTION

Decommissioning of spent nuclear fuel (SNF) requires several decades of storage before direct disposal. In case of reprocessing the fission products are transferred to vitrified high level waste (HLW) which has to be stored also over several decades before it can be disposed in a repository. In Germany most of the spent fuel produced until 2005 went to reprocessing in La Hague, France and Sellafield, UK. Since July 2005 German utilities are forced by law to store spent fuel in storage facilities located at the NPP sites. Before that decision, the old decommissioning policy was based on two central storage facilities in Ahaus and Gorleben. Since 1979 it was decided in Germany to store SNF and HLW under dry conditions in transport casks. This concept of Dual Purpose Casks (DPC) was at the first time developed with the types of CASTOR® casks by GNS (Gesellschaft fuer Nuklear-Service GmbH, Essen, Germany). The central transport cask storage facility Ahaus was mainly used for the storage of 305 CASTOR® THTR/AVR casks with the complete inventory of the Thorium-High-Temperature-Reactor (THTR) during its decommissioning since 1992 (and 3 CASTOR® V/19, 3 CASTOR® V/52, 18 CASTOR® MTR). The central transport cask storage facility Gorleben was mainly used to store 108 casks (74 CASTOR® HAW 20/28 CG, 1 TS 28V, 12 TN85 (from TN-International), 21 CASTOR® HAW28M) with vitrified HLW received back from France (and 1 CASTOR® IIa, 1 CASTOR® Ic, 3 CASTOR® V/19). Besides 12 transport cask storage sites at NPPs (there were stored 332 CASTOR® V/19 and V/52 SNF casks at the end of December 2013), there are additionally two storage sites at Research Centre Juelich (for 152 CASTOR® THTR/AVR casks with the complete inventory of the research reactor AVR) and in Lubmin the ZLN storage site at the decommissioned former GDR NPPs with 65 CASTOR® 440/84 casks (and 4 CASTOR® KNK, 5 CASTOR® HAW 20/28 CG). These loaded 1000 (the exact number of DPC stored in Germany at the end of December 2013!) SNF and HLW transport and storage casks have to be transported in future after a storage period which in currently per license limited to 40 years, but which is expected to be some decades longer due to outstanding evaluation, selection and licensing of a high active waste/spent fuel repository.

Responsibility for future generations requires from the beginning that there will be a safe transfer of the existing DPC to their currently unknown destination. All stakeholders (vendors, transport and storage operators, authorities, regulators, technical experts) involved in that process need to follow a strict course of keeping the foundation for transport safety, the transport package safety report (or safety case) effective through the entire lifetime of these objects [1]. This task must include the assessment of aging mechanisms influence on the transport package safety case which is the basis for safe future transport operations after storage.

2. DUAL PURPOSE CASKS SAFETY ASPECTS

2.1 DPC Design Aspects

A typical DPC in the "transport package version" as used in Germany is shown in Figure 1; the containment components (cask body with primary or secondary closure lid) or equipped with impact limiters. When the cask is stored inside a storage hall (Figure 2) the impact limiters are disassembled, and it is equipped with a multiple lid closure system (primary lid with metal seals, secondary lid with metal seals and interspace pressure switch, additional protection lid) as shown in Figure 3.

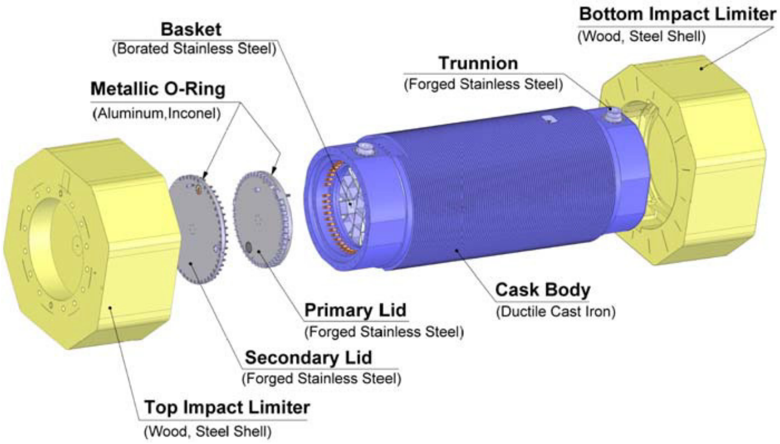

Figure 1: Main components of a CASTOR® V/19 spent fuel transport cask (Photo: GNS)

