THERMO-MECHANICAL FINITE ELEMENT ANALYSES OF BOLTED CASK LID STRUCTURES

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ABSTRACT / INTRODUCTION

The analysis of complex bolted cask lid structures under mechanical or thermal accident conditions is important for the evaluation of cask integrity and leak-tightness in package design assessment according to the Transport Regulations or in aircraft crash scenarios. In this context BAM is developing methods based on Finite Elements to calculate the effects of mechanical impacts onto the bolted lid structures as well as effects caused by severe fire scenarios.

In case of fire it might be not enough to perform only a thermal heat transfer analysis. The complex cask design in connection with a severe hypothetical time-temperature-curve representing an accident fire scenario will create a strong transient heating up of the cask body and its lid system. This causes relative displacements between the seals and its counterparts that can be analyzed by a so-called thermo-mechanical calculation.
Although it is currently not possible to correlate leakage rates with results from deformation analyses directly an appropriate Finite Element model of the considered type of metallic lid seal has been developed. For the present it is possible to estimate the behaviour of the seal based on the calculated relative displacements at its seating and the behaviour of the lid bolts under the impact load or the temperature field respectively.

Except of the lid bolts the geometry of the cask and the mechanical loading is axial-symmetric which simplifies the analysis considerably and a two-dimensional Finite Element model with substitute lid bolts may be used. The substitute bolts are modelled as one-dimensional truss or beam elements. An advanced two-dimensional bolt submodel represents the bolts with plane stress continuum elements. This paper discusses the influence of different bolt modelling on the relative displacements at the seating of the seals. Besides this, the influence of bolt modelling, thermal properties and detail in geometry of the two-dimensional Finite Element models on the results are discussed.

1 FIRE LOAD

In order to analyze the cask integrity and leak-tightness according to the Transport Regulations [1] or in aircraft crash scenarios [2] the thermo-mechanical behaviour of the cask and its lid seal system has to be evaluated and a time-temperature function and other fire characteristics are needed. In this paper the derivation of a temperature-time function will not be discussed. In the literature [3, 4] standard fire testing curves and approaches to estimate loadings can be found. As an example for a loading which results from an aircraft crash into a building, see [5]. For the purpose of this paper it doesn't matter where the time-temperature function comes from. That's why two fire scenarios have been chosen, namely the IAEA fire test as a basis for comparison and a hypothetical fire as shown in Fig. 1.

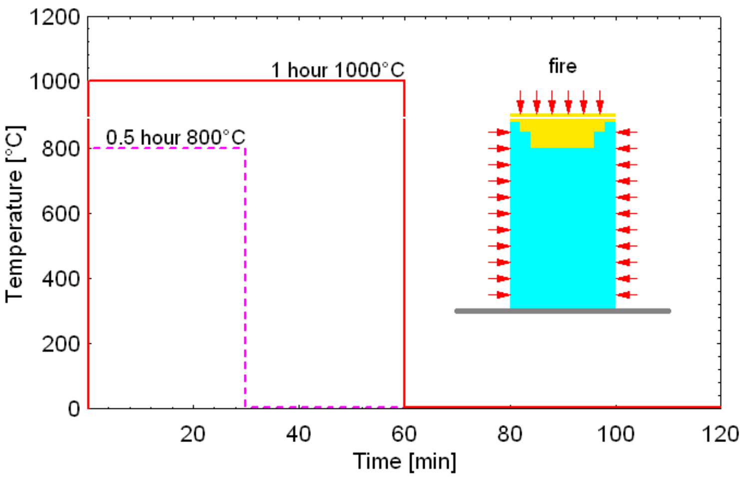


Fig. 1: Time-temperature functions (IAEA: 800°C)

In the following, firstly general aspects of modelling the physical problem are discussed. Then, within the framework of sensitivity studies, the influence of temperature dependent material properties, two different constitutive equations for the material and diverse modelling of the lid bolts on relative displacements at the seating of the seals is investigated.

2 MODELLING

Geometry and model

To clearly show the effects of highly transient thermal loads on the lid seal system with respect to its leak tightness some requirements concerning the modelling are necessary. A typical German cask design for transport and storage of radioactive material was used for the geometric model. The mean goals of the thermo-mechanical investigations were the determination of the displacements of the whole lid seal system and the estimation of the behaviour of the primary lid bolts. That's why the whole lid system consisting of the primary and secondary lid, as well as a cover and a moderator plate was modelled exactly with all gaps and voids in it.

