Proceedings of the 17th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2013
August 18-23, 2013, San Francisco, CA, USA

REFLECTION ON BAM MECHANICAL DESIGN ASSESSMENT OF TN®24E SPENT FUEL TRANSPORT PACKAGE

Martin Neumann **Frank Wille**

Konrad Linnemann **Sven Schubert**

Viktor Ballheimer **Jens Sterthaus** **Bernhard Droste**

BAM Federal Institute for Materials Research and Testing, Berlin, Germany
martin.neumann@bam.de

Abstract

TN®24 E, a new package design, was developed and applied for by Areva TN for German transport approval certificate. The certificate was issued by BfS, Federal Office for Radiation Protection, on 24th of July 2013. The package is designed as a dual purpose cask for transport and storage of up to 21 PWR spent fuel assemblies from German NPPs. BAM is the German competent authority responsible for the design assessment of RAM packages regarding mechanical and thermal safety cases, activity release analysis and all issues of quality assurance during manufacturing and operation of packages. Certain assessment experiences as well as new developments resulting from the BAM TN®24E approval procedure are presented. The mechanical safety case of the TN®24E is based mainly on finite element calculations, which were verified by the TN®81 1/3 scale drop test program performed at BAM. Thermal analyses rely upon calculations, while the activity release criterion is based upon leakage rate results of TN®81 drop tests. The BAM-GGR 012 guideline for the analysis of bolted lid and trunnion systems has been fully implemented. Due to requirements by BAM, AREVA TN developed a new assessment strategy for fracture mechanical evaluation of welding seams. The material qualification and documentation is also an important aspect of BAM assessment; the qualification of borated aluminum basket material, the determination of strength values for thermal aged hardened aluminum alloys for the basket or consideration of high burn-up fuel assemblies are remarkable issues in this context. In addition, the consideration of the material compatibility, especially taking into account a transport after 40 years of dry interim storage in German facilities, has gained significant importance in the licensing process of the TN®24E. Next to obvious mechanical issues such as the assessment of shell ovalization under 9 m drop test scenario and its impact on basket load, thermo-mechanical interactions had to be addressed in the safety case. Due to BAM requirements, AREVA TN performed a full thermo-mechanical analysis of the cask behavior under fire test conditions.

Introduction

BAM, Federal Institute for Materials Research and Testing, is German competent authority responsible for the design assessment of packages for radioactive materials regarding mechanical and thermal safety cases, activity release analysis and all issues of quality assurance during manufacturing and operation of packages. BAM maintains drop, fire and leakage test facilities as well as hard- and software for numerical analyses for assessment and research purposes.

During a transport approval procedure BAM requires a conclusive verification concept by the applicant, among others regarding ability of the construction to withstand the loads under routine, normal and accident conditions of transport (RCT, NCT and ACT). Concerning the drop tests representing ACT, the concept has to encompass in particular the reasoned choice of relevant drop positions with detailed objectives for individual drop sequences (considering the maximum damage requirement), the verification of the cask instrumentation, the reasoned choice and verification of models for accompanying calculations as well as the final assessment according to specified safety criteria. Drop or fire tests of type B(U) package specimens are performed by BAM.

BAM also determines and supervises within type assessment and periodical inspections detailed quality assurance measures in order to ensure the conformity of every manufactured packaging with the package design approved.

Here certain assessment experiences as well as new developments resulting from the approval procedure for TN®24E cask design shall be presented. They represent the state-of-the-art for safety cases for transport casks. Certain requirements for general approval procedures at BAM are highlighted. The German competent authorities BfS assessment work concerning nuclear inventory, criticality safety and shielding are not presented here.

Description of the TN®24E transport package

The TN®24E is a dual purpose cask for up to 21 PWR fuel assemblies. It was developed for the storage of up to 40 years of fuel assemblies from German nuclear power plants. The cask body consists of a cylindrical shell made of forged steel ASTM A508, welded to a massive forged steel bottom made of A508 as well. Copper sheets for heat removal to the outer shell of the cask, are screwed onto the shell. The cavities between copper sheets, inner and outer shell are filled with a resin for neutron shielding. The cask is closed by a double lid system and a combination of elastomeric and metallic seal with outer silver jacket (primary lid) or outer aluminum jacket (secondary lid). The lids are made of the same forged steel as the shell and bottom and are screwed to the cask body. The transport package is equipped with two cylindrical impact limiters, attached to the lid and bottom side, and two ring shaped aluminum impact limiters. The two bottom and lid side impact limiters consist of inner steel construction, attached to an outer shell made of stainless steel. The voluminous cavity between inner construction and outer shell is filled with wood of different species and orientation. Two sets of two trunnions made of stainless steel are attached to the lid and bottom side of the cask for handling and tie down of the package. The basket is a construction of borated and non-borated aluminum sheets, fastened by tie rods. The package mass is around 140 metric tons, including about 18 metric tons of fuel assemblies. The package is transported in a horizontal position, tied down by the four trunnions on a transport frame. Handling with transport frame is not allowed. The package is transported under a canopy. Transport approval certificate was issued by BfS on July 24th 2013.