Figure 2: CASTOR® V/19 casks in transport cask storage facility Ahaus (Photo: GNS)

The thick-walled cask body is made of monolithic ductile cast iron for the CASTOR® casks, or made of forged steel with welded bottom to the shell for the TNI casks (TN85). With respect to aging influences much more sensitive are the cask internals, like the basket structures for the spent fuel assemblies or HLW canisters, the contents itself, and the lid closure system. The lids are usually also thick-walled, but sensible parts are all the lid bolts and specifically their metal seals. A schematic view of a closure system and a description of the metal seals used for the large lids are shown in Figure 3. The neutron shielding components are in case of the CASTOR® casks Polyethylene materials incorporated in boreholes in the cask body wall, or as resin materials put onto the outside of the forged cask shell in case of the TNI casks; in or on the lids and on the bottom side are neutron shielding material plates located. Other components sensible for aging influences are the trunnions and the trunnion bolt connections to the cask body.

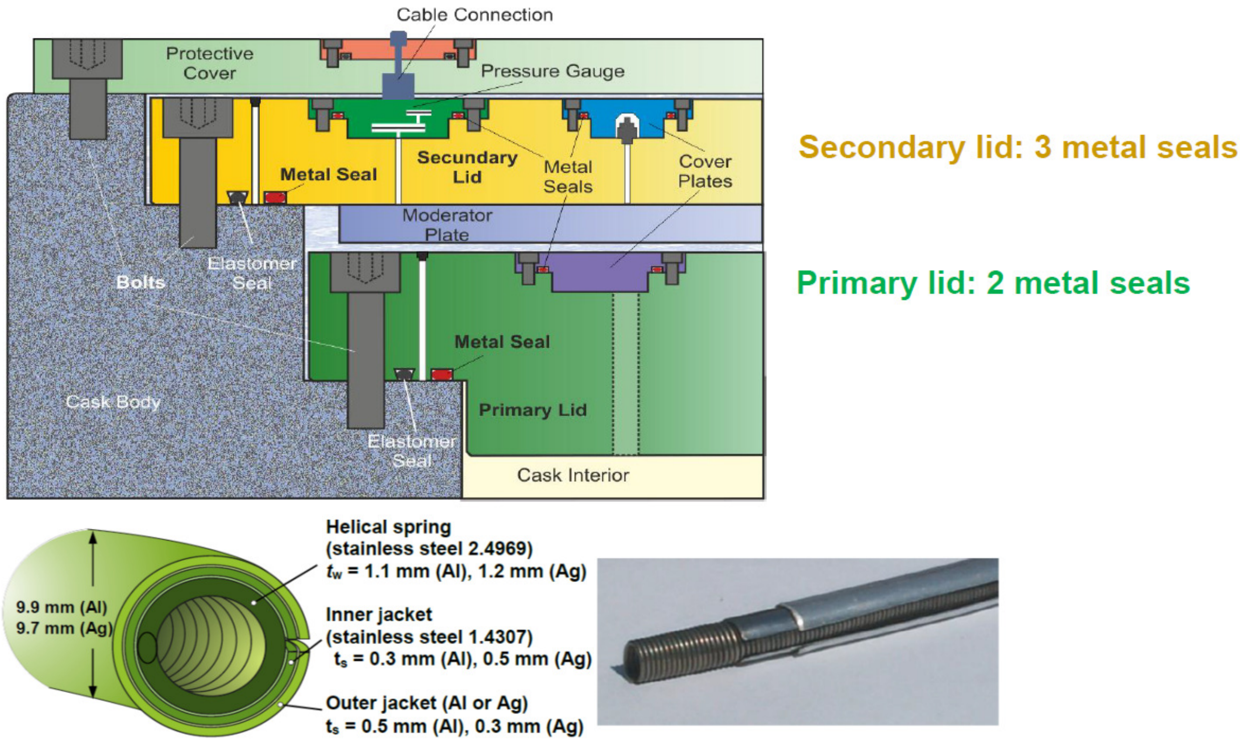

Figure 3: Lid closure system of a DPC storage cask (above) and Helicoflex® metal seal (from Völzke et al. [2]); the containment boundary of the transport package is either the primary lid or the secondary lid.

2.2 DPC Design Assessment Aspects

The protection aims are the same for both DPC versions, the transport package and the storage cask, as schematically drawn up in Figure 4.

