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Design Assessment of a Dual Purpose Cask for Damaged Spent Nuclear Fuel

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ABSTRACT

German package design approvals were granted recently for dual purpose casks (DPC) intended for loading with encapsulated damaged spent nuclear fuel (DSNF). Comprehensive assessment procedures were carried out by the authority BAM with respect to the mechanical and thermal package design, the activity release of radioactive material and quality assurance aspects for manufacturing and operation of each packaging. The objective of each procedure was to verify the Package Design Safety Report (PDSR) and the relevant guidelines fulfils the requirements of the IAEA regulations.

Previous approvals of German SNF package designs consider mainly standard fuel assemblies with defined specifications and properties for transport and interim storage. Due to the nuclear power phase-out in Germany all kinds of SNF, e.g. damaged spent fuel rods shall be packed in DPC now. Therefore specific requirements shall be considered in accordance with international experiences including IAEA technical reports. The main requirement for DSNF is a tight encapsulation with specific defined properties under transport and storage conditions.

Due to the interim storage period of currently up to 40 years the encapsulation with DSNF in the casks shall also be long term durable. Thus specific loading and drying procedures are necessary and had to be qualified during the approval process. BAM assessed these drying procedures and could confirm the long-term behaviour of the encapsulation and the suitability of the drying equipment. This special equipment was qualified in a “cold handling”. In addition, it was shown that the behaviour of the test equipment used in the qualification process was comparable with the original equipment, e.g. test fuel rods or test encapsulation. In the development of the drying process, experience was obtained in how to put the requirements of the IAEA regulations and related IAEA technical reports into practice.

The paper gives an overview of approval assessment and testing experience made by BAM and point out the main resulting requirements on drying processes for these kinds of encapsulations with DSNF.

INTRODUCTION

In accordance with German guideline R003 [1] the approval procedure and the associated package design assessment are carried out by the Federal Office for the Safety of Nuclear Waste Management (BfE) and the Federal Institute for Materials Research and Testing (BAM) as the competent authorities in Germany. BAM is responsible for the mechanical and thermal design assessment, the assessment of activity release of radioactive material and the quality assurance aspects of manufacturing and operation. BAM also operates test facilities and performs drop tests as well as thermal tests during package approval procedures. The assessment of shielding and criticality safety is in the responsibility of BfE. The boundary conditions of the package resulting from mechanical and thermal aspects are the basis for the shielding and criticality assessment and has to be confirmed by BAM. The assessment is based on the package design safety report (PDSR), which should be structured according to the European PDSR Guide [2] and demonstrates compliance with all applicable requirements according with the IAEA transport regulations SSR-6 [3].

The decommissioning of nuclear power plants (NPP) initiates new requirements on the inventory of packages for the transport of radioactive materials. In addition to standard SNF assemblies all other types of high level waste, e.g. control rods or non-standard-assemblies as well as defect fuel rods or fuel rod sections, which are called damaged spent nuclear fuel (DSNF) shall be transported and stored now. This DSNF needs a tight closure and dry conditions in special encapsulations to ensure safety. For loading of these special encapsulations in existing package designs the applicants shall show in the corresponding PDSR that all applicable requirements are fulfilled. Thus the influences of the encapsulations on the package and their long-time behaviour shall be analysed and evaluated in the PDSR. The approval certificates were issued for two CASTOR®-package designs enable the loading of encapsulated damaged spent nuclear fuel. The encapsulation system which is used in both DPCs was developed by GNS (Gesellschaft für Nuklear-Service mbH) and is presented under the trade name "quiver" in [4].

This paper describes BAM experience during the design approval procedures. Thereby information about the definition of DSNF, different types of encapsulation systems and the main aspects in the assessment procedures are described with focus on the drying processes for these kinds of encapsulations.

