German Competent Authority Guidance in FE Methods Applications for Package Design Assessment

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Abstract / Introduction

The development of new methods in analysing package designs by using the finite element method (FEM) is of increasing importance. Package designers are more and more applying the growing opportunities of numerical methods to perform safety assessments for their products which requires suited methods also for competent authorities like BAM to verify the applicants' results. This presentation gives an topical overview of the experiences and tendencies within the complex field of finite element design testing.

There are at first some general and more formal aspects concerning the correct finite element program selection and documentation of modelling, material properties, boundaries and calculation results including their interpretation. To give a reliable basis to the applicants in Germany BAM has drawn up and published a Finite Element Guideline recently.

Secondly, the paper discusses actual technical questions which are of a wide interest and range from mechanical reflections on cask drop and extreme impact scenarios to thermal reflections on decay heat removal and fire scenarios. Examples from BAM work on FE-development activities are shown to demonstrate the great opportunities as well as the difficulties of using finite element methods for package safety analysis and design testing.

1. BAM Guidance to Finite Element Methods Applications

In view of the increasing use of numerical calculation methods for package safety assessment by an growing number of applicants BAM decided to work out a Finite Element Guideline to fix a common basis for all safety proofs. This paper called "Guidelines for Numerical Safety Verifications within the Scope of the Design Assessment of Transport and Storage Casks for Radioactive Materials" was published in 2003 [1].

The object of the guideline is to provide quality assurance for the preparation, checking and evaluation of safety verifications based on numerical analysis of problems belonging to the scope of evaluation and expertise of transport and storage casks. Its main purpose is to provide a base for the correct performance of numerical analyses according to the state of the art, thus supporting the possibility to check the numerical safety verification. Its application assures the follow-up of calculations and of the conditions on which they are based. Considering that numeric safety verifications only can be based on approximation solutions, depending on the quality of modelling, the demonstration of good accordance with the reality is a fundamental topic. The following terms are of basic importance:

<u>Verification and validation:</u>
A verification report provides evidence that the used FE model with its input parameters (especially material laws and characteristic values, among others) gives a sufficiently precise description of the technical problem, that is, the investigated physical reality. This may be achieved through comparison with sufficiently ascertained experimental results, or through relation with exact analytic solutions. Validation in this context means the confirmation by the competent authority (here BAM) for an accepted verification of a finite element model and/or important input parameters, e.g. complex material properties.

<u>Benchmark investigation:</u>
The object of benchmark investigations is mainly to verify the calculation algorithms of a FE programme, e.g. on the base of analytically solvable physical problems [2]. Comparative calculations with different programmes, using the same FE model with the object of testing a programme foreseen for the concrete considered application, also belongs to benchmarking (see for example SANDIA report „Sample Problem Manual for Benchmarking of Cask Analysis Codes" [3]).

Parameter study:
Parameter studies are used for the specific investigation of the effects on the results of calculations, when definite preliminary conditions (material laws or parameters, defining of elements, boundary or contact conditions) are varied for a given scenario, taking into account possible bands of fluctuation.

Conservative design calculation:
Conservative design calculations are performed in order to assess limit values within the target magnitudes of technical problems (e.g. stresses, deformations, temperatures). This may appear to be useful or necessary when important input parameters (e.g. material laws) are only insufficiently known, and the results obtained through conservative assumptions are within admissible areas.

Quality assurance for numeric safety verifications is another basic topic. Even though all common commercial closed source FE codes are permanently checked and optimised by suppliers and/or independent user organisations that doesn’t guaranty correct calculation results automatically especially in cases of new software versions, or any kind of changes in the individual software environment. In case of open source FE codes this is evident. The plausibility of calculation results through comparison with comparable earlier calculations, and thus the suitability and precision for the concrete utilisation, has to be verified individually. For qualified FE code application personnel qualification is another aspect. Next to employees’ adequate technical and scientific training in the fields of computer science, numerical theory and engineering, specific experience in solving similar technical problems by means of numerical applications is required.