The “service loads”, resulting from operational conditions, e.g. radiation, decay heat, corrosive agents inside the containment boundary, internal pressure and time-induced effects, like creep or relaxation of metal components, are the same for both, the transport package as well as the storage cask version. But the “accident loads” resulting from accident conditions to be considered are significantly different:

- The transport package design has to be assessed according to the transport regulations (IAEA Safety Standard Series No. SSR-6 [20]) mechanical and thermal test requirements; i.e. cumulative effects from 1-m puncture drop test and 9-m drop test onto an unyielding target, and 30-minutes fire test; water immersion test (200 m).
- The storage cask design has to be assessed according to the scenarios resulting from accident analysis of the storage facility; typical accident conditions are handling drop events [3], but also the assessment of severe impacts from low probability accidents, e.g. from an aircraft crash could be required [4].

Not only the accident conditions, but also the casks design acceptance criteria with respect to dose rate limits, activity release control, sub-criticality, maximum surface temperature are often different for transport or storage regime. Both cases are covered usually, as in Germany, by two different licensing regimes, the transport package design approval, and the storage facility licensing.

The storage cask qualification is accompanied by an assessment of all relevant storage service and accidental loads over the licensed storage period (up to 40 years currently in Germany). The transport package design approval certificates are usually issued for periods of up to 5 or 10 years [1], and in the past had been based on a safety analysis report considering these shorter periods only. The renewal of

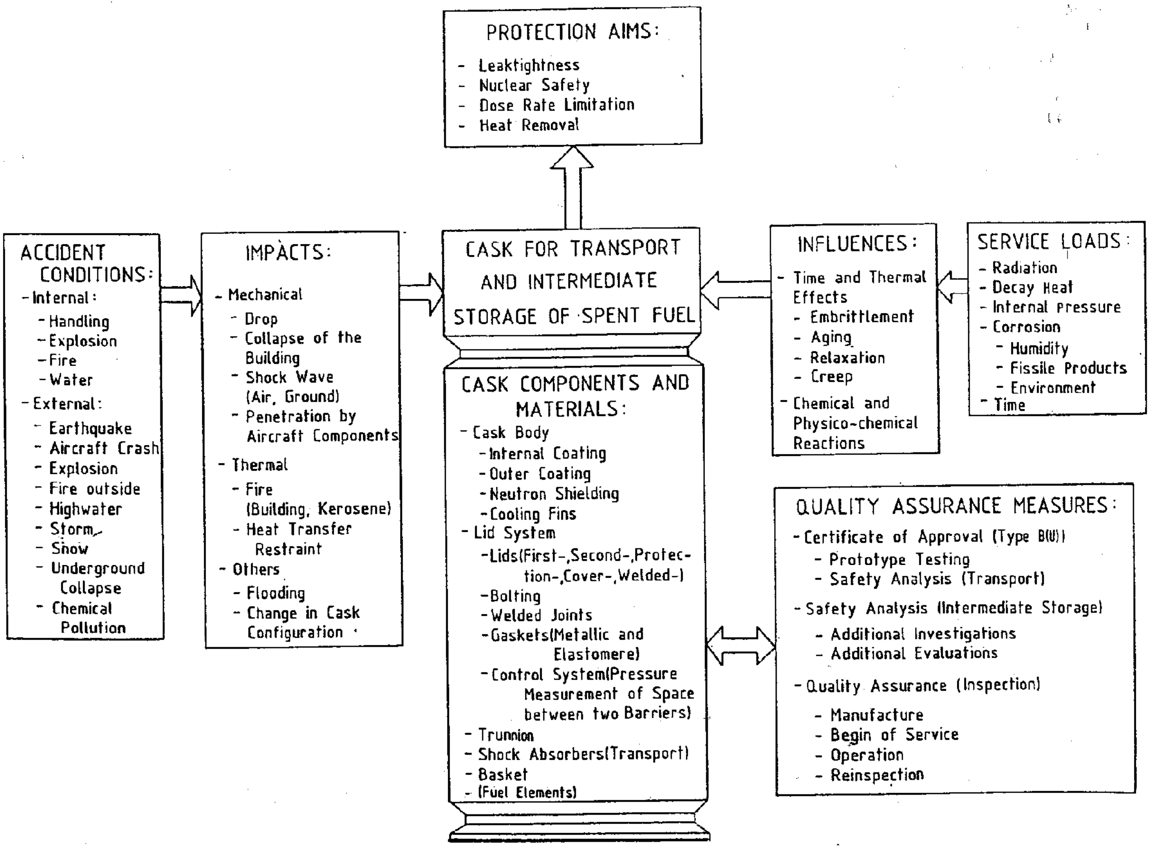

Figure 4: DPC Safety Assessment Considerations

the DPC transport package design approval during the lifetime of the DPC storage cask is evident, and the consideration of storage cask service conditions on the transport package design safety case has to be considered as recommended in an IAEA guidance document [5] and as it is going to be implemented in German DPC package design approval procedure [6].