BACKGROUND OF SPECIAL ENCAPSULATIONS FOR DSNF

To avoid additional handling of spent fuel and to reduce radiation exposure as well as the risk of radioactive release or contamination the use of dual purpose casks (DPC) for the transport and interim storage of SNF or high level waste (HLW) is preferred in Germany. These DPC shall fulfil both the transport regulations based on IAEA SSR-6 [3] and the requirements of the storage facilities based on the recommendations of the German Nuclear Waste Management Commission [5]. The main requirement for long-term interim storage is the dry storage of spent fuel and heat-generating waste. Concerning to a transport afterwards this requirement is also mandatory to avoid corrosive influences and to achieve the specified transport properties of the package.

Due to Germany's nuclear phase-out the typical radioactive content for DPC is changing. The previous package designs usually consider mainly standard SNF assemblies as radioactive content. According to the information of different German NPP operators more than 1000 non-standard fuel rods have been detected yet which cannot all be placed in non-standard assemblies. Therefor a non-standard handling with special encapsulations shall be considered.

During reactor operation defects or damage on SNF rods can occur due to reactivity events, debris or handling. Moreover different mechanisms lead to fuel rod failures, e.g. fretting, crud corrosion, pellet cladding interactions, stress corrosion cracking, debris, mishandling, fabrication failure or baffle jetting (Figure 1). All of these rods with the damage mentioned are grouped as damaged spent nuclear fuel (DSNF). The IAEA technical report NF-T-2.1 [6] is engaging intensively with this issue.

Fig. 1. Failures examples - crud caused corrosion, debris fretting, PCI with SCC from [6]

Furthermore the IAEA technical report NF-T-3.6 [7] presents management procedures of DSNF from over 20 countries. To ensure safety and to protect persons, property and the environment from the effects of radiation a tight encapsulation of DSNF is a regulatory requirement in Germany [5]. For these large numbers of DSNF new encapsulation concepts for the transport of DSNF in common packages were necessary.

Fig. 2. Examples: Single rod system from AREVA [8] and multi rod system from GNS [9]

The leak-tight containment of DSNF is the main requirement for the design of these special encapsulations. Further requirements result from criticality safety and handling issues. Moreover the transport of these special encapsulations into existing package designs is preferred. Therefor the dimensions (e.g. geometry, mass) of these special encapsulations for DSNF need to be conform to standard fuel assemblies to place these components in the existing baskets. The types of special encapsulation systems for DSNF range between single-rod systems with one capsule for each DSNF rod and multi-rod systems with a specific amount of DSNF rods capsuled together (Fig. 2).

The encapsulation system by AREVA (now Framatome) [8] is a single rod system and consists of capsules with single DSNF rods and a capsule canister for the handling like standard fuel assemblies. The loading procedure of this encapsulation involves typical steps of loading, drying at high temperature, welding and tightness testing. Thereafter the capsules are collected into the capsule canister and are ready for loading in a cask.

The encapsulation system by GNS [9] is a multi-rod system and consists of an inner basket for DSNF and an outer capsule made of forged stainless steel. This system is named 'quiver'. It is designed to be loaded in existing CASTOR®-package designs, which are commonly used in Germany. There are two different 'quiver' designs, one with the dimensions of PWR fuel assemblies for the loading in CASTOR® V/19 packages and a second with the dimensions of BWR fuel assemblies for CASTOR® V/52 packages. The 'quiver' system can capsule up to 66 DSNF (PWR design) and 18 DSNF (SWR design) in dry and tight conditions.

Due to the fact that these special encapsulations are exclusively manufactured for the assimilation of damaged spent nuclear fuel, they cannot be considered as content of the package; they are components of the package. Therefore the applicants have to prepare and submit the complete set of documents for the corresponding PDSR which are assessed by the German authorities BAM and BfE.