By the usage of available symmetry conditions (symmetry of the geometry and the thermal loading) a computer efficient, two-dimensional, axisymmetric FE model could be created despite the detailed model request (Fig. 2). The lid bolts of the three available lids were represented by several mechanically equivalent substitute bolts. Performing different FE analyses the bolts were either modelled as trusses, beams, two-dimensional continua (Fig. 2b) or by a constraint condition (fixing two nodes between the lid and the cask body at the bolt pitch circle in axial direction). According to the real bolt material these substitute bolts were associated with temperature-dependent material parameters for bolts of the German strength class 8.8.

For the evaluation of the thermally induced displacements between the cask body and the respective lids contact faces were defined which allowed relative movings both in normal and in tangential direction between the bodies in contact. Before the beginning of the heating the clamp force of each of the joints between the three lids and the cask was adjusted by tuning the screw force which acts on the pre-stressing section of each of the FE bolt models to its assembly state. Therefore, a possible loss of the locking forces of the screws due to different heating and thermal mismatch between lid and screw material is well taken into account by the calculation. Furthermore friction between the contact faces was simulated. For the calculation of the temperature fields between the contact faces the heat transfer was described by means of a contact heat transfer resistance. For this sake a gap of 0.2 mm was assumed. The heating up of the primary lid is therefore underestimated in case of fire. Therefore, conservative displacements are evaluated in the area of the large primary lid metal gasket. In addition a sensitivity study showed that the contact heat transfer resistance may be varied within a bright range without changing the relative displacements significantly.

Throughout the analysis the thermal properties of the so-called moderator zone were homogenized. This means that the material parameters for density, specific heat and thermal conductivity were smeared according to the area ratios of the cast iron housing and the moderator. The radially extending fins on the outer surface of the casing were not modelled because their influence upon the absorption of heat in case of a fire is negligible because of the dominance of heat radiation. As far as the steady state conditions of the cask before the fire and during the cooling phase after the fire are concerned the fins have to be taken into account. This is done with sufficient accuracy by multiplying the heat transition coefficient of the horizontally lying or vertically standing smooth cylinder by the so-called fin factor. It accounts for the surface area ratios of the casing with and without fins.

In the numerical simulation the carrier together with the spent fuel rods was homogenized on behalf of the thermal properties and heat generation (according to the procedure for the moderator zone). As far as the cavity upon the carrier is concerned only heat transfer by radiation was considered due to a conservative estimation.

In addition it is emphasized that the model is focused exclusively on the heating of the cask housing and not upon the temperature distribution within the inner cavity concerning especially the maximum temperatures of the spent fuel elements.