2.3 Aging Mechanisms Influence on DPC Components

Table 1: Examples of design considerations against deterioration of DPC components [5]

Components	Material	Degradation factors	Design consideration
neutron shielding	resin, polyethylene	thermal, radiation	Establishment of weight loss rate of neutron shield material in shielding analysis, thermal expansion limitation
basket	aluminum alloy, boron-aluminum alloy, neutron absorbers	thermal, radiation	Establishment of allowable stress, considering ageing deterioration in structural and compositional analysis für criticality control.
metal seal	coating: aluminum, silver spring: nickel alloys, stainless steel	chemical, thermal, creep	Moisture control and establishment of temperature limit of the metal seal.
elastomeric O-ring	EPDM, FKM	chemical, radiation, thermal	Material selection
cask body, lids	steel, ductile cast iron or coating	chemical	Moisture control; Inspection and necessary maintenance
trunnions	stainless steel polymer sealants	chemical	Material selection; Inspection and necessary maintenance

Table 1 gives an overview of the major relationships between DPC components and relevant aging mechanisms. These aging mechanisms influence on components safety had been investigated in first priority for the use as storage casks, and will be discussed in this paper primarily with respect to their relevance to the transport package safety assessment.

2.3.1 Containment Components

Cask body and Lids

For protection of the cask body and outer lid surfaces appropriate resistant materials or coatings have to be selected to prevent environmental corrosion effects; gaps between trunnions, trunnion screws and cask body shall be covered by silicon paste to prevent water ingress. The lids are usually made of stainless steel with a good corrosion resistance, but the seal flange surfaces of ductile iron or ferritic steel cask body need special attention. Cask body flange surfaces of those DPC which are loaded in dry, controlled environment like in a hot-cell (HLW canisters, THTR/AVR spent fuel) were left only surface finished. The surfaces, where the metal seal is compressed on, of casks which are loaded under water, what is the case for LWR spent fuel, need to be covered by a more noble material, e.g. galvanized Nickel or weld plated stainless steel. The assessment of materials with specific consideration of material compatibility is in more detail addressed in [9].

Metal Seals Corrosion

In any case casks loaded in water pools need to be dried and evacuated very effectively to meet very low values of residual humidity inside the cask cavity and inside the lid interspaces to prevent corrosion of metallic containment components.

During cold trial tests with CASTOR®440/84 casks in 1998 it was identified that after compression of metal seals (Figure 3) by the primary lid under water, a small amount of water is “locked” between the inner and the outer metal seal jacket. This water inclusion had to be prevented by changes in the cask loading procedure, e.g. by dewatering and evacuation of the cask cavity with a not completely compressed metal seal, so that the space between the outer and inner jacket could be dried effectively, Another option was the change of the outer jacket material from Aluminum to the more noble Silver; this solution currently is the preferred option. Since some casks between 1994 and 1998 had already been loaded with potentially encapsulated water in the primary lid seal, an additional reaction in that case was the experimental investigation of the influence of encapsulated water inside metal seals by BAM, contracted by the storage licensing authority BfS (German Federal Office for Radiation Protection). These experiments, partially still running, have shown that no corrosion induced seal failures occurred, although some seal specimen had been in contact with water containing 10^{-3} mole Na Cl as corrosion increasing agent [23] . This reported operational experience on the discovery of remaining water inside the closure system, which was not considered before in the safety case, is a typical example of experience feedback that has to be managed by updating the DPC safety case, e.g. due to changes in the management system and/or in the DPC construction, supported by additional investigations.