ASSESSMENT EXPERIENCES ON THE APPROVED ENCAPSULATION SYSTEM

Aspects of mechanical design assessment

For the mechanical design it shall be considered that in any case the stiffness of an encapsulation system is always higher than of a standard fuel assembly. Therefore the influence on the basket and the lid system of a packaging shall be analysed and evaluated by the package designer. Usually the design of the lid system of a package is taking into account the secondary impact of the content. Therefor mass and stiffness of standard fuel assemblies are significant factors. Furthermore the maximum axial gap between the content, e.g. fuel assemblies and the lid is essential, and shall be considered for the mechanical design. BAM investigated this content interaction with a comparison of a 9 m vertical drop test (full scale package) and an analytical multi-degrees-of-freedom (MDOF) system [10]. It could be shown that a larger internal gap increases the loads on the lid and corresponding design measures to avoid higher loads are necessary for encapsulations.

At the multi rod system by GNS [9] special head and bottom parts were used as shock absorbers to reduce the impact load on the lid. Experience has shown that numerical calculations are not sufficient to determine the complex behaviour of shock-absorbing components. BAM requires experimental drop tests to analyse the complete load-deformation-performance of shock-absorbing components. The limit force of the lid system must not be exceeded during the complete impact process.

BAM operates a qualified testing facility to carry out such kind of tests in the framework of approval procedures [18]. In frame of this approval procedure another facility was used by the applicant. To ensure the applicability of the test results for the safety analyses the facility was qualified, validated and at the end accepted by BAM with a specific test procedure in advance to the encapsulation tests which was also assessed by BAM.

Furthermore, the influence of these new package components ('quivers') on the existing safety analysis was analysed by the package designer and assessed by BAM.

Specifics in assessment of thermal design

The analysis of temperature gradients is very important for the package design to avoid major loads from thermal induced deformations. Due to the lower amount of fuel in a loading with special encapsulation, the heat flux is normally less to standard fuel assemblies. It results in lower maximum temperatures than those incorporated in the safety analysis for the existing approved packages. But especially for multi rod systems with a much higher stiffness the analysis of temperature gradients is very important to avoid major loads from thermal induced deformations. Regularly the positions in baskets for standard fuel assemblies have not enough space for content deformations. Because of the great length even small temperature gradients are sufficient to result in bending of the encapsulation which can create high contact forces [11] in the basket. Thus the heat flux of the content should be balanced or arranged in an even manner. Therefore, a combined loading of standard fuel assemblies with high heat flux and encapsulation systems into the same package is not recommended under this view. For loading with lower heat fluxes, like for encapsulations with DSNF, minimum temperatures shall be taken into account for the design, because that can have an influence on first operation steps (e.g. the drying process).

Specifics in assessment of quality assurance measures

BAM also assesses the management system for the design, construction, manufacturing, operation and maintenance of packagings for the transport of radioactive materials according with national regulations. As mentioned before, the encapsulation system for DSNF is specified as a component of the packaging. Thus all the components shall be classified according with the guideline BAM-GGR 011 “Quality Assurance Measures of Packagings for Competent Authority Approved Package Designs for the Transport of Radioactive Material” [12]. The design of a special encapsulation shall be specified in the PDSR (with drawings, parts lists, material specifications, working and testing instructions) and will be assessed by BAM. The drawings shall include all relevant information for the technical analyses and the manufacturing.

The quality surveillance for the operation of transport packages is done by BAM in general only with the acceptance of documents for the working and testing instructions and plans for periodic inspections, which ensure to keep the specified conditions of the packaging according to the approval certificate during the whole operation time. Additionally the result of every periodic inspection shall be confirmed by BAM.

During the operation of the encapsulations for DSFN special measures are necessary for the quality surveillance especially for encapsulations with permanent closing concepts like welding (e.g. the ‘quiver’ by GNS). The manufacture of a ‘quiver’ is not finished until the final and permanent leak-tight closure which cannot be tested before operation or before loading. Therefore the welding process is considered as an operational step which finalizes the manufacture of a ‘quiver’. For the closing of a ‘quiver’ new welding procedures and specific welding equipment were necessary which also needed a corresponding qualification procedure during the approval process. This was done in compliance with ISO 15613:2004 [13]. During operation only non-destructive testing in kind of visual and leak-tightness tests are possible. These tests are supervised by independent experts authorised by BAM and sufficient for the issuing of the certificate about the final closing of the ‘quiver’. Together with the previous confirmations and approved protocols from operation the BAM authorised expert is able to issue the final certificate for each ‘quiver’ to confirm the condition according with the package approval certificate. Only then a ‘quiver’ is eligible for loading in a CASTOR®.