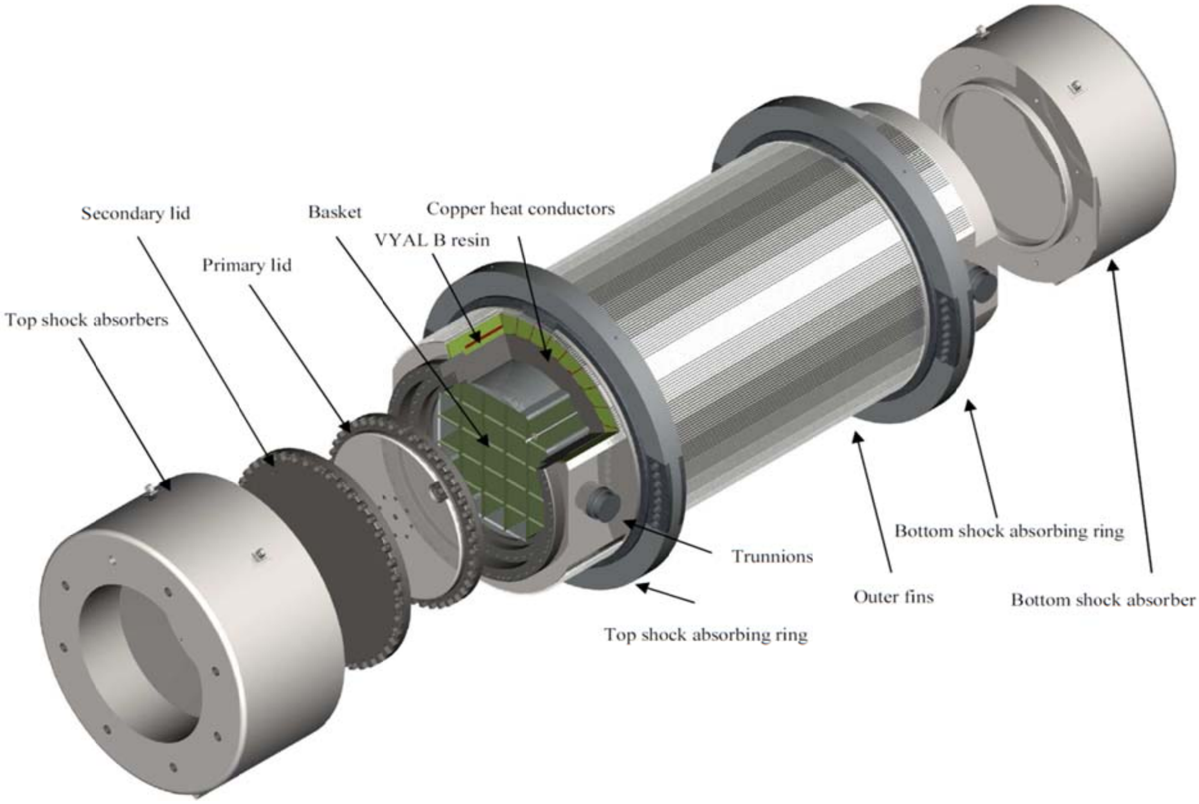

Figure 1. TN®24E transport cask (courtesy of AREVA TN)

Mechanical safety case

The mechanical safety case of the TN®24E is based mainly on finite element analyses (FEA) according to IAEA SSR-6 [1] 701(d), supported by analytical calculations. The calculation procedures and parameters were proven to be reliable and conservative, mainly by verification with the TN®81 drop test program. The TN®81 drop test program used a 1/3 model cask in a series of 12 drop tests performed at BAM. The TN®81 is of sufficient similar nature regarding shell, lid and lid screw geometry, mass and material to allow a verification of mechanical FE models of the TN®24E. The design leakage rates for the activity release evaluation result from the TN®81 drop test measurements. The BAM-GGR 011 and BAM-GGR 012 guidelines [2, 3] have been fully implemented. The BAM-GGR 011 guideline defines the quality assurance measures of packagings for competent authority approved package designs for the transport of radioactive material. The BAM-GGR 012 guideline deals with analysis of bolted lid and trunnion systems including methodology and acceptance criteria. Additionally some accompanying material or component tests were performed.