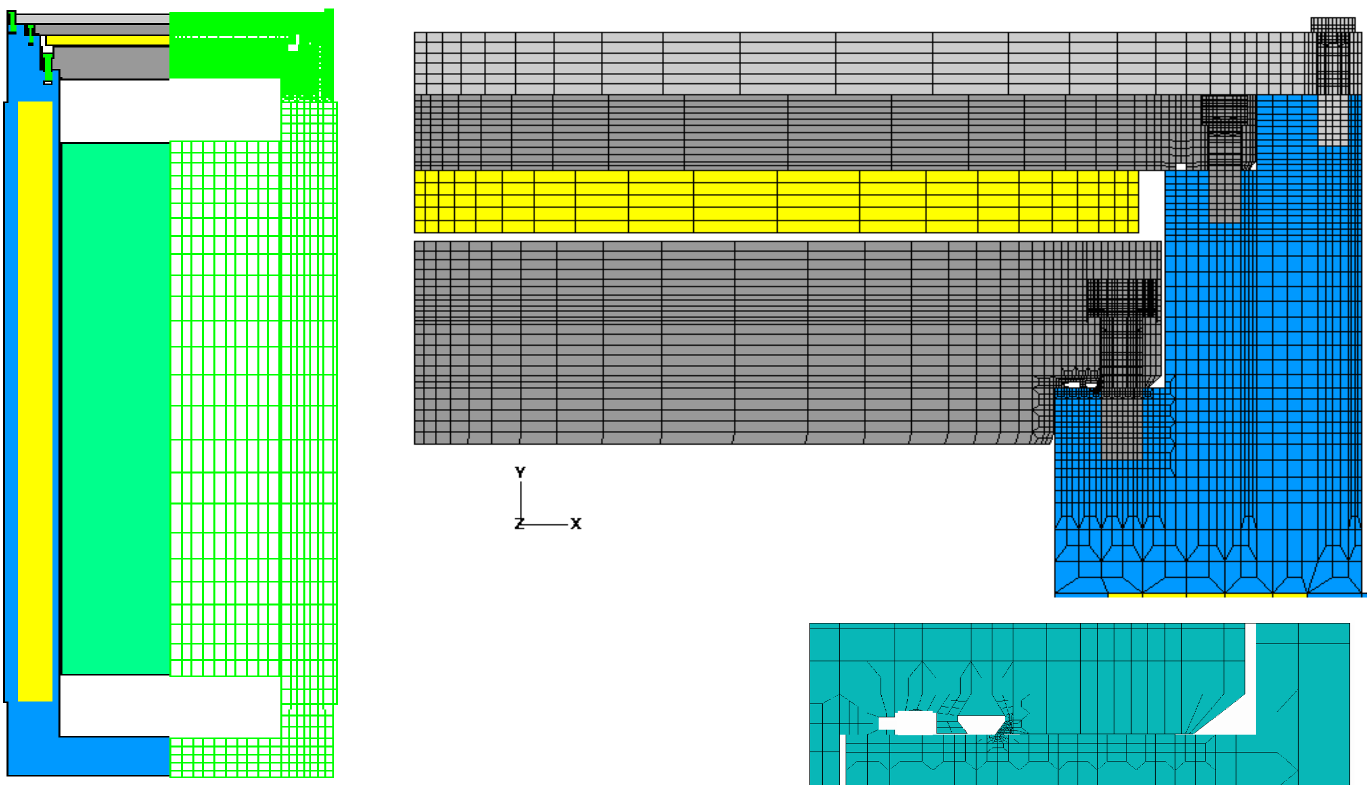
Fig. 2 shows the geometry and the mesh of the cask model carried out with the finite element preprocessor PATRAN. The left part of the Figure shows the materials (cast iron, stainless steel, polyethylene, and the homogenized areas of moderator zone and carrier) drawn in different colours. This Finite Element mesh clearly illustrates the detailed degree of fineness of the model.

The nonlinear transient thermal and thermo-mechanical calculations where executed with the Finite Element program ABAQUS Version 6.3 [6].

Initial and boundary conditions

Starting point for the thermal analysis is its state of thermal balance depending on the cask inventory at a maximum environmental temperature of 28 degrees Celsius inside a storage facility. The loss of heat via radiation is hindered for casks that are surrounded by other warm casks. To take this into account the original emissivity of the cask surface is reduced to a certain value which has to be found out by a separate calculation analyzing the

concrete cask storage allocation. For this study the emissivity was reduced from 0.93 to 0.1. The derivation of the convection heat transfer coefficient was already mentioned above.
The fire load is characterized by a flame emissivity coefficient and a convection heat transfer coefficient. In case of a standardized fire curve an average emissivity value of 0.8 for the area on fire and convection heat transfer coefficient of 25 W/m^2 can be chosen according to [3]. For this study a conservative flame emissivity coefficient of 1 and the mentioned convection coefficient have been taken also for the IAEA fire test. Therefore the calculations are based on conservative thermal boundary conditions.
For the cooling down phase of the cask the same thermal boundary conditions were used as for the thermal steady state analysis. Thus, the effects of an upheated storage building with its inventory on the cooling down phase are taken into account.



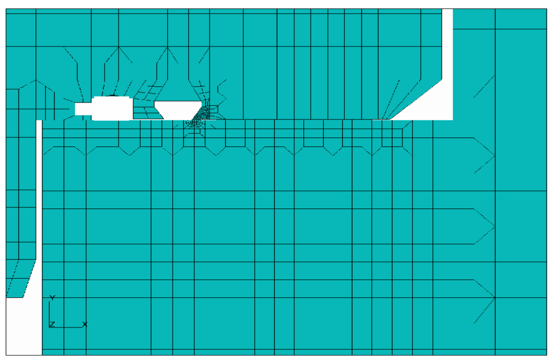


Fig. 2: Finite element model of a typical German double lid transport and storage cask,
a) components (left),
b) lid system (right),
c) detailed view of the sealing area (below).