SPECIAL MEASURES FOR THE DRYING PROCESS OF QUIVERS

According with the recommendations of the German Nuclear Waste Management Commission [5] the drying of spent fuel and heat-generating waste is necessary for long-term interim storage and has been in good practice for many years for standard cask loadings. Up to now drying procedures were qualified for the cask cavity only but not for encapsulations with DSNF. Therefore a comprehensive qualification procedure for the drying process of the quiver system by GNS had to be performed within the assessment procedure of the package safety case.

The handling of the 'quiver' system should be applicable for each NPP in Germany. If a loading campaign for DSNF starts, the special encapsulations must be transported in the containment area of a NPP and go into the pool for loading. After loading they are dried and closed permanently outside the pool. Thereafter the encapsulations go back in the pool and wait for a loading campaign into a DPC. Until now DPCs are generally stored in Germany in interim storage facilities close to the plants until a final HLW disposal facility has been found. For the interim storage facilities the authority BfE approves a maximum interim-storage time of 40 years. The assessments of BAM need to cover this time period to ensure the transportability after the interim storage period. The long-term behavior of the encapsulation and the inventory is significantly influenced by the quantities of enclosed residual water, which still shall be assumed after a qualified drying procedure. The amount of residual water should be as less as possible to reduce influences on the package and the packaging materials. These effects should be addressed by the package designer in the PDSR submitted to the authorities BfE and BAM.

Several aging effects influence the safety functions of a package. BAM reported in [14] about this topic and give recommendations to ensure safety by corresponding material selection, careful operation and aging management measures. Thereby residual water is a main point that decisively influences the long-term durability of an encapsulation. The presence of water favors a wide range of corrosion possibilities, which can influence all materials inside an encapsulation as well as the sealing material. To investigate the long-term behaviour of sealing materials, at different temperatures and in the presence of water, BAM has been carrying out long-term tests on sealing samples [19] for more than 17 years. In addition radiolysis shall be considered where water is split into its constituent elements, hydrogen and oxygen. This leads to further corrosion processes and can also change the pressure build-up as well the gas composition in the closed system. In order to reduce these influences encapsulations must be dried in an appropriate manner.

In case of the 'quiver' system a new drying process for encapsulations with DSNF was developed by the applicant and had to be qualified, assessed and accepted by BAM within the approval procedure. Therefore the applicant prepared a corresponding qualification program which shows the dryability of a 'quiver' and its content of DSNF. The documents for the qualification program were accessed by BAM prior the tests. The two main points during the approval procedure were:

- the dryability of the 'quiver' and the DSNF and
- the applicability of the test conditions for real boundary conditions in the NPP.

The dryability of DSNF could be shown with corresponding tests on real DSNF and with a specific test program for the qualification of the drying process. The main requirements which have resulted from the evaluation process of this qualification are described in the following.

In accordance with para. 673 of [3], supplemented by para. 673.5 of [15] residual water shall be considered in a package before transport. The drying procedure for DSNF, especially for defect fuel rods in special encapsulations is different to regular SNF assemblies in packages. For regular SNF it is assumed that water could not enter into a rod and the water in a package is free available for the drying process. For DSNF it has to be assumed that any water amount can also be beyond very small leaks, in broken pins or in water traps. In [4] this topic will be discussed further. Here is shown which challenges have arisen in the development of the drying process for the 'quiver' system. The drying process shall ensure that water can be dried even in defective fuel rods with very small leak sizes. BAM accepted a leak size which is usually water tight [16] under operating conditions. For this reason the tests for the drying qualification requires the use of test rods with clearly defined leak sizes. The water permeability of the fuel inside the fuel rods shall be considered as well. In order to define how much residual water behind a test leak is left, the relationships between test leaks, drying rate and drying time shall be shown. For this purpose, test rods and test leaks shall be weighed and checked before and after the drying process. In combination with the above-described pressure increasing method under vacuum and higher temperatures a statement about the amount of residual water can be estimated. In addition the temperature on several points inside the encapsulation shall be measured to ensure the required minimum temperature at all points of the equipment and inventory.