Requirements for safety cases and applicable methods have to be updated continuously according to the state-of-the-art technology. Therefore we present hereafter some assessment experiences as well as new developments resulting from the TN®24E assessment procedure. We concentrate hereby on two fields, on general material behavior characterization and on structural analysis issues.

Feedback on material behavior characterization

The material behavior is an essential aspect of the assessment process. According to [4] it can be split here into three groups:

1. Material characterization for material modeling in the design and model verification process
2. Determination of material assessment criteria
3. Inspections during manufacturing to ensure that specified upper and lower bound criteria are met.

Certain points from the three groups are presented hereafter.

Material fracture toughness of cask body

The TN®24E cask body and lids are made of steel A508 [5]. This steel can be seen as not brittle fracture exposed under -40°C conditions due to its properties in connection with additional argumentation and testing as well as certain inspections and requirements during manufacturing.

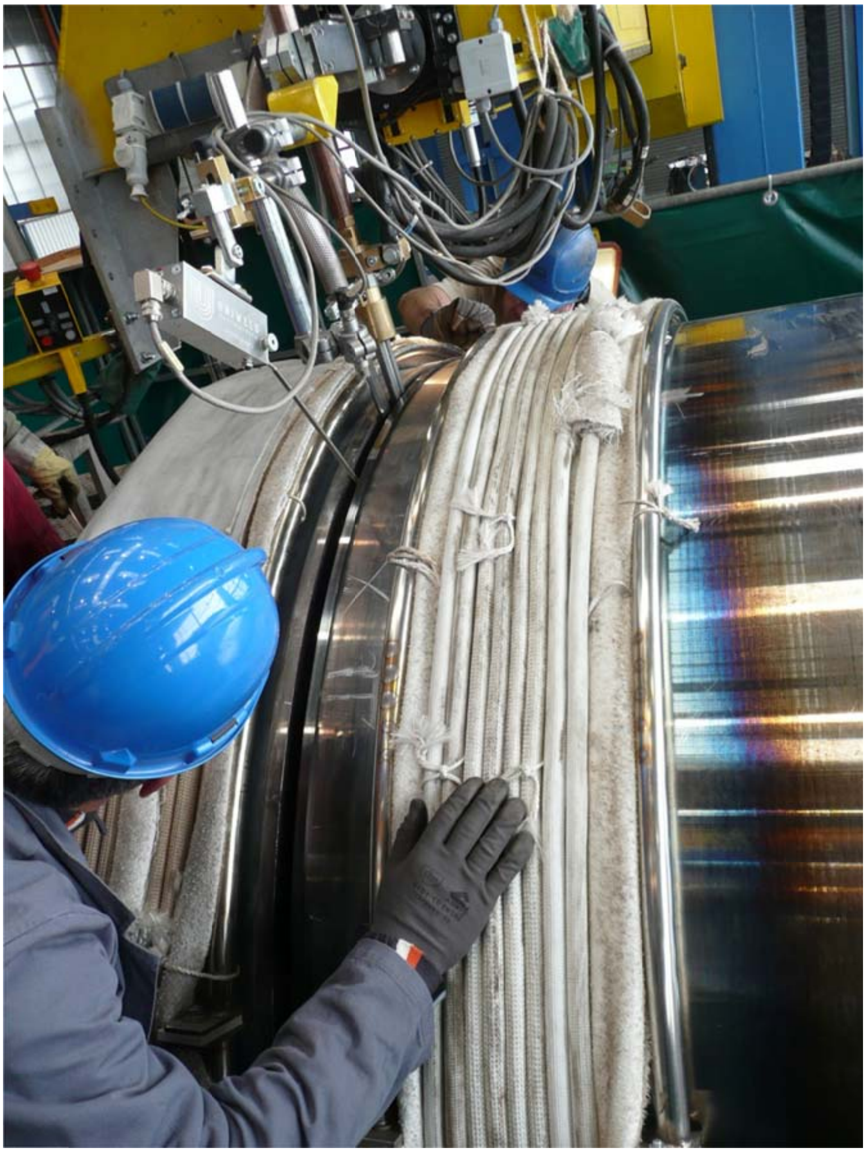

Figure 2. TN®24E bottom to shell welding (courtesy of AREVA TN)

The safety demonstration against brittle fracture of the welding seam between cask bottom and cylindrical body has been presented in [6] in detail. As main prerequisite for the fracture exclusion the welding process at each manufacturer has to be adequately qualified to ensure sufficient material fracture toughness. This was performed here with destructive testing of a welding procedure qualification coupon, which is in form and dimension comparable to a cask weld. In addition to the manufacturer qualification, the destructive testing of preparatory welding procedure coupons has been used for assessing quality during manufacturing. The material fracture toughness in the welding seam as well as in the heat affected zone was determined from samples taken from the welding procedure coupon. The properties can then be assumed as characteristic for the following butt weld. Necessary conditions for a destructive test of welding procedure coupon include an identical dynamical loading (strain rate comparable to the drop test) and a sample temperature of -40°C. The derived fracture toughness has to exceed the minimal value required for design safety. A detailed testing of the filler metal including melt and strength analysis is necessary for this procedure. Identical technological welding conditions as well as filler metal from the same manufacturing batch have to be ensured.