Sensitivity studies

The goal of the sensitivity studies is to work out which parts of the model are important and which could be simplified to do a conservative safety analysis. Especially, results concerning the leak-tightness during the fire loading and for the derivation of a leakage rate to estimate a possible radioactive release are the main criteria for these studies.
The influence of a lack in high-temperature material properties will be discussed firstly and importance is attached to the definition of a material data set for further sensitivity studies. Then, the results of different substitute bolt models and their capability of reducing relative displacements of the lid system are discussed, which are important for the leak-tightness of the metallic seals. At last, the influence of the chosen constitutive equations is considered.

Influence of material properties

In many cases the thermo physical material properties of substances are measured within temperature ranges needed for typical industrial applications. That's why material data even for metals are available often up to 350°C

only. But, for this investigation there maybe a need for high-temperature material data especially for the cask body. In the first place the behaviour of the cask body must be investigated properly, because its thermal expansion causes the relative displacements of the lid system.
The following material data sets for the cask body (Fig. 3) like thermal conductivity, specific heat, coefficient of thermal expansion and the modulus of elasticity were used:

- Data set I: All material properties are defined from room temperature up to 400°C [7] and then kept constant.
- Data set II: All material properties are defined from room temperature up to 400°C [7] and then linearly extrapolated up to 1000°C.
- Data set III: The material properties are taken from [8] except Young's Modulus [unpublished BAM measurement].

Fig. 4 shows the results of the simulations for the three different material data sets for the 1000°C fire. For comparison, the same figure shows the results for the IAEA fire test incorporating the normally used material data set I. It can be seen easily, that the material data set I is sufficient concerning the accuracy of the temperature distribution at certain positions of interest.

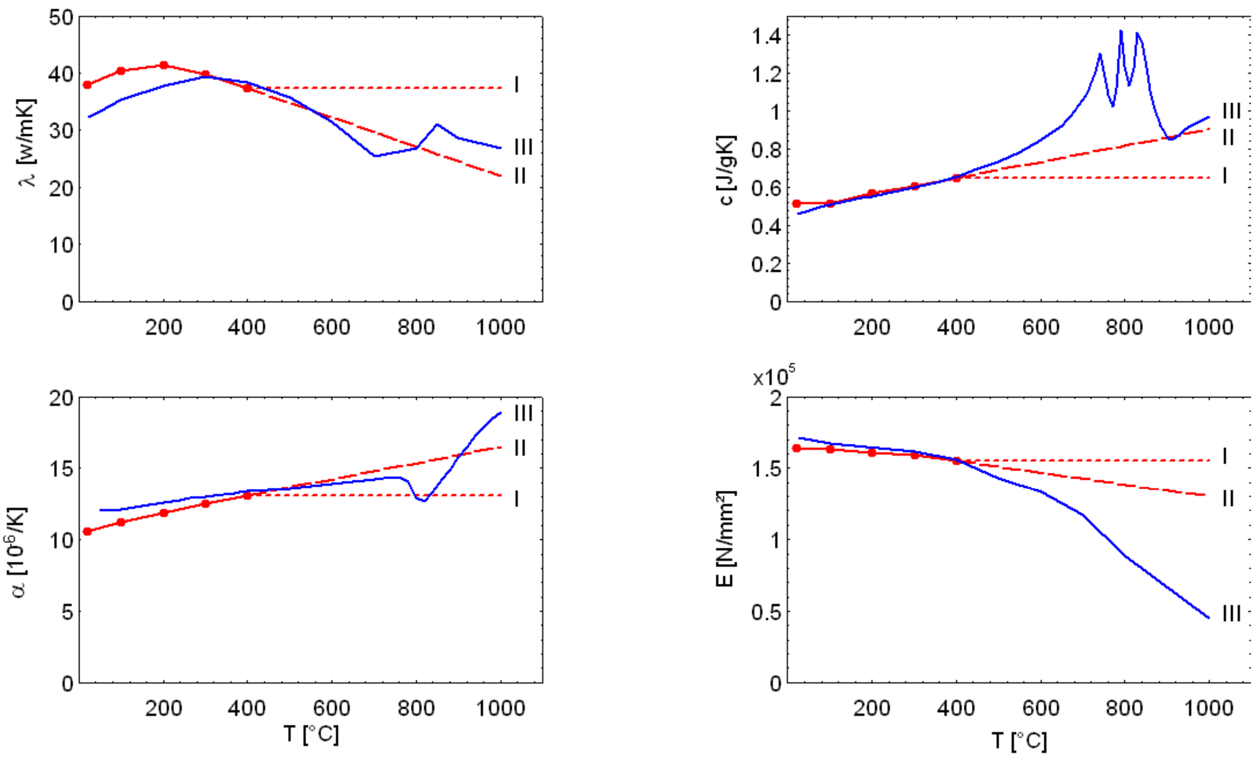
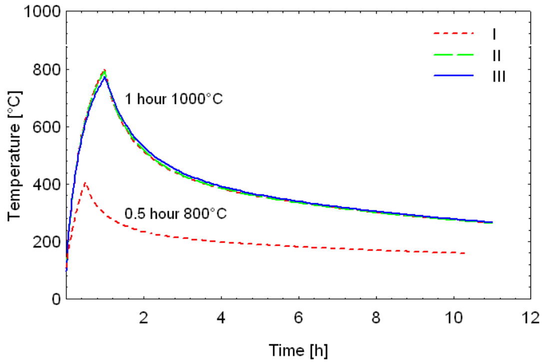