During BAM`s first storage cask safety evaluation around 1982, it was identified that inside the cask cavity not only residual water from the wet pool loading could be a potentially corrosive medium, but also Cesium and Rubidium as fission products released from defective fuel rods [7]. At first this corrosion potential for the metal lid seals could be limited to due to the demonstration of very low Cs and Rb diffusion through the primary lid flange gaps with a width of below 10 micrometer. After changes of the lid flange design with machined groves in front of the seal seats, to ensure a better drying and leak tightness measurement procedure, this “diffusion barrier” did not exist anymore. The need for updating the DPC safety case was given. For that reason BAM performed experiments where the influence of Cesium vapor on the performance of lid closures with metal seals, and on Aluminum specimen (the outer seal jacket material) and Silicon rubber specimen (the material of elastomer seals placed inside the early CASTOR® cask cavity in front of the large metal seals) was investigated. Figure 4 shows the test arrangement with 9 small cylindrical stainless steel flasks, where the lids were sealed with axially compressed Helicoflex® metal seals; these containers were heated up to a maximum service temperature of 120 °C at the seals, and 190 °C at the flask bottom, so as to force Cesium (1 g was given into every flask) condensation on the coldest area at the metal seals. 4 flasks with Cesium had only metal seals, some for comparison were additionally equipped with radially compressed Silicon rubber seals, and some with no Cesium as blind test. 3 larger flasks were filled with Aluminum and Silicon rubber tensile test specimen, in 2 of these flasks exposed to vapor of 5 g Cesium (Figure 5), and heated up to 120 °C. The results of these experiments over up to two years could demonstrate that Cesium did not have a negative influence on the material properties and the closure system performance because there was no difference between specimen exposed with Cs and those not exposed [8]. Some changes, e.g. loss of around 10% of Al yield strength, were found under Cesium exposition as well as in blind test conditions, what indicates the influence of temperature in this case.

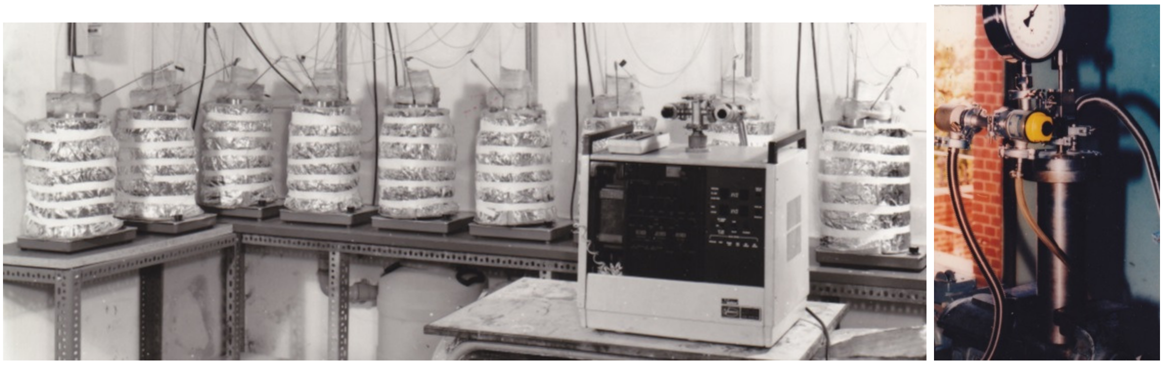

Figure 4: Test arrangement of 9 small flasks with Cesium exposure of the lid metal seals; left: insulated and heated flasks; right: Helium filling of one flask, after Cesium input.

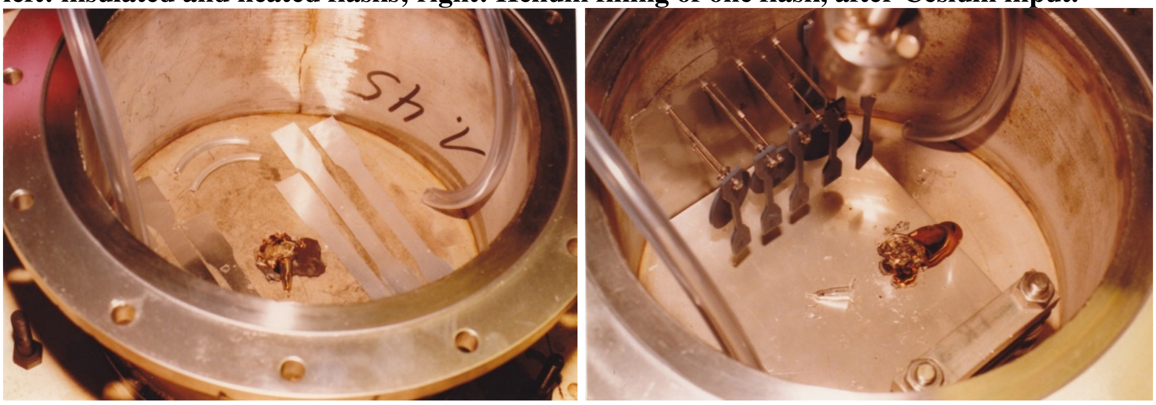

Figure 5: Aluminum (left) and Silicon rubber specimen (right) prepared in flasks with exposure of 5 g Cesium; Cesium released from a destroyed glass ampoule on the bottom.