Parallel to a direct determination of material fracture toughness at maximum strain rate and minimum corresponding temperature, the Reference Temperature RTNDT [7] was also evaluated in order to establish a concept to determine minimum fracture toughness from the RTNDT. This concept has been verified theoretically as well as by a sufficient number of tests (Pellini and notched bar impact tests as well as direct fracture mechanical tests such as tests with CT samples). A more detailed description of the approach can be found in [6].

Aluminum boron composite material of the basket

A not standardized aluminum boron composite material is main construction material of the basket. Strength at high temperatures and after thermal long term aging as well as ensuring Boron-10 distribution have been major focus of material qualification, manufacturing inspections and auditing of manufacturers. Tests regarding mechanical properties (yield stress and tensile strength, percentage elongation etc.) covered

- Strain rates from quasi static till 100 /s
- Temperature range from -40°C till maximum operational temperature of the basket
- Heat aging durations between 1000 h and 10000 h
- Different sheet thicknesses
- Anisotropy resulting from manufacturing process
- Homogeneity of the material

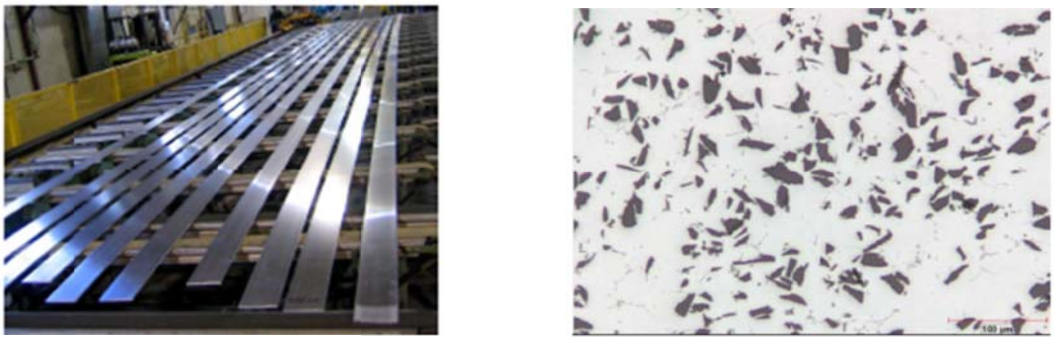

Figure 3. TN®24E basket boron composite material left: Profiles during manufacturing, right: B4C distribution in aluminum matrix (courtesy of AREVA TN)

The mechanical properties were statistically evaluated and incorporated therefore a sufficient number of tests per parameter set. Two times the standard deviation was taken into account for derivation of guarantee values.

Further tests included:

- Metallographic and chemical analysis
- Neutronic absorption measurements
- Isotopic analysis (in order to guarantee Boron-10 content)
- Boron density
- Corrosion tests
- Additional physical properties (e.g. elastic modulus, density, specific heat, thermal expansion, thermal conductivity, emissivity)

For manufacturing inspections specimens with simulated long-term thermal aging as well as not aged specimens are tested to ensure the guaranteed mechanical properties for each production batch. Homogeneity of distribution and amount of Boron-10 content are tested for each production batch with neutronic absorption measurements and isotopic analysis.

Basket aluminum (non borated)

Strength at high temperatures and after thermal long term aging has been major focus of material qualification. Tests regarding mechanical properties (yield stress and tensile strength, percentage elongation etc.) to ensure specific values from technical literature covered

- Strain rates from quasi static till 100 /s
- Temperature range from -40°C till maximum operation temperature of the basket
- Heat aging durations up to 100 000 hours

The mechanical properties were statistically evaluated and incorporated therefore a sufficient number of tests per parameter set. Two times the standard deviation was taken into account for derivation of guarantee values. For manufacturing inspections specimens from artificial aged aluminum additional with several hundred hours of holding time as well as not aged specimens are tested to ensure the guaranteed mechanical properties for each production batch.

Material compatibility

Due to BAM requirements possible corrosion issues were analyzed for all class 1 as well as for specific class 2 and 3 components according to [2]. This encompasses their associated materials and material combinations including coatings. The boundary conditions such as temperatures, exposure to liquid or gaseous substances or radiation result not only from the package transport but also from wet loading in the spent fuel pool and the following drying. It could be demonstrated that corrosion is effectively prevented or not safety relevant.