Fig. 3: Thermal and mechanical material properties used for ductile cast iron:
Conductivity λ, specific heat capacity c, expansion coefficient α,
modulus of elasticity E

The thermal displacements are calculated based on the foregoing thermal analysis. Because the three material data sets show comparable results concerning the time-temperature curves for the 1000°C fire at the chosen significant positions of the structure (Fig. 4) they also result in similar thermal displacements of the large primary lid seal. This is a first important result of the sensitivity studies. Within the frame of the considered fire loads a lack of high temperature material properties or of their variations depending on different material qualities has no relevant effects on the main results of the FE calculations.



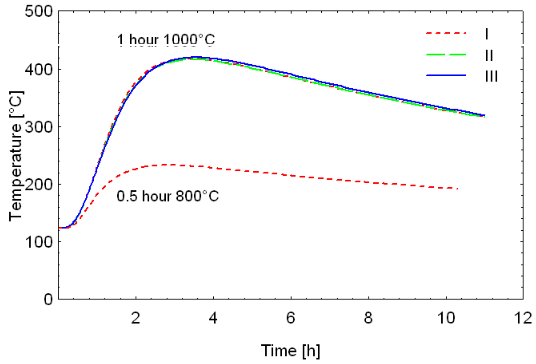
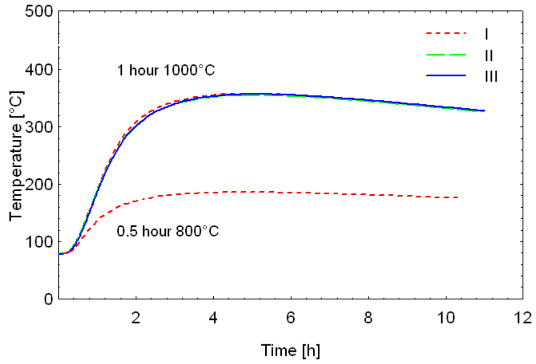


Fig. 4: Time-temperature curves for selected points depending on the three material data sets

a) Max. surface temperature in the middle of the cask body (above, left)
b) Max. inner wall temperature in the middle of the cask body (above, right)
c) Temperature of the large metallic seal (below, left)