Mechanical Behavior of Metal Seals and Bolted Closure Systems

Besides evaluating chemical compatibility (see [9], for containment components) the change of mechanical behavior during storage is an important assessment factor. Due to creep and/or stress relaxation of metal seal components, their characteristic values used in the design assessment, like the restoring seal force (under compression) and the usable resilience r_u (the decompression way till loss of leak tightness) are reduced, depending on temperature and time [2]. In mechanical assessment of the lid closure system the deformation and displacement of the flange components are calculated or experimentally estimated. Of specific interest is the maximum widening between the lid and body flange surfaces, which can result from deformation of the bolts, bending of the lid as well as by different thermal expansion of lid and body material. The seal must be able to compensate these displacements; the possible flange surfaces widening shall not exceed the usable elastic resilience r_u of the seal to maintain the specified leak tightness.

Finite element analysis of a vertical 9-m drop [10] can provide the relation between the flange surfaces widening at the seal and the usable seal resilience r_u as shown in Figure 6.

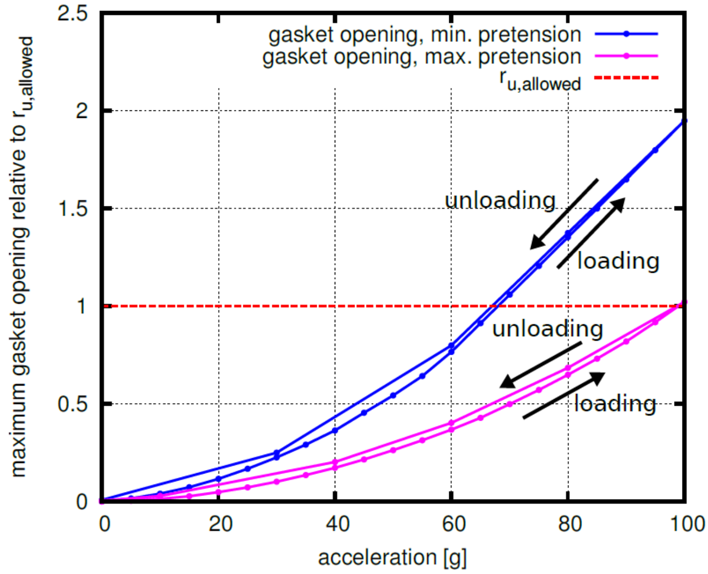

Figure 6: Values of widening between the lid and the cask body flange surface at the metal seal (gasket) for a reference cask in a 9-m vertical drop test onto an unyielding target, calculated for deceleration values of up to 100 g (from Linnemann et al. [10])

For the transport package design safety assessment also the fire accident has to be considered. Temperature resistance of the metal containment components is not a major problem, but numerical calculations have shown that thermo-mechanical phenomena with highly non-linear nature cause deformations in the seal area resulting in a flange surfaces widening there [11].
Safety justification needs for all cases a demonstration that the estimated value of flange surfaces widening is smaller than the smallest r_u value that can be guaranteed in the seal area flange geometry.

In a 9-m lateral drop the sliding of the lid has to be prevented by appropriate lid bolts pretension [10], or the influence of the lid sliding on the leakage rate of the metal seal has to be investigated as described in [12, 13].

The lid bolts behavior after long-time stress relaxation also has to ensure in transport accident impacts a sufficient closure system performance. All time-induced effects and interactions between lids, lid bolts and metal seals, that are necessary to be preserved for a safe DPC transport package design appropriately over the storage period, need to be studied in much more detail. There are a lot of single pieces of knowledge which need to be integrated and evaluated on basis of the transport regulatory requirements.

An important study of relevant aging influences on transport casks safety after interim storage is given in [21], including drop tests with a full scale cask equipped with lids sealed by “artificially aged” metal seals (due to thermal treatment).