Corrosion and ageing of containment components (cavity, primary and secondary lids including covers for openings, screws and seals) and basket were evaluated in detail for transport after an interim storage period of up to 40 years. BAM conservatively required the evaluation of a residual amount of water in liquid form in the cavity. Therefore, among others, the inner surface of the shell as well as seal contact areas have to be coated by overlay welding and any aluminum used had to be anodized. The impact of radiation for up to 40 years was also analyzed for metals and polymer shielding materials.

Fuel assembly behavior

The radioactive content to be transported in TN®24E package consists of up to 21 PWR fuel assemblies having the maximum average burn-up of 65 GWd/tU. Physical state of spent fuel and fuel rod cladding as well as geometric configuration of fuel assemblies are important information for the evaluation of package capabilities under transport conditions. Although in Germany the Federal Office for Radiation Protection (BfS) is responsible for the assessment of shielding and criticality safety, the geometrical and material assumptions for the fuel assemblies used as input data in shielding and criticality safety analysis are assessed by BAM.

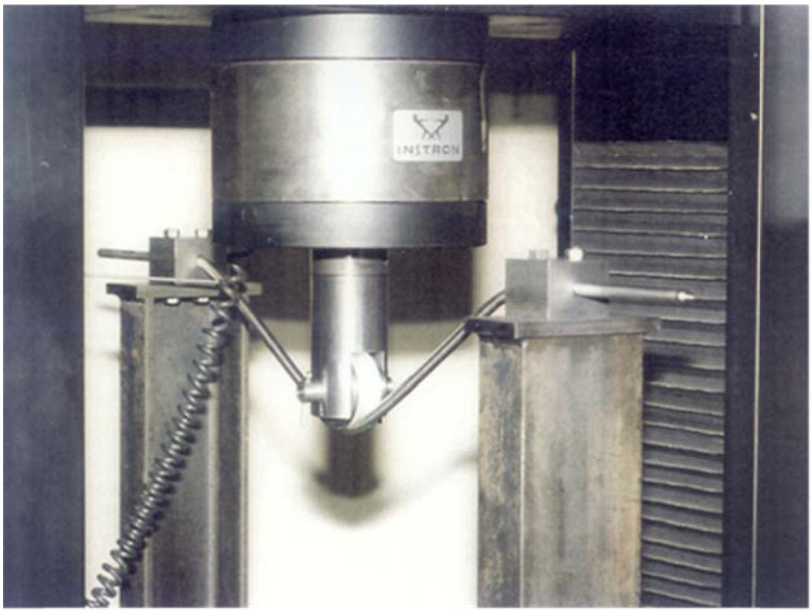

Figure 4. Bending test set-up with unirradiated fuel pin sample with fixed condition at both ends (courtesy of AREVA TN)

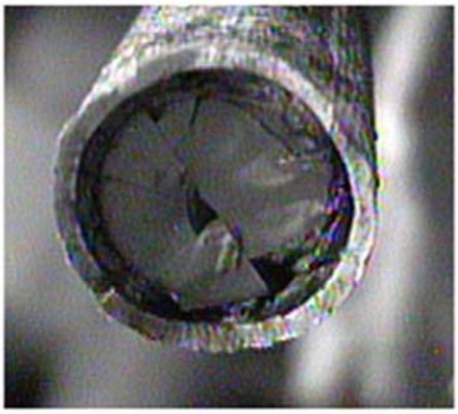

Figure 5. Cladding and bonded fuel at the rupture location after the bending test of a spent fuel pin(cladding sample cut from a BWR fuel rod with average burn up ≈ 50 GWd/tU) (courtesy of AREVA TN)

The potential cladding failure followed by release of fuel particles or fragments into the cask cavity is one of the effects to be considered for the criticality safety analysis. This issue is especially important for high burn-up spent fuel (> ca. 50 GWd/tU) due to degradation of the material properties at extended use. AREVA TN and International Nuclear Service (INS) carried out a joint project (fuel integrity project FIP) to investigate the behavior of high burn-up spent fuel under loading conditions specific for transport (e.g. [9]). In particular, the experiments included two series of static bending tests with irradiated fuel rod specimens (5 PWR and 3 BWR). The specimens with approximately 50 GWd/tU burn-up were loaded at slow deformation rate up to a complete break and released amount of fuel fragments was measured. These experimental data were used in safety analysis report to estimate the potential release of fissile material into the cask cavity. The AREVA TN approach is generally in agreement with BAM methodology discussed e.g. in [10]. BAM confirmed the covering nature of AREVA TN assumptions on fissile material release into the cavity of the cask used finally in the demonstration of nuclear safety.