Influence of the lid bolts modelling

How differ the displacements at the large primary lid seal when different simplified bolt models are used for the Finite Element analysis? To answer the question, four different bolt models were compared. The two-dimensional bolt model has the highest mechanical accuracy and will be the basis for the comparison. See [9,10] for further details on the modelling requirements. This bolt model and the two other one-dimensional bolt models with one truss and beam element, respectively, are able to simulate pre-stressing and thermal expansion. A simple way to simulate the locking action of the bolts is to tie two adjacent nodes of the cask and lid at the bolt pitch circle. The latter has the disadvantage that stressing of the bolts is unknown, but a possible reduction of the pre-stressing can be estimated analytically depending on the calculated temperature of the nodes.
Fig. 5 shows the results for the different lid bolt models. It can be seen that besides different curve progressions all four bolt models deliver similar maximum sliding and opening displacements at the position of the large metallic primary lid seal. Furthermore the pre-stressing of the bolts (for tied=infinite high) can limit the opening displacement only to a small degree, see Fig. 5b.

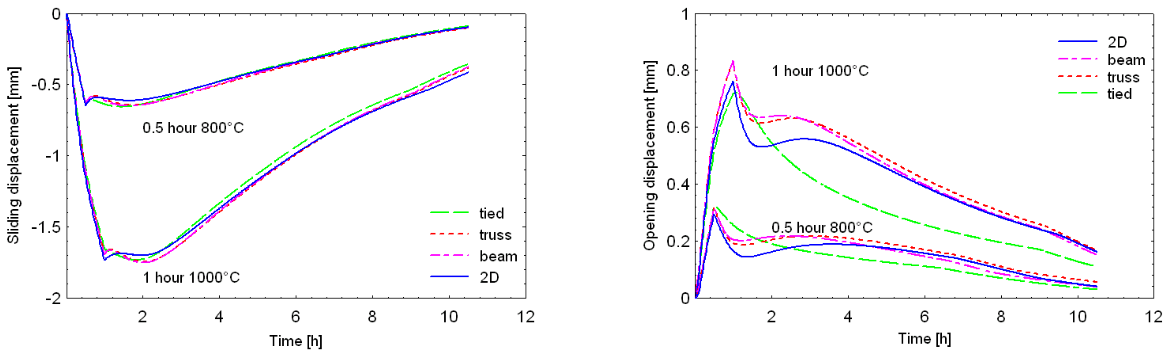
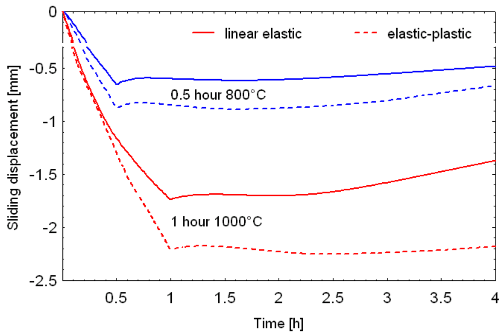


Fig. 5: Seal displacements due to different modelling of the lid system bolts
a) Sliding (radial) displacements (left),
b) Opening (axial) displacements (right)

Influence of constitutive equations

A thermo-mechanical simulation using only linear elastic material behaviour gives conservative results concerning relative displacements at the position of the large primary lid seals (Fig. 6a, b) but also predicts unrealistic high stresses inside the cask body or for the lid bolts (Fig. 6c) at areas of force transmission. For a more realistic simulation von Mises plasticity has been used as the constitutive law. This means that yielding caused by compression occurs at the same absolute value as for tension. For ductile cast iron values for the tensile yield strength depending on the temperature are known up to 500°C [7] but not for the yield strength in compression. Because the real values for the compression yield strength are generally higher than the tensile one's, the elastic-plastic simulation is not conservative but also not far away from reality.



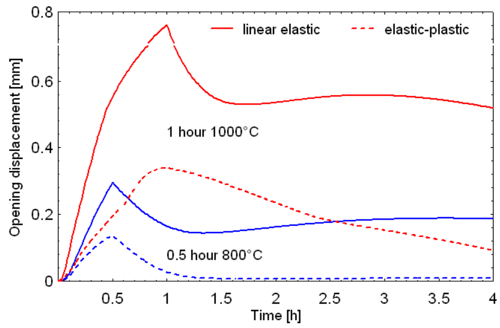
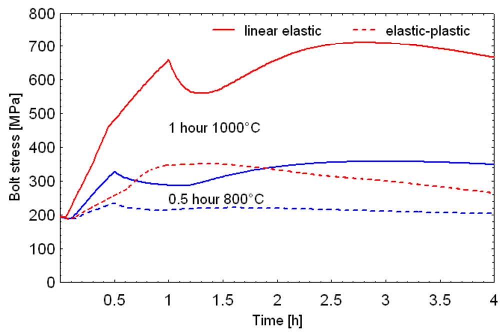