Requirements towards numeric safety verifications are specified by the BAM Guideline as follows:

i Formal requirements:
All relevant variables (e.g. selection of terms, formula symbols, units, order systems etc.) shall be described and defined unambiguously.

ii Completeness:
The numeric safety verification report shall include all information and data being essentially relevant for checking the results as described below. Legal requirements concerning the results must be considered in particular.

iii Programme/FE code documentation and description:
This shall include also evidence of programme suitability, reliability and quality assurance as discussed above.

iv Modelling:
The definition of a suitable mathematical model for the corresponding mechanical or thermal safety verification is essential for each numerical analysis ([4], [5], p 2 and following pages). This includes the determination of the load, of the geometry, of the material characteristics and the contact, transition, boundary and initial conditions. At this stage, an idealisation of the technical problem usually takes place, due to the simplification of the geometry and the selection of boundary conditions (e.g. contact conditions). The mathematical model is solved in a second step, e.g. by means of the finite element method. For this, the geometry is discretised by means of so-called finite elements (FE grid). The selected grid density, related to one or several types of elements which must be suitably selected, and the further used solution parameters (material laws, etc.) is decisive for the precision and the convergence behaviour of the used numeric substitution model (FE model). The FE model thus represents the sum of input data for the calculation programme of the numeric description of the selected mathematical model.
The suitability of the used material models to the problems to be solved shall be justified. The used material data and their dependence from significant influencing variables shall be indicated. If no sufficiently verified data are available for safety relevant components (e.g. cask body, lids, screws, gaskets, shielding materials) or for parts having a strong influence on the results of numerical analyses (e.g. shock absorbers, yielding impact targets during mechanical analyses), individual experimental investigations shall be performed to obtain the material data. Alternatively, a parameter study may be used to demonstrate the conservativeness of calculation results concerning the selected material data range.

v Data documentation:
This shall include complete input data sets, decisive results and further results. Input data shall completely include those values required to assure independent reproduction of the FE calculations. This includes the data base of the pre-processor, the input-file for the FE programme and, if necessary, the output-file of the pre-processor, when this is processed manually by means of an editor, in order to generate the mentioned input file.

The decisive results are the base for the final safety evaluation of the analysis results. The selection of the physical magnitudes which are decisive for the safety verification (e.g. certain local stress components or equivalent stresses, accelerations, temperatures and their history) must be justified.

All further results (e.g. global deformation images, stress distributions, energy balances, heat flow and temperature fields) shall be used to demonstrate the correctness of the calculations which were performed, and shall permit simple plausibility checks.

vi Data presentation:

Result data shall be presented in such a way that all points of view, which are essential for the processing of the corresponding task (documentation, discussion and possibility to test the selected FE model, evaluation and, if necessary, verification of the calculation results) shall be available in a comprehensible form.

The graphic presentation of calculation results should be done whenever possible. Detailed results for the particularly critical, and thus design relevant parts of the structure shall be presented based on the global illustration of e.g. certain temperature, stress or strain fields of the total structure or larger substructures. These detailed results shall be presented as functions of location and/or time. All simulations of dynamic cask impacts or fire scenarios shall be performed up to the point when the maximum values of the corresponding safety relevant parameters like stresses, deformations, temperatures, etc. are reached beyond any doubt.

Typical graphic presentations include for example:

- initial geometric configurations,
- deformations of structures or substructures,
- stress or temperature distributions of structures or substructures and
- stress and strain histories.

Certain results, which are essential for the safety evaluation, shall be clearly presented in tables, and in comparison with boundary values.

Presentation of further results includes for example:

- graphic presentations of strongly deformed FE grids in the region of impact (deformation of shock-absorbers, cask penetration into the yielding ground)
- graphics of paths, speeds and accelerations of centres of gravity or of temperatures of selected structural parts as a function of time (lids, cask body, gaskets, contents, moderator, etc.),
- energy balances (breakdown of partial energies for the total model or for selected partial systems), or heat flux fields and, if necessary, heat transfer coefficient figures calculated by the programme.

vii Evaluation of calculation results:

Checking by suitable items as there are for example:

- analytical or numerical checks with a simplified structure,
- checking by comparison with experimental results,
- checking by grid refinement or
- comparisons with reference examples.

Additionally, the precision of the calculation results as an approximate solution should be estimated. If the verification of an FE model is carried out through comparison with an exact analytic solution, the deviation of the results may not exceed ±5%. When comparing with the experiment, the calculation results shall be within the confidence range of the measurement results.

In order to indicate statements concerning the numeric precision in such a way as to allow for their verification, it is necessary to verify sufficient discretisation through grid refinement ([6], Attachment B 3.3.3.3.1), to carry out a variation of the time intervals and an analysis of the stress (temperature) bounces in neighbouring elements, within regions with large stress (temperature) gradients ([6], Attachment B 3.3.3.3.2). As far as the estimation of errors and convergence statements of FE results are concerned, reference is made to [5], p. 263 and following.

The criteria which have to be observed for the evaluation of the results and the comparison with admissible material stresses, are derived from the specific results towards the stress (temperature) evaluation, related to the corresponding cask component and material. As far as mechanical evaluation and characteristic material values are concerned, for example FKM guideline [7], IAEA-TECDOC-717 [8], BAM guidelines “Ductile Cast Iron” [9] and KTA standards 3905 [10] and 3201.2 [6] should be considered.

Altogether the practice of this comprehensive BAM guideline should lead to a common basis for elaboration and checking of FE safety assessments to minimise the iteration process between applicants and the checking competent authorities and to guarantee adequate precision of calculation results with respect to the reality.

2. Current Developments in Finite Element Analyses of Cask Structures

With the rapid development of software and hardware capabilities more and more detailed structure analyses of casks and their components including screws, lids or seals are possible. This allows quantifying safety reserves of casks regarding structure integrity and leak tightness in particular. Two fields of interest are pushing this trend: Firstly, the market mechanisms which make the cask manufacturers to produce more efficient and economic products, and secondly, questions by the public and the authorities with reference to existing safety margins in cases of severe accident scenarios including terror attacks.

2.1 FE-Analyses of Casks Hit By an Aircraft Crash

The discussion of overcritical safety properties of casks has become of increasing relevance after the terror attacks of Sept. 11th 2001. In Germany an investigation programme has started shortly after that date. It includes the investigation of cask structures and the consequences for their inventory under transport as well as under interim storage conditions. In case of cask storage in large storage buildings the possible interaction of different casks after hit by aircraft or building wreckage and the estimation of resulting cask stresses if the worst comes to the worst is an important task.

In case of an investigation of several casks in a single dynamic FE-calculation it is evident to look for an appropriate simplification of cask modelling. That means to find appropriate geometric modelling for each cask without to much detailing as well as a simplified but adequate material modelling. Additionally, it is important to include that in the case of these extreme impact scenarios only more general conclusions in terms of cask integrity and leak tightness were required. For that reason BAM has decided to calculate representative cask accelerations and decelerations and to compare them with approved values from transport design tests. If more detailed safety assessment including detailed stress analyses of cask structures is required it would be generally possible but would cause much higher effort.

Fig. 1 shows a typical configuration of storage casks inside a storage building (without impact limiters) including relatively simplistic cask models. The wreckage strike of one cask is represented by a given load function, which accelerates one directly hit cask and leads to following cask collisions as shown in **Fig. 2**.

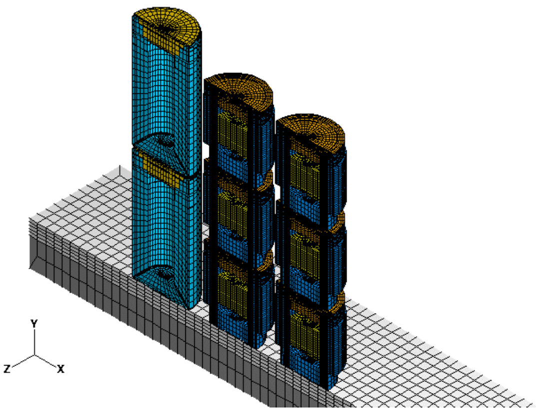

Fig. 1. Representative cask location in a storage building

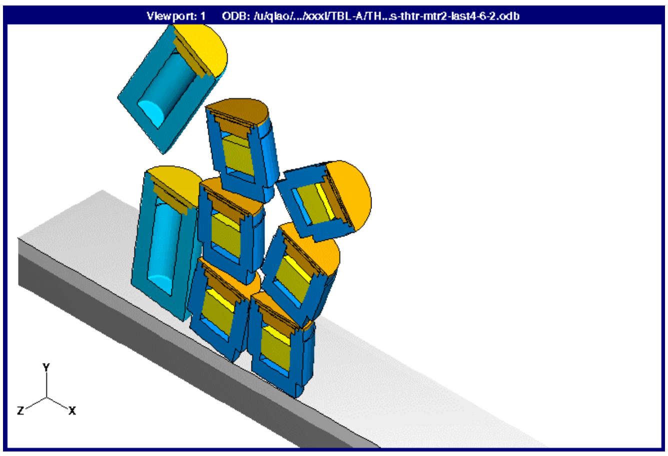

Fig. 2. Cask collisions 0.25 s after hit of left bottom cask

Several involved casks and a relatively long calculation period generates high effort in computer performance. To get first results quickly it is helpful to start calculation with at least partially rigid cask models. Generally, that results in overestimated acceleration values but basic information about the kinematic process and the identification of the most critical collisions are given. With following calculations more and more elastic and elastic-plastic material properties can be considered with the opportunity not to calculate the whole impact scenario but single critical sections like the collision of the first cask with the second adjoining cask or a final cask drop onto the ground. Additionally, the assumed surface friction parameters of the involved components can influence the results. **Fig. 3** exemplifies the average acceleration/deceleration history of the two bigger and the three smaller casks in the middle from Fig. 2. Maximum accelerations of up to 270 g (g = 9.81 m/s^2 = acceleration of gravity) affect the smaller top cask after about 45 ms when hit by the bigger cask from the left. In this case the calculation has been performed with elastic-plastic material properties. In case of rigid cask modelling calculations result in much higher accelerations of some thousand g in maximum.

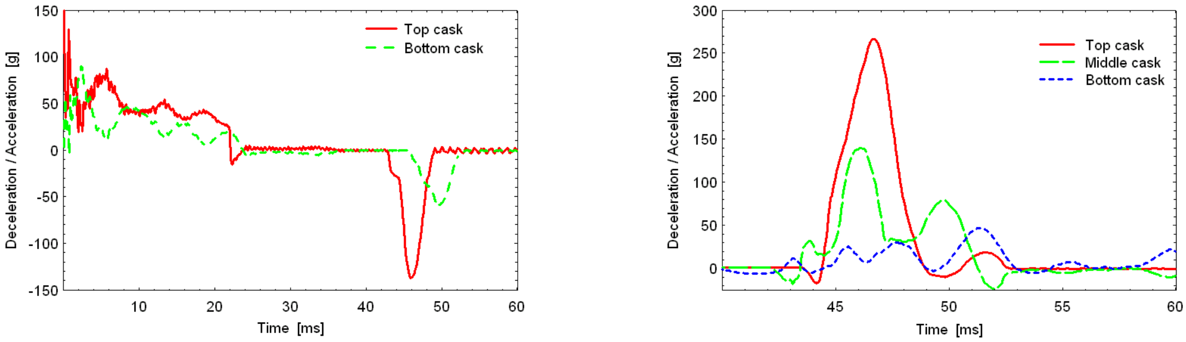

Fig. 3. Exemplary acceleration/deceleration history of the two bigger casks (left) and of the three smaller casks in the middle from Fig. 2 (impact load function not given because of confidentiality)

Generally, the most critical cask stresses occur in case of direct wreckage impact on smaller casks which then hit a much more massive cask or drop directly onto the massive building foundation. Especially such scenarios may lead to maximum accelerations or decelerations well above accepted values also in case of calculation with elastic-plastic material properties and with that quantified leakage rates for the sealed lid system are not available. But with reference to numerous cask drop tests, mostly performed by BAM, see e.g. [11] and [12], it has been possible at least to confirm the maintenance of cask integrity. With these conclusions referring to every single cask's leak tightness and integrity complete activity release calculations for a whole aircraft crash scenario into a storage building can be done.

2.2 FE-Analyses of Cask Lid Systems in Case of a Central Impact Load

Concentrated impact loads onto casks and in the most critical case central onto cask lid systems can also occur in case of accidental or terroristic aircraft crashes. The impact can be caused by massive aircraft structures like the central parts of an engine as well as by massive building structures like a heavy roof truss of the storage hall. With a given load over time function numerical analyses of the sealed lid system of the cask are an appropriate opportunity for getting detailed information about dynamic structural deformations and stresses and possible consequences with respect to the lid system's leakage rates. **Fig. 4** shows a typical Finite Element Model of a sealed lid system developed by BAM and its maximum deformations and stresses after a central impact.

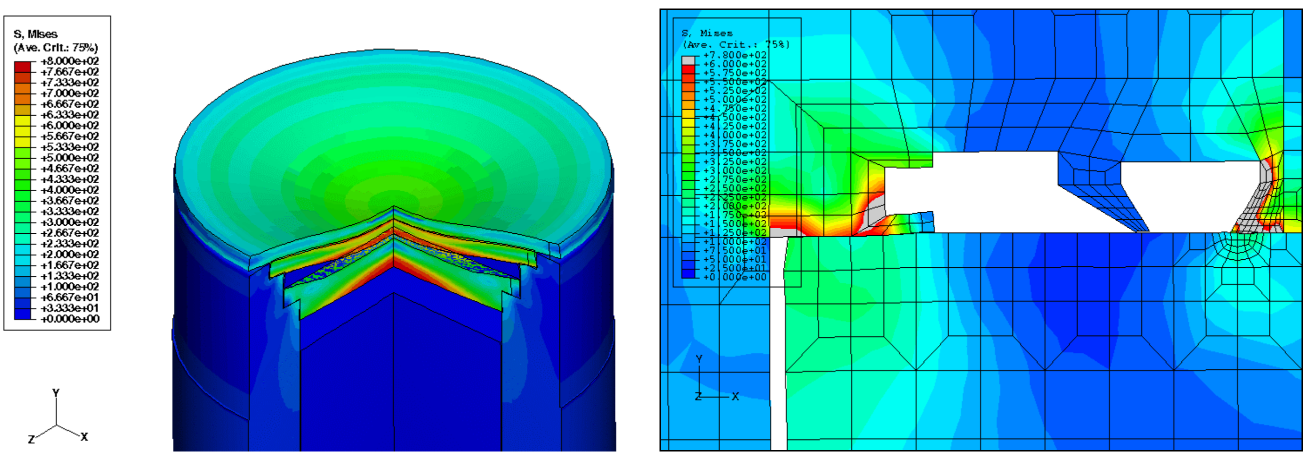

Fig. 4. Maximum stress levels after central impact. Complete lid system of a typical storage cask (left) and the modelled sealing system of a primary lid in detail (right)

The BAM Finite Element model represents a detailed image especially of the complex construction of the lids, metallic seals, screws and involved upper cask body section. Generally, the cover plate and the secondary lid including their bolted fastenings are deformed plastically in a manner that a specified leakage rate can't be assumed any longer. Only the massive primary lid and its screws get loaded at a level which leads to only very limited deformations and may keep a quantified leakage rate. The impact scenario is characterised by intense structure vibration continuing when the primary impact is just over. Stresses and deformations of the lid, the metallic seal system and the screws have to be analysed during the impact as well as when the system is in stable static condition again. The changing level of the screw's pre-stress during the dynamic impact and the remaining level after the impact determines the leak tightness of the primary lid system and thus of the whole cask mainly. Geometry data of major importance in that case are radial and axial displacements between the sealing surfaces of the lid and the cask body (**Fig. 5**). Further information is given by [13]. It should be noted that BAM uses the same approach for the assessment of the lid system behaviour of transport casks subjected to the shock wave due to detonation of an explosive charge. Instead of the cover plate the modified FE–model includes the wooden impact limiter, which outer surface is loaded by a pressure over time function [14].

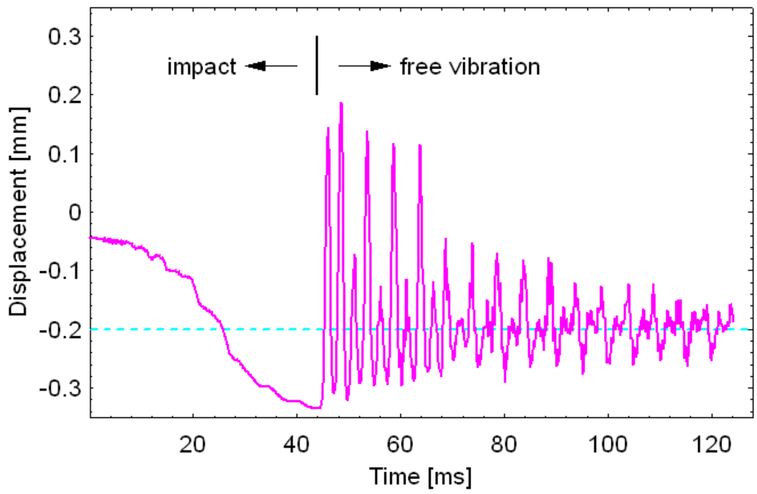

Fig. 5. History of axial displacement between primary lid and cask body at the metallic seal position during and after central impact on a cask lid system (impact load function not given because of confidentiality)

2.3 FE-Analyses of Casks Under Severe Fire Scenarios

Fire scenarios which might be well above the 30 minutes 800°C IAEA test scenario may also become relevant in case of a terroristic aircraft crash. The most severe conditions have to be assumed if a big passenger jet like a Boeing 747 or Airbus 340 crashes into a storage building just a short time after starting and introduces most of its kerosene. Depending on the kerosene dispersion inside the damaged storage building a covering burning duration including the maximum fire temperature profile and history can be estimated.

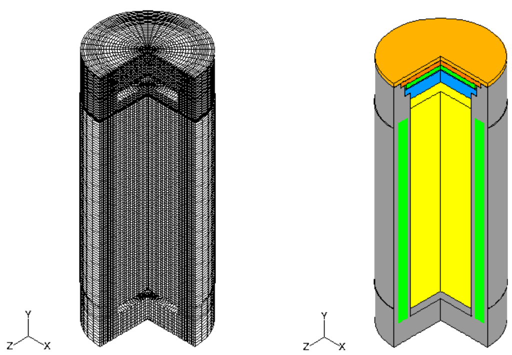

Fig. 6. BAM Finite Element model (grid left, materials right) of a CASTOR® cask for thermal calculation

With that given thermal input BAM has performed thermal calculations with special Finite Element cask models considering mechanical and thermal material properties (**Fig. 6**). Different thermal coefficients of expansion of the different cask materials in combination with unsteady and non-uniform temperature distributions (**Fig. 7**) result in partially massive thermal deformations and/or stresses. With precise and well verified BAM FE-models absolute temperature and stress levels as well as displacements between sealing surfaces have been evaluated conservatively; see [15] for more details.

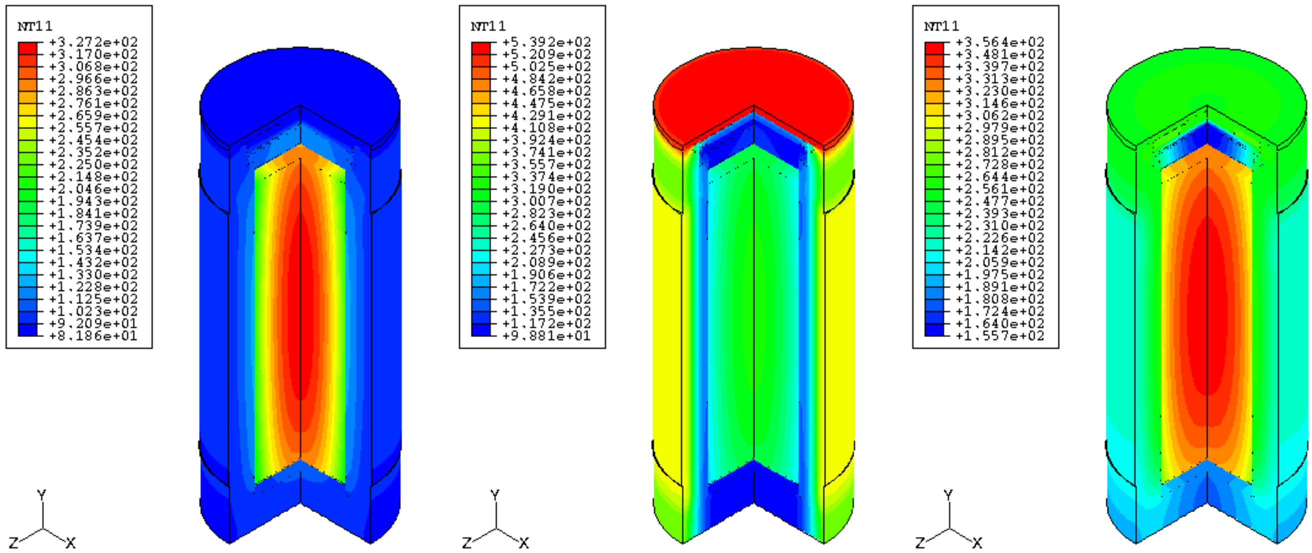

Fig. 7. Calculated temperatures (°C) of a CASTOR® cask with a spent fuel decay heat of about 40 kW before the fire starts (left), after 20 minutes fire duration of up to 1000°C (middle) and 2 hours after end of fire (right)

3. Conclusions

The paper has given a comprehensive overview about fundamental requirements for well qualified numerical calculations of complex cask structures under extreme mechanical and thermal loads. BAM as a competent authority in this field has developed a basic guideline summarising necessary requirements for the application of numerical safety assessment methods for transport and storage casks. Based on a comprehensive knowledge of cask design testing BAM has been calculating cask behaviour under different extreme accident scenarios during the last years. Especially the more precise modelling of complex lid-seal systems has enabled calculation of stresses and deformations in that area and with that BAM is able to evaluate the leak tightness of the casks and their lid systems. Further investigations are necessary for a better understanding and quantification of the cask's safety potentials especially in cases of extreme accident scenarios as discussed here.

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