Feedback structural analysis issues

Multiple mass effects

Technological gaps from basket or spent fuel assemblies to cask body or lid can be a reason for significant dynamic loadings of cask components and its internals due to additional impact interactions in the cask cavity [11]. AREVA TN considered these so called multiple mass effects in case of 9 m axial drop onto the lid side impact limiter in different calculation steps. A global FE model of the package was generated for the explicit dynamic analysis of the axial drop. In this model the content was fixed to the primary lid. Its inertia force, which acted on the lid during the impact event, was assessed. Separate simplified FE models for basket and fuel assemblies were built to estimate their response (in terms of force-time-functions) to the drop onto an unyielding surface. In these calculations AREVA TN initially chose the component impact velocity on the basis of tests results with the scale model of TN®81 cask. On BAM demand the impact velocity was increased to cover the imprecision in the simplified method and to consider the maximum axial gap in the cavity. A comparison between the forces obtained in the different steps allowed the conclusion that the configuration with content fixed onto the primary lid results in maximum closure system loading. This conclusion is confirmed by BAM calculations with a FE model created in ABAQUS/Explicit Code for the independent assessment of the lid/content interaction. An important result of the discussion of this issue during the progress of the approval procedure was the improvement of basket design to reduce the impact loads onto the primary lid. The basket contains now shock absorbing components.

Shell ovalization, basket load

During assessment of ACT an additional aspect arose for the 9 m drop test in lateral position. The shell itself manufactured of forged steel is capable to withstand the loading by remaining in the elastic range of the material. The stresses are well below the yield strength of the forged steel. But the deformation of the shell results in an elastic ovalization of the cavity which was initially not assessed in the safety report. In this context ovalization means the change of the diameter of cavity Δd, see Figure 6. BAM requested an assessment of the ovalization concerning its consequences on the basket design.

The resulting ovalization was greater than the minimal gap between basket and cavity. This would have led to a plastic deformation of the basket. On the one hand the basket is already rather highly loaded by its own mass and inertial loads of fuel assemblies due to drop deceleration, on the other hand any plastic deformations are undesirable for the boron aluminum composite in the view of brittle failure assessment. A decrease of the basket diameter was not possible, since the increased gap between basket and cavity would have reduced the heat transfer from the fuel assemblies out of the package, according to numerical calculations about the thermal behavior.

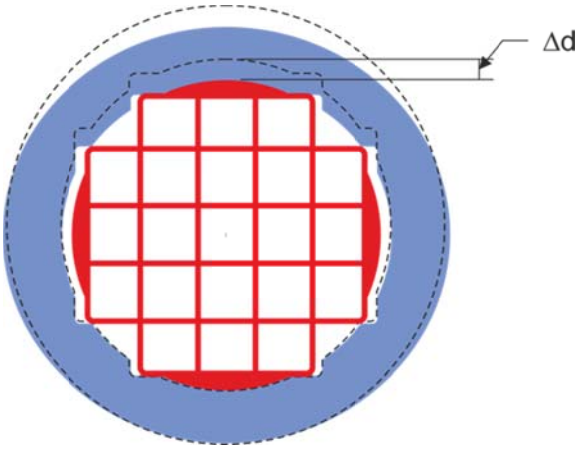

Figure 6. Schematic sketch: shell ovalization and basket load

The solution proposed by the applicant and accepted by BAM was to change the design of the basket by adding frictional elements in the area of its outer surface. The frictional elements are designed to withstand loads resulting from RCT and NCT without deformation. For higher loads from ACT the frictional elements will be activated. The ovalization of the cavity will not lead to plastic deformations in the boron aluminum composite material of the basket. It can be concluded, that temporary elastic deformations, which are not substantial for the cask itself, have to be included in the assessment of the basket design.

Temperature profile for basket analysis

Basket heat load resulting from the temperature profile of the content is rather inhomogeneous. The lower and upper basket ends as well as outer basket areas have comparably lower heat loads than the center of the basket. The artificial aging nature of the main basket materials and the load distribution, which tends to lead to highest loads at the ends, led to the application of a temperature profile for the basket strength (Figure 7). Highest loads occur in rather cold areas, therefore strength is higher there.

