MECHANICAL ASSESSMENT CRITERIA OF SPENT FUEL ASSEMBLIES BASKET DESIGN

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ABSTRACT

Packages for the transport of radioactive material are generally equipped with specific structures (basket) to support the radioactive content in defined position. The safety function of the basket depends on the kind of transported inventory. In case of transport cask for spent fuel, the basket design has to ensure the subcriticality of the fissile material in all conditions of transport in particular. Therefore the evaluation of structural integrity and neutron absorption capability of the basket is an important part of complete safety analysis. Sufficient heat transfer to maintain fuel assembly and cask temperature within allowable limits has to be verified as well. Corrosion resistance is an additional requirement on basket materials owing to contact with water during loading and unloading operations.

Computational and experimental methods or their combination along with additional material and component tests can be used to analyse the mechanical and thermal basket behaviour under transport conditions defined in IAEA regulations. By deciding between the analysis methods, the design features (including material selection concept) as well as specific safety function should be accounted.

In approval procedures of transport packages for radioactive materials, the competent authority mechanical and thermal safety assessment is carried out in Germany by BAM. Some questions of safety evaluation of basket designs are discussed in this paper based on the BAM experience within approval procedures. The paper focuses primarily on the mechanical behaviour of baskets with regard to the assumptions that have to be used in the criticality safety demonstration. The state of the art methodologies for computational basket stress and deformation analysis as well as for interpretation of drop tests results are presented.

FUNCTION AND STRUCTURE OF BASKETS

Packages for spent fuel are designed for the transport of spent fuel assemblies from pressure water reactors (PWR), boiling water reactors (BWR), research or test nuclear reactors. By means of special equipment, for example so-called quivers or tin cans, broken fuel rods or sections of fuel rods can be transported in these casks as well. Particular constructions of baskets to support the inventory within the cask cavity are required due to multitude of designs and dimensions of spent fuel.

A basket for spent fuel assemblies usually consists of many metal sheets or plates, made of steel or aluminum. These sheets and plates are screwed or welded together and form the load-bearing structure as well as the box sections for the spent fuel assemblies or other content. For the purpose of neutron absorption particular boron alloys (so called boron-stainless-steel or boron-aluminum) are used. Additional aluminum or copper sheets are often integrated to

guarantee sufficient heat dissipation. Favorable corrosion properties due to underwater loading and radiation resistance of basket materials have to be assured.
The main function of baskets is the exact positioning of the spent fuel assemblies or other radioactive contents within the cask under routine, normal and accident conditions of transport (RCT, NCT and ACT) according to the IAEA regulations [1]. The geometric arrangement of the spent fuel assemblies is used as basis for the criticality safety evaluation. A further important function of the basket is the safe heat dissipation from the radioactive content to the cask body.
To ensure these functions mechanical and thermal requirements have to be met by the basket design. The safety demonstration can be carried out by analytical, numerical and experimental methods. The kind and complexity of the methods depend on the properties of the radioactive content and the design of the basket as well as on assumptions and safety margins in ensuing analyses (e.g. in criticality safety evaluation).

ASSESSMENT OF FUNCTIONAL CAPABILITY

The objective of the mechanical analyses under all conditions of transport according to IAEA regulations [1] is to demonstrate the structural integrity and to evaluate the possibility permanent of deformations of the basket structure. The accuracy of the determination of these kind of deformations depends on the boundary conditions considered in the criticality safety analysis (e.g. if a critical configuration of the spent fuel is excluded, a determination of permanent deformations is not essentially required for the basket).
The basket design analysis could consider the loading onto components of cask containment system (e.g. onto the lid) as well as onto additional containment system inside the cavity. The separate containment systems for damaged fuel rods or sections of fuel rods (quiver or boxes) can be referred as an example. The objective in this case could be limitation of the loading to guarantee specified leak tightness.
The thermal analyses are based on the decay heat of the radioactive content and the different ambient temperatures of the conditions of transport. The shape of the basket incl. relevant gaps and thermal properties of the structural elements are important parameters of these analyses. The maximum permissible temperatures of the cask components and the content are usually applied as verification criteria to assess sufficient heat dissipation. Furthermore the temperatures of components under different conditions of transport are derived from the appropriate thermal analysis. The strength values used in the mechanical design of the basket structure are based on these results as well. Combined mechanical-thermal analysis has to be done to define possible unacceptable thermal stresses in the basket structure.

Other questions to be addressed relate to quality assurance measures while manufacturing and operation. The appropriate requirements are given in the German guideline BAM-GGR 011 [2]. Additional analysis according to KTA 3905 [3] are necessary for the handling of baskets in German nuclear power plants. The guideline KTA 3905 exceeds the IAEA requirements [1]. The requirements according to KTA 3905 [3] are related to load attaching points and their mechanical dimensioning, as well as quality assurance while the manufacturing and periodical inspections. Tab. 1 shows the most important objectives by assessment of functional capability of the basket design.