BAM accepted as dryness criterion for encapsulations with DSNF the pressure increasing method under vacuum and higher temperatures according to the IAEA information in [7]. Additionally, it is important to record the water vapor mass during the whole drying process to recognize the development of the specific drying rate over time. The acceptance criterion for the drying of the 'quiver' bases on the pressure increase of ≤ 4 E-4 MPa over 30 min noticed in [7] and is related to the specific test volume and test temperature. The test temperature should exceed the maximum operating temperature to cover all later temperature situations. The final acceptance value of maximum pressure increase is associated with the necessary drying rate for DSNF in the 'quiver' system which has been determined within the qualification tests. The lower the drying rate, the less residual water can be assumed in the encapsulation during drying. By assuming pure water vapor the value of maximum pressure increase can be calculated by using the ideal gas equation (see equation 1).

$$\dot{p} * V = \dot{m} * Rs * T \qquad (1)$$

Here $\dot{p}$ is the maximum pressure increase, V the drying volume, $\dot{m}$ the drying rate per unit of time, Rs the specific gas constant of water vapor and T the drying temperature. If the test volume or the temperature deviates the permissible pressure increase must be adjusted accordingly. Figure 3 graphically illustrates the relationship between drying volume and pressure increase based on a constant temperature.

Fig. 3 shows that the necessary drying rate (red solid line) with the drying criterion according to [7] (red dashed line) is able to dry a calculable test volume. The corresponding drying criterion is a theoretical operating point, marked with the number 1 in Fig. 3. The real drying volume usually differs from the test volume. This context is shown by the black dashed lines. The corresponding pressure increase criterion shall be adapted accordingly. The operating point of the drying criterion shifts along the red line of the drying rate. At higher drying volumes the associated pressure increase must be reduced accordingly.