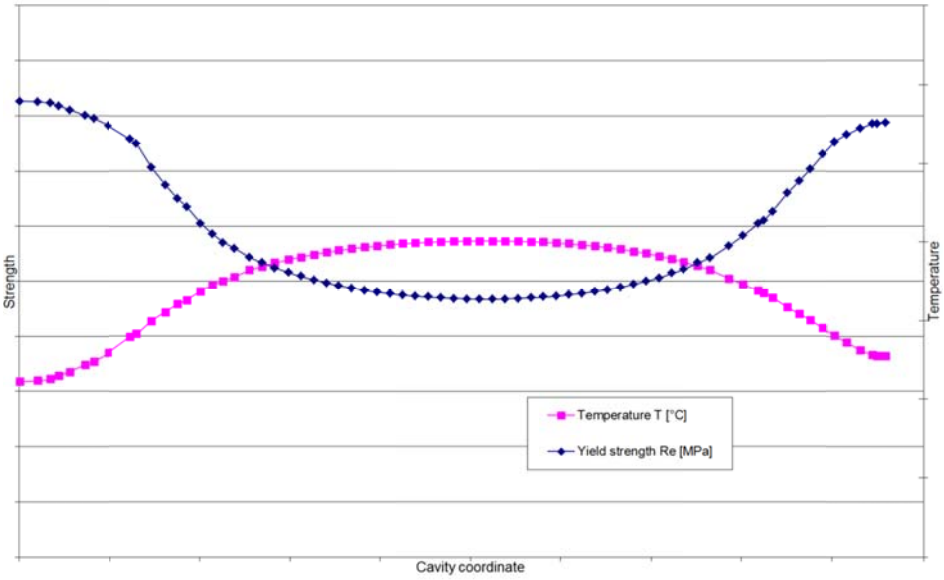

Figure 7. Temperature and yield strength profiles for TN®24E basket analysis

Thermo-mechanical calculations

Due to temperature gradients resulting from the fire test significant thermo-mechanical loading on the containment components may occur. A detailed description if this phenomenon and exemplary its numerical assessment by BAM is presented in [12]. This loading may lead to bolt failure or loss of leak tightness due relative movement of lid and cask flange in the gasket area. Even if all strains remain elastic, loss of leak tightness for a limited amount of time during or after the fire test is possible. Therefore BAM required AREVA TN to perform a sequentially thermo-mechanically coupled simulation. BAM expects the applicants to use appropriate methods and strategies avoiding not necessary numerical effects. For instance, the use of dynamic solver is not recommended here since any dynamic effects are not part of the physical problem. Also the use of strategies like bolt pretension by temperature method should be avoided. If it is applied it will be not acceptable to “freeze” the shaft. Therefore AREVA TN used different reference temperatures. The bolt assembly pretension was reached by giving the bolt an artificially low reference temperature. Consequently the bolt did not have to be excluded from the mapping of temperatures later on.

To assess the mechanical behavior of the cask the development of temperature over time has to be determined. It is recommended to couple the thermal and the mechanical simulations sequentially. The results of thermal simulation covering heat transfer problems by radiation and conductivity shall be mapped to the mechanical model over a range of time including the development of a stationary state.

For a complex structure it is not possible to gather the point of extreme mechanical loading and deformations from the temperature gradient by visual inspection only. Therefore the assessment of a few single time points is inappropriate. It is mandatory to consider the history of loading and unloading if nonreversible material properties or contact conditions are applied. Conclusively the model has to be built in a way that the impact on straining, remaining bolt force and working conditions of seal for any meaningful value in time can be assessed and the extreme value can be determined.

Ultrasonic tightening trunnion screws

An ultrasonic tightening procedure is used in order to limit the range between maximum and minimum screw pretension for the trunnions. A more detailed description is given in [8].

Transport frame

The cask is transported in a horizontal position, attached to the transport frame via four trunnions. Only the package without transport frame is handled in lifting operations. The transport frame is made of a base frame and four attached support columns for the trunnions. The connection between trunnion and transport frame is designed as predetermined breaking point. It ensures safe fastening in RCT, while disconnection at loads way below loads endured in ACT ensure that transport frame has no negative effect on package safety.