Fig. 6: Thermo-elastic vs. elastic-plastic calculation

a) Sliding (radial) displacements (above, left),
b) Opening (axial) displacements (above, right)
c) Tension stress of the primary lid bolt shank



Discussion of the sensitivity studies

For fire loads being much severe than the transport regulatory fire test it could be important not only to calculate maximum seal temperatures but also to investigate the relative displacements between the lid seal system components. Especially in the latter case a leakage rate can be assessed for the estimation of a radioactive release. The BAM sensitivity studies have shown that using only linear elastic material properties up to 400°C and a simple bolt model like a truss element or even a constraint condition sufficiently conservative results can be obtained. Nevertheless the calculations are in many respects nonlinear thus a simple extrapolation of the results for other fire loads is not admissible.

3 MAIN SAFETY ASSESSMENT CRITERIA

Seal temperature

On behalf of the assessment of the thermal stressing of the metal seals the maximum allowable service temperatures were taken from the producer's product catalogue [11]. They depend on the material of the outer coating and the diameter of the cross-sectional area. E.g., in case of large seals for primary lids (Aluminium coated) with a diameter of 9,8 mm the maximum allowable temperature is T_{max}=380°C. Referring to the seal of a small closure lid within a primary lid of e.g. 4,7 mm of diameter this value is T_{max}=280°C.

Permitted thermal displacements near the seals

As far as the evaluation of the effects of radial displacements of a seal is concerned results from tests carried out within the framework on the assessment of Aluminium (and Silver) coated metal seals exist. In these tests flanges

were displaced relatively up to 3 mm with the seal under pre-stressing. The leakage rates forced by the displacement were < 10^{-4} Pa m³/s. Similar Japanese tests on Aluminium coated Helicoflex seals [13] confirm leakage rates of < 10^{-7} Pa m^3/s in case of displacements up to 1,5 mm at 25 °C and 150 °C. As a rule the acceptable relative radial displacements have to be clearly below the thickness of the permanent metallic seal print.
A temporary gap near the large metallic primary lid seal can be assessed by considering the decompression behaviour (elastic resilience) of the seal according to the seal resilience characteristics [11, 12]. If the compression load caused by the bolts decreases below a characteristic value Y_1 [11] then the seal losses its specified leakage rate. As a criterion BAM used a so-called useful elastic recovery e_1 of 0.1 mm for the safety assessment of Type B-packages. In reality, e_1 lies for Aluminium between 0.2 and 0.3 mm. For gaps bigger than 0.4 mm the cask lid gets leak.
Concerning the following remarks only the leak-tightness of the primary lid is taken into account. The leak-tightness of the secondary lid may be taken as lost under conservative aspects. Furthermore, for the also existing Elastomere seals no thermal long-term stability is assumed and so no credit is taken from its sealing effect, as well.

Behaviour of the lid bolts

A considerable loss in the pre-stressing forces of the bolts due to the thermal load may be expected. This is mainly caused by the thermally induced decrease of Young's Modulus and the thermal mismatch of the materials of the components (bolts, primary lid, casing). The basis for the evaluation of the change of the pre-stressing forces is the knowledge of the steady state or transient temperature fields according to the problem. For an analytical approach, see e. g. [14]. By means of a thermo mechanical simulation this behaviour can be analyzed directly. As a main criterion, during and after the fire (no relaxation effects happened), the bolts must provide sufficient compression for the seal to keep in stable position without an increase in the leakage rate.

Mechanical integrity

A loss of the mechanical integrity of the cask due to thermal stress can be negated because the cask can expand freely. Locally high thermal stress caused by large temperature gradients inside the cask and coming either from an only particular fire engulfment (e.g. areas protected by the impact limiter) or just as a result of the cask design in combination with a transient heating up of the cask is limited by local plastic deformations.