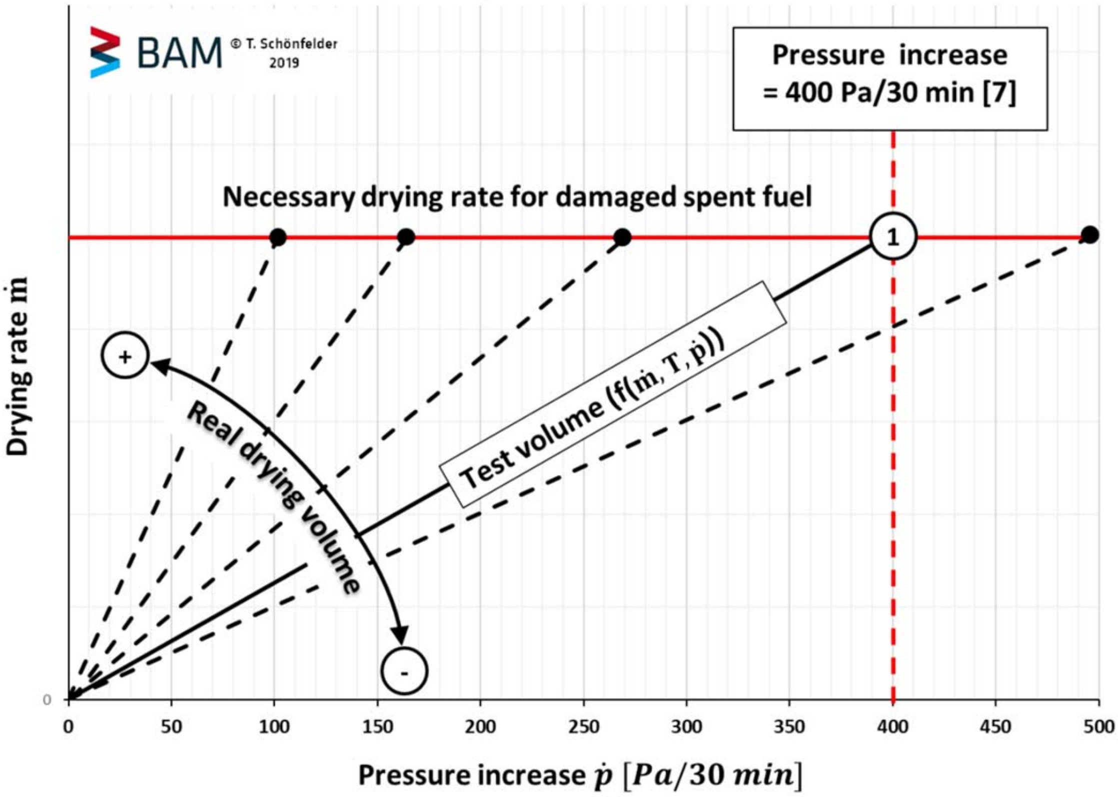

Fig. 3. Relationship between drying rate, pressure increase and drying volume

In accordance with [15] and [17] it shall be observed that the maximum permissible temperatures of the components at the time of vacuum drying are not exceeded. This prevents thermal damage of the components. In addition the possibility of human errors during drying shall be prevented by independent inspections and the drying efficiency should be guaranteed. The verification and the assurance of the qualification of drying were ensured through audit support and detailed inspection and schedules. Furthermore, all necessary steps of the procedure were carried out on basis of working steps and test instructions.

The qualification of the drying process was carried out by using test models. Prior to the qualification all used components, the test equipment, the test media and the procedure itself were described and assessed in a qualification report. This approach is intended to evaluate the suitability of the procedure in advance. If components or media are used which differ from the components in the NPP, the differences and the transferability to the original equipment and the transferability of the test results to the drying in the NPP has to be shown. After this steps the qualification of drying can be carried out. In the qualification procedure as many as possible of the original equipment should be used. The advantage is that functions of the equipment and the handling of the devices can be checked and practiced. The users of the equipment should get the opportunity to practice all handling steps in advance. Similarly the associated work instructions can be tested for their applicability. All drying steps and measurement results should be documented to ensure reproducibility and error control. Finally, the drying qualification procedure was summarized in a final report. BAM evaluated all documents and confirmed the suitability of the procedure for ensuring the ability to dry the encapsulation. Any change of the equipment due to operational experiences needs a re-evaluation by BAM.

CONCLUSIONS

Due to Germany's nuclear phase out an increased amount of DSNF in particular special or damaged spent fuel shall be packed in transport and storage casks (DPC) now. To ensure a fast and safe disposal of DSNF special encapsulations are necessary for the use inside existing DPCs. Recently two package design approvals for CASTOR® design with a multi rod encapsulation system for DSNF from GNS were issued by the German authorities. Therefor specific procedures for the assessment of the mechanical and thermal design, containment and quality assurance were performed by BAM in accordance with international experiences according to IAEA technical reports [6] and [7].

In Germany DSNF need a leak tight encapsulation with clearly defined properties and dry conditions to ensure the fulfilment of the IAEA regulations [1]. The main findings from the BAM assessment are:

- Special encapsulations for DSNF are components of the package and need a detailed safety case for the PDSR of the package used.
- Influences of special encapsulations on baskets and lid systems of the packages used shall be determined in detail and should be covered by the design of the package.
- First operational steps of special encapsulations are similar to standard packages but specific handling and testing instructions are different.
- Since special encapsulations are sealed and an opening is no longer provided the suitability for drying shall be extensively evaluated and tested in advance.

Every special encapsulation for DSNF with permanent closing needs a specific final certificate after loading and closing to enable the final loading in a package. This certificate finishes the manufacturing of the encapsulations and confirms the final condition in accordance with the licensed specification. To enable the issuing of the final certificate it has to be considered that BAM can survey the final manufacturing steps during operation.

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