Table 1. Assessment of functional capability

<table>
<tr><th></th><th>Objective</th><th>Criteria</th></tr>
<tr><td rowspan="4">mechanical and thermo-mechanical analysis</td><td>structural integrity</td><td>no damage of load-bearing components</td></tr>
<tr><td>permanent deformations</td><td>correlation with boundary conditions for the criticality safety analysis</td></tr>
<tr><td>gap closing</td><td>correlation with boundary conditions for the criticality safety analysis, boundary condition for thermal analysis</td></tr>
<tr><td>safe handling in nuclear power plants</td><td>compliance with requirements of KTA 3905 [3]</td></tr>
<tr><td rowspan="2">thermal analysis</td><td>safe heat dissipation</td><td>maximum permissible temperatures of the cask components and the content</td></tr>
<tr><td>determination of temperatures for dimensioning</td><td>correlation with strength values in mechanical analysis</td></tr>
<tr><td>quality assurance</td><td>quality assurance while manufacturing and operation</td><td>compliance with requirements of BAM-GGR 011 [2]</td></tr>
</table>

DEMONSTRATION OF COMPLIANCE

The demonstration of compliance with the required performance standards shall be accomplished by any of the following methods (TS-R-1 [1], para. 701):

(1) test of prototype or serial specimens,
(2) reference to satisfactory demonstration for sufficiently similar structure,
(3) tests with models of appropriate scale,
(4) analytical and numerical calculation methods.

The BAM experience in assessment of Safety Analysis Reports (SAR) shows, that a combination of these methods are usually applied. In recent years a lot of efforts were invested to enhance the calculation methods, mainly the Finite-Element-Method (FEM). But such complex numerical analysis has to be supported by drop tests, component tests, material investigations or additional analytical calculations. These attended investigations allow a reliable application of FE calculations within the entire process of design evaluation.
In addition to the development of the state-of-the-art of technology due to an expansion of modern calculation methods like the FEM, the conventional analytical calculation methods are applicable as well. The analytical approaches can be applied if the basket itself or the basket components have simple forms and sufficient safety margins can be shown by considering of conservative load assumptions.

LOAD ASSUMPTIONS

The load assumptions are based on the IAEA transport conditions according to TS-R-1 [1]. For the mechanical analysis under RCT specific values of accelerations are listed in table IV.1 in TS-G-1-1 [4] for the transport modes road, rail, sea/water and air. These acceleration values are used for the definition of inertia forces.

The load assumptions for NCT and ACT depend on cask design and have to be determined in each specific case. A common approach for the definition of inertia forces acting on the basket is based on the calculation of impact deceleration values by analytical methods [5]. As long as the structural calculations of the basket are performed by quasi-static methods, dynamical effects have to be considered as well, e.g. multiple-mass effect [6]. Dynamical effects are often relevant for the dimensioning of complex and multi-part basket constructions. These loads are captured by drop tests with prototypes or scaled models or by appropriate investigations of components.

For the handling of spent fuel in German nuclear power plants the dimensioning of load attachment points has to consider the load assumptions in KTA 3905 [3]. The load assumptions for the thermal calculations are based on the decay heat of the radioactive content and the regulatory given values for ambient temperature according to TS-R-1 [1].

- RCT: -40°C up to 38°C (70°C)
- NCT: -40°C up to 38°C (70°C)
- ACT: 800°C, 30 minutes
- ACT: 800°C, 60 minutes for Typ C package

The thermal analysis gives information about possible gap closing and load results through thermal expansion in the basket construction. The associated load-distribution, the thermal stress and changes of material properties are important boundary conditions for the entire mechanical analysis.

EXPERIMENTAL INVESTIGATIONS

As described above experimental investigations are meaning in the global concept of safety evaluation strategy. There are three categories of experimental investigations:

- test of prototypes or models with an appropriate scale factor
- component tests
- material tests

Experimental investigations of prototypes or models are carried out to support calculated results or simplified analytical approaches. The results of the tests supply knowledge about dynamic properties of the basket structure. Furthermore it is possible to detect gap closing or permanent deformations and to obtain data the verification of the assumptions in the ensuing analysis.

Component tests are mainly carried out for investigations of specific components of the basket structure. Stability analysis and strength testing of separate box sections are examples

for this approach. These kinds of component tests reduce costs and is often the only possibility measuring strains (by strain gauges) or accelerations (by accelerometers).
Material testing is carried out to get appropriate values of material properties for the analysis. The investigations could include the identification of static and dynamic strength values but also the material resistance under the relevant radiation level.

MECHANICAL ANALYSES

Mechanical analyses are

- analysis of the structural integrity for load-bearing elements
  (stress or limit analysis, brittle fracture),
- stability analysis and
- deformation analysis.

The analyses have to consider the combination of conditions of transport according to TS-R-1 [1]. This means that the damage or permanent deformation and incl. closing of gaps under RCT and NCT must be taken into account for ACT.
The above mentioned analyses with specific modeling, material and loading assumptions have to be carried out separately. However, the complete assessment result could only get by a combination of these analyses. For example the deformation analysis postulates a sufficient load-bearing capacity of basket structure.