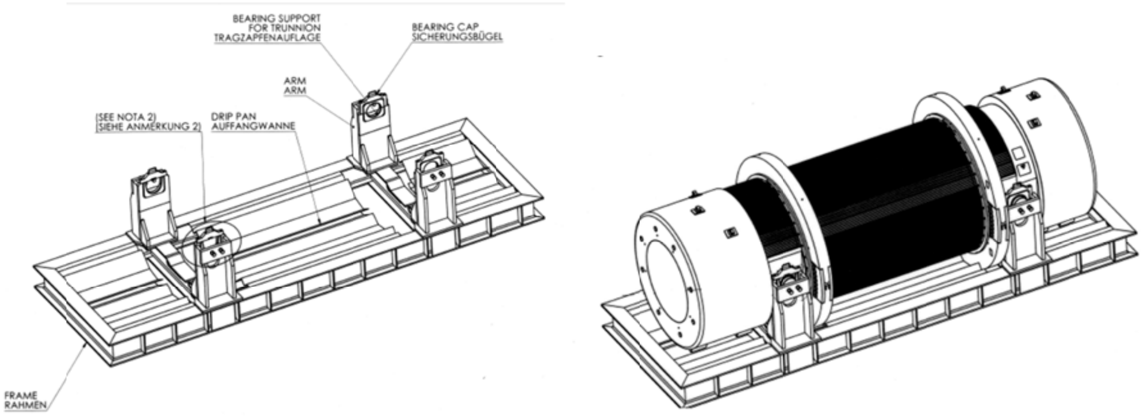

Figure 8. TN$^{®}$24E transport frame (courtesy of AREVA TN)

Conclusions

After a short introduction we presented here certain assessment experiences as well as new developments resulting from the BAM TN$^{®}$24E mechanical and thermal safety assessment. We concentrated on material and structural analysis issues.

Exemplarily it has been shown for the aluminum basket, what kind of tests have to be and have been performed to ensure performance of thermal ageing alloys. The high burn-up fuel rod and assembly behavior has been assessed by AREVA TN including static bending tests with irradiated fuel pins. Some BAM requirements regarding required material compatibility considerations are shown. Regarding structural analysis we present some basket issues with the ovalization of the shell and our requirements for the assessment of stresses and strains during the fire test with a thermo-mechanical calculation. The consideration of multiple mass effects for the TN$^{®}$24E is shown. Main conclusion was that due to discussions between BAM and AREVA TN the basket design had been improved to include shock absorbing components.

Acknowledgements

We would like to thank AREVA TN for allowing to use pictures, sketches and drawings from the TN$^{®}$24E project.

Literature

[1] International Atomic Energy Agency (IAEA). Regulations for the Safe Transport of Radioactive Material, 2012 Edition. Specific Safety Requirements No. SSR-6, Vienna, 2012

[2] Federal Institute for Materials Research and Testing (BAM): BAM-GGR 011 Quality Assurance Measures of Packagings for Competent Authority Approved Package Designs for the Transport of Radioactive Material Rev.0, June 25th 2010. www.bam.de/en/service/amtl_mitteilungen/gefahrgutrecht/gefahrgutrecht_medien/ggr-011.pdf

[3] Federal Institute for Materials Research and Testing (BAM): Leitlinie zur Berechnung der Deckelsysteme und Lastanschlagsysteme von Transportbehältern für radioaktive Stoffe. Edition 2012-11 www.bam.de/de/service/amtl_mitteilungen/gefahrgutrecht/gefahrgutrecht_medien/ggr-012.pdf

[4] Neumann, M. et al.: Material Characterization and Modeling within Safety Analysis of Packages for Transport of Radioactive Material. ASME PVP2012, Toronto, Canada, July 15-19, 2012

[5] American Society for Testing and Materials: Specification for quenched and tempered vacuum-treated carbon and alloy steel forgings for pressure vessels ASTM A 508M-95, 1995

[6] Neumann, M. et al.: Experiences by german authority with safety case approach for welding seams as part of SNF transport package containments. Proceedings of RAMTRANSPORT, Institution of Nuclear Engineers, London, U.K., May 2012

[7] U.S. NRC: Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Container Vessel with Wall Thickness Greater than 4 Inches (0,1 m) but not Exceeding 12 Inches (0,3 m). Regulatory Guide 7.12, June 1991

[8] Bekrar, J. and Günther, U.: Improving the safety of bolting system – use of the ultrasonic test stress tightening method. PATRAM 2013, San Francisco, USA , August 18 – 23, 2013

[9] Purcell, P. C. and Dallongeville, M., "Testing of LWR fuel rods to support criticality safety analysis of transport accident conditions," *Packaging, Transport, Storage and Security of Radioactive Material,* 15, (3-4), pp. 265-272, (2004).

[10] Ballheimer, V., Wille, F. and Droste, B., "Mechanical safety analysis for high burn-up spent fuel assemblies under accident transport conditions," *Packaging, Transport, Storage and Security of Radioactive Material*, 21, (4), pp. 212-217, 2010

[11] Quercetti, T., Ballheimer, V., Droste, B. and Müller, K.: Internal cask-content-collisions during drop test of transport casks for radioactive materials. PATRAM 2013, San Francisco, USA , August 18 - 23, 2013

[12] Sterthaus, J., Ballheimer, V., Bletzer, C., Nehrig, M., Linnemann, K., Wille, F.: Numerical approach for containment assessment of transport packages under regulatory thermal test conditions. PATRAM 2013, San Francisco, USA , August 18 - 23, 2013