4 SUMMARY

This paper describes methods to analyze the stressing of transport and storage casks for spent fuel in case of severe fire loads e.g. related to an aircraft crash and based upon that, a conservative leakage rate for calculating the amount of radioactive release can be estimated. To do the latter, the relative displacements at the groove of the large primary lid seal must be calculated in connection with the determination of the maximum stressing of the primary lid bolts. If these bolts keep their pre-stressing then the leakage rate remains still very low, although relative displacements and stressing of the metallic seal may happen temporarily. The calculated relative displacements are compared with lab-examined [12, 13] and based upon expertise in this field conservative leakage rates can be derived. The main safety assessment criteria to do this are discussed in Chapter 3. At present, a quantitative relationship between the calculated deformations of the lid system and leakage rates is not possible because leak tightness is primarily influenced by the microscopic interaction of the involved material surfaces and their special conditions. Such relationships will have to be confirmed experimentally.
Sensitivity studies have been undertaken to work out which parts of the Finite Element modelling procedure are important to get the relevant data for the assessment. These studies indicate that using only linear elastic material properties up to 400°C and a simple bolt model like a truss element or even a constraint condition can provide sufficiently conservative results.

5 REFERENCE

[1] International Atomic Energy Agency (IAEA)
Regulations for the Safe Transport of Radioactive Material, 1996 Edition (As Amended 2003)
Safety Standards Series No. TS-R-1, Vienna, 2004

[2] Thomauske, B.
Realization of the German Concept for Interim Storage of Spent, Nuclear Fuel -Current Situation and Prospects-
WM'03 Conference, February 23-27, 2003, Tucson, AZ

[3] U. Schneider, Ch. Lebeda
Baulicher Brandschutz
Stuttgart, Berlin, Köln, Kehlhammer, 2000

[4] Kerntechnischer Ausschuss (KTA) / Nuclear Safety Standards Commission (KTA)
KTA 2101.2 (12/200); Fire Protection in Nuclear Power Plants; Part 2: Structural Components; Appendix A: Simplified Validation Procedure for Determining the Required Fire Resistance Rating of Structure-Related Fire Protection Measures
http://www.kta-gs.de/e/standards/2100/2101_2e.pdf

[5] Brücher, W., Röwekamp, M.
FDS3 Simulations of Indoor Hydrocarbon Fires Engulfing Radioactive Waste Packages
PATRAM 2004, 20-24 Sept. 2004, Berlin, Germany

[6] ABAQUS User's Manual Version 6.3
Hibbitt, Karlsson & Sorensen Inc.
Pawtucket, RI., 2002

[7] Palmer, K. B.
The mechanical and physical properties of engineering grades of cast iron up to 500°C
BCIRA Report 1717, Birmingham, 1986

[8] Overfelt, R.A., et al.
Thermophysical Properties of 201 Aluminium, Ductile Iron and Sebiloy II
AFS Transaction 02-146
http://www.moderncasting.com/archive/WebOnly/0802/02_146.pdf

[9] ABAQUS Example Problems Manual, Vol.1, Version 6.3
1.1.1 Axisymmetric analysis of bolted pipe flange connections
Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, 2002

[10] Wieser, G., Qiao, L., Völzke, H., Wolff, D., Droste, B.
Safety Analysis of Casks under Extreme Impact Conditions
PATRAM 2004, 20-24 Sept. 2004, Berlin, Germany

[11] Garlock Sealing Technologies
Helicoflex® Federelastische Metalldichtungen; Technische Daten
Produktkatalog 2001

[12] Weise, H. P., et al.
Untersuchung von Dichtsystemen und dichten Umschließungen zum Transport und zur Lagerung radioaktiver Stoffe, Report Forschungsvorhaben ST.-Sch. 943 (Berlin: BAM, 1986)
BMU-Schriftenreihe, Reaktorsicherheit und Strahlenschutz, BMU-1989-210

[13] Matsuoka, T., et al.
Verification of Packages Containment System Using Metallic Gasket to Comply with Requirement for both Transport and Storage,
PATRAM 2001, 3-8 Sept. 2001, Chicago, USA

[14] VDI Verein Deutscher Ingenieure (Association of German Engineers)
Guideline VDI 2230 Part 1, Systematic calculation of high duty bolted joints - Joints with one cylindrical bolt
Beuth Verlag GmbH, Berlin, Germany, February 2003