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STATE-OF-THE-ART ASSESSMENT OF PACKAGE DESIGN SAFETY ANALYSES

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ABSTRACT

The Federal Institute for Materials Research and Testing (BAM) is one of the two German competent authorities responsible for the Safety Analysis Report (SAR) assessment in conformity to the IAEA Regulations for the Safe Transport of Radioactive Material (TS-R-1) [2] with respect to the mechanical and thermal safety analysis, the safe containment of the radioactive material and the quality assurance program during manufacturing, operation and maintenance.

The methodology in the field of safety analysis including associated assessment criteria and procedures has evolved rapidly since implementing the new regulations [2]. New aspects relating to analysis and assessment methodologies are summarized in this paper.

All relevant chemical, physical and technical properties of the materials used are assessed in detail in relation to clear and comprehensible documentation with respect to the qualification.

BAM requires without exception, clear and detailed descriptions of the concepts and the aims for the primary mechanical and thermal demonstrations. The consequences of the safety concept choice on the package design safety analysis must be clear at the beginning of the type testing. The concept significantly influences the depth of an experimental or calculation proof. All relevant boundary conditions with respect to TS-R-1 [2] must be taken into account, e.g. the assessment of stresses, strains and fracture mechanical considerations from -40°C until maximum operational and thermal accident temperature.

In the containment analysis, BAM requires detailed and comprehensive qualification of seals as well as a calculation of an activity release based on well specified release values, depending on the radioactive contents.

Concerning quality assurance, a fully aligned program for manufacturing, assembling, operation and maintenance is necessary to get the compliance control with the SAR before starting any manufacturing process.

INTRODUCTION

The Federal Institute for Materials Research and Testing (BAM) is the nominated German authority responsible for

- Mechanical and thermal type design testing of approved packages for the transport of radioactive material,
- Mechanical and thermal assessment regarding validation of foreign approval certificates,

- Testing and approval of special form radioactive material,
- Testing of low dispersible radioactive material (in cooperation with BfS).

These tasks are assigned to the BAM by the legislator [1] and the German Ministry of Transport, Building and Urban Affairs [7]. The BAM's working brief associated with this, contain the assessment

- of the mechanical design,
- of the thermal design,
- of the containment design of the radioactive content,
- of the geometry and material input conditions for the design of the radiation shielding,
- of the geometry and material input conditions for the design of the criticality safety and
- of the quality surveillance programs and quality assurance systems for the development, the manufacturing, the use and the maintenance [12].

The BAM devision "Safety of Transport Containers" executes the above assessments on the basis of the recommendations of the International Atomic Energy Agency (IAEA) [2] and the appropriate conversions in national [7-10] and international [3-6] regulations for the transport of radioactive material. All BAM tasks are performed in close cooperation with the official German competent authority, the Federal Office for Radiation Protection (BfS).

All packagings manufactured after 31 December 2006 must fully meet the present regulations [3-10] on the basis of the recent IAEA regulations [2].

Compared to the edition 1985 (as amended 1990) of the IAEA recommendations, there are not any essential new technical demands (regarding to the parts of assessment of BAM) in the recent regulations [2]. Nevertheless, the BAM increased the demands on the methods of safety analysis and the depth of assessment in recent years. The reason for this procedure is the higher utilization of the proposed package designs due to cost reductions and the particular specifications of customers. Increasingly higher masses, higher heat inventories, higher activities and/or higher burn-ups of fuel elements need to be considered. Associated with this is often a reduction in previous safety margins in the package design concepts or the need to introduce new optimized impact limiter designs.

The validity of approval certificates for package design was previously restricted to 3 years according German regulations. With appearance of the new edition of the national guideline R003 [11] at the end of 2004, other durations of validity of approval certificates are, however, possible.

Now it is (for special exceptions) possible for package designs and the appropriate approval certificates which are updated from the old to the current regulations [3-10] to get a 10 year approval certificate. The hereby associated requirement is an exclusion of a further manufacturing of the particular package design. For example, this procedure can be used for package designs whose casks stand loaded in an interim storage site and a new manufacturing is impossible. Depending on the cask design, particular time intervals of maintenance and updating of the SAR are determined.

For the assessment of the safety analyses, the BAM builds on the legal regulations and, according to [2] para. 638, takes internal and external guidelines, applicable national and international standards or expert reports into account, as long as they serve the used assessment method in accordance with best practice.

The increase of the requirements for the safety analysis concepts and the depth of assessment, makes the continuous development of the technologies and related testing necessary. The following paragraphs outline relevant aspects of BAM assessment issues with regards to the package design approval process in relation to current technology.

A comprehensive representation of all items can not be given here, due to the fact that the package designs, the individual constructions and application profiles differ widely.

ASSESSMENT OF THE MECHANICAL DESIGN

The BAM requires from the applicant to present conclusive proof concepts for the safety analyses illustrating mechanical resistance in routine, normal and accident transport conditions [2]. This could mean the selection of relevant drop test positions with defined goals for individual drop test sequences based on precalculated outcomes, the comprehensive and reasonable instrumentation and measurement program for a drop test model with suitable measuring processing, the verification of suitable numerical Finite Element models up to the final comprehensive evaluation of the original package design behaviour by specified evaluation criteria.

With regard to the accident transport conditions it is typically necessary to consider for Type B(U) approvals the temperature range of -40°C until operating temperature [2]. This is used for both the evaluation of local loads, e.g. with regard to plastic deformations at operating temperature or local stresses under the lowest temperature at -40°C in regard to fracture mechanical behaviour. Appropriate evaluation criteria have to be defined depending on the materials used. For example if ductile cast iron is used, BAM expects the correct application of the guideline BAM-GGR007 [15].

Possible welding seams in the cask design are areas of the construction which need intensive considerations. The brittle fracture analyses on basis of a detailed calculation by finite element model could be necessary.

Not in every case it is possible to obtain appropriate values for material properties from literature. If non-standard materials are used experimental investigations for identification of mechanical properties (e.g. yield stress, fracture toughness etc.) are essential for a complete mechanical evaluation concept. These materials need to be qualified sufficiently. For example, the characteristics of boron-treated materials and the effects on the material properties, e.g. on the ultimate strain, have to be shown.

It is also important for all considerations (material investigations and/or calculations of loads) to correctly identify the existing dynamic loading rate due to the IAEA test conditions (9m drop, 1m puncture bar drop test).

For the analyses of the lid system including both bolted fastening and trunnions a new BAM guideline for lid and trunnion systems [16] was developed.

The safety analysis of the basket structure with regard to the definition of the geometrical input conditions for the criticality analysis is to be carried out depending on the complexity of the individual construction with an analytical approach, numerical models or experimental testing. BAM attaches importance to a sufficient verification of the models used in connection with sensitivity analysis. The chosen approaches need to be justified.

Some packages require additional equipment components during transport, e.g. a