Reliability of Metallic DPC Closure Systems

As reported above, at the end of 2013 in Germany 1000 DPCs equipped with **5000 metal seals** are in storage operation; the oldest **since 22 years**. From this huge amount of assembled metal seals and closures there was **no seal failure** noticed up to now. We only got notice of three seal failures in foreign countries caused by remaining water inside the lid system due to inefficient dewatering and humidity control.

During the initial German assessment 1982 the knowledge of metal seal reliability under long-term storage conditions was rather pure. For that reason a “lid repair concept” was introduced: In case of a

hypothetical failure of the secondary lid, this lid can be changed without using a hot-cell. In case of a hypothetical failure of the primary lid, an additional welded lid could be attached, reestablishing a double barrier closure for storage. Part of this concept is the possibility of a cask transport with a secondary lid, qualified as transport package containment boundary, to another nuclear installation for follow-up maintenance actions; if the secondary lid is not qualified as independent transport package containment boundary, a primary lid change in a hot-cell is to be considered.
Based on the excellent data base on metal seal reliability under the licensed operational conditions in Germany, the old “lid repair concept” seems to be more and more inadequate, and should be adjusted or modified according to actual knowledge on metal sealed closure systems reliability.

2.3.2 Spent Fuel Basket, Spent Fuel Assemblies, Shielding materials

The basket construction for spent fuel assemblies has to keep its properties specified on basis of the safety case to ensure criticality safety. Under impact of temperature (in the maximum during service up to 400 °C), stresses and time, changes of the basket material properties are of major concern.
Very often Aluminum alloys or Aluminum-Boron composite materials are used . In those cases very much effort has to be given in consideration of thermal aging, leading to structural changes in the alloy what influences material strength or Boron (B_4C) distribution. Both effects have to be considered in the safety case, in the material qualification program and in quality control during manufacturing [14].

The effects of aging on the integrity of spent fuel assemblies are also of major concern [15]. The different failure modes of the fuel rods (bending, rupture or fine cracks) can cause a rearrangement of the fissile content and release of gas, volatiles or fuel particles into the cask cavity. We considered the loss of integrity of high burn-up spent fuel assemblies quite conservatively in the transport package design assessment under accident conditions [16], e.g. by consideration of a breakage of a high number of fuel rods with potential release of fissile materials into the cask cavity, leading to a significant large amount of fissile material to be considered in the criticality safety analysis. For the activity release calculation the amount of defective fuel rods also has to be justified conservatively [12]. The development of investigation programs on the behavior of spent fuel under aging conditions should be observed with respect to necessary adjustments of the assessment strategy used up to now.

For metallic components radiation as aging mechanism is not a major problem; the maximum flux of fast neutrons is even over several decades of storage some orders of magnitude lower than that flux leading to property changes. For organic materials used as neutron moderators radiation as well as thermal aging has to be assessed in more detail. The influence of gamma radiation on structural changes of specific Polyethylene materials, as they are used e.g. in CASTOR® casks has been investigated, and no negative results could be observed so far [17]. For Vinylester neutron shielding materials, used e.g. in TNI casks, the thermal aging was investigated [18]; further investigations will cover time-induced effects.

3. Aging of Safety Cases and Knowledge

Not only DPC components are subject to ageing, this is also the case for regulations, standards, technical and scientific knowledge, and also for institutions, persons responsible for the safety case, the certificates, approvals and the regulatory regime. Their ageing mechanism is the change. Therefore, it is essential, for keeping a PDSR up-to-date for periodic transport package design approval renewal, to evaluate in a periodic review the impacts of these changes and of consequences of operational experiences onto package safety. The method for that is a gap analyses. In a corresponding publication [19] the review of safety cases by gap analyses is covered in more detail. All those aspects are to be considered in the management system of the license holders and in appropriate package design approval update processes.

4. CONCLUSION

If spent nuclear fuel is stored over periods of several decades, and has to be transported after that storage, don`t forget the first law of loss prevention: "Those who ignore the past are condemned to repeat it". Translated to our case this means that we, as currently acting persons and institutions, have to ensure with high reliability and high margins of safety the appropriate safety of SNF/HLW dual purpose cask operations to be performed in future, perhaps by a future generation, and future institutions. Considering those possible institutional and personnel changes in future, the preventive consideration of aging mechanisms in the origin safety case, the periodic review and update of the safety case and the transport package design approval is an important element of aging and knowledge management.

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