Stability analysis

The basket design made up often as a slender (sheet) structures, therefore stability analysis has to be performed. The buckling loads for simple structure elements can be found by analytical approaches. Complex structures are often calculated by Finite Element Analysis (FEA). The FEA include stability analysis on a model with no imperfections in order to estimate critical buckling loads or to determine the imperfections for non-linear buckling analysis. In the next step the non-linear buckling analysis is carried out on a geometrical imperfect model. The imperfect forms and amplitudes can be taken e.g. out of the German standard DIN 18800 [7]. For load assumptions the weight of the content and basket as well as the thermal-mechanical loads are used.

Stress and limit analyses (analysis of load-bearing capacity)

If the materials of load-bearing structure of basket show sufficient ductility, the demonstration of structural integrity can be carried out in dependence on appropriate standards like KTA 3201.02 [8] or DIN 18800 [7].
In the safety concept of KTA 3201.2 [8] different loading levels and respective assessment criteria are determined. The stress intensity factor S_m is used as the basis for the stress limitation in linear elastic stress analysis and for definition of fictitious yield stress in case of limit analyses. The S_m value has to be obtained from strength properties of materials and service temperatures of components.

The assessment criteria defined in KTA 3201.2 [8] can be adopted for the evaluation of structure integrity of basket in following manner:

For RCT it should be demonstrated by means of linear elastic stress analysis that no plastic deformations occur in the structural elements of basket under correspondent mechanical and thermal loading. If this condition is not met, the possible progressive deformations have to be additionally analyzed.

Since the level of mechanical loadings under NCT and ACT is in general too high for a linear stress analysis, the demonstration of structural integrity can be carried out by limit analyses. The fictitious yield stress for ideally elastic-plastic behaviour of the material and safety factors concerning the lower bound collapse loads are different for NCT and ACT.

Deformation analysis

The geometric boundary conditions in the criticality safety analysis base on the possible permanent deformation of the basket structure. Analytical approaches but also complex FEA can be applied. Analysis results can be the approach of single box section to each other or to the geometric centre of the entire construction.
Another important result is the permanent deformation of single sheets or plates. If the analysis is carried out by FEA, different material properties (ideally elastic-plastic model or real flow curve) and their influence can be investigated. A conservative approximation will be achieved with an ideally elastic-plastic model considering the yield stress of the material.
The investigation of possible gap closing of the basket structure under specific loading situations is an additional objective of the analysis Shell elements are usually applied for modeling of slim and slender basket constructions in FEA. Attention should be paid to correct definition of parameters of contact pairs and boundary conditions. It should be noted that imperfections based upon fabrication tolerances are an influencing parameter for FE calculations. The German standard DIN 18800 [7] provide a couple of examples for such kinfd of imperfections and the approaches for the analysis.
A reasonable criteria or parameters have to be defined for comparison between results of deformation analysis and geometric assumption in criticality safety analysis. An example for such a parameters is the radial approach for all box sections to the centre of the basket. In this case the maximum computed value of the approach can be conservatively considered for all construction.
For the structural elements having simple cross section the deformation analyses especially for vertical drop orientation can be carried out by analytical calculations. The calculations under consideration of axial inertia loads are usually based on principle of energy conservation.

CONCLUSION

In approval procedures of packages for the transport of radioactive material, the competent authority mechanical and thermal safety assessment is carried out in Germany by BAM. Some questions of safety evaluation of basket designs are discussed in this paper based on the BAM experience during several approval procedures. The paper focuses primarily on the mechanical behaviour of baskets with regard to the assumptions that have to be used in the criticality safety demonstration. The state-of-the-art methodology for computational basket stress and deformation analysis is presented.

REFERENCES

[1] International Atomic Energy Agency (IAEA).Regulations for the Safe Transport of Radioactive Material, 2009 Edition. Safety Standard Series No. TS-R-1, Vienna, 2009 .

[2] BAM-GGR 011: Maßnahmen zur Qualitätssicherung von Verpackungen zulassungspflichtiger Bauarten für Versandstücke zur Beförderung radioaktiver Stoffe. Rev.0 vom 25.06.2010.

[3] KTA 3905 (6/99) (incl. rectification of 7/00) Load Attaching Points on Loads in Nuclear Power Plants, (Lastanschlagpunkte an Lasten in Kernkraftwerken).

[4] International Atomic Energy Agency (IAEA). Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material. Safety Standard Series No. TS-G-1.1, Rev.1, Vienna, 2008.

[5] M. Neumann; F. Wille; V. Ballheimer: Approximation of package deceleration and shock absorber deformation under 9m drop test conditions using simplified numerical tool ImpactCalc in Packaging, Transport, Storage & Security of Radioactive Material, 2008 Vol 19.

[6] V. Ballheimer, T. Quercetti, P. Zeisler Effect and Consequences of Interactions between Containment Components and Content of Typ B Packages during 9 m Drop Tests. RAMTRANS, Vol. 130, No.3-4, pp. 305-312 (2002).

[7] DIN 18000 Stahlbauten - Teil 1: Bemessung und Konstruktion, Ausgabe 2008-11.

[8] KTA 3201.2 (06/96) (incl. rectification from BAnz 129, 13.07.00). Components of the Reactor Coolant Pressure Boundary Components of the Reactor Coolant Pressure Boundary Components of the Reactor Coolant Pressure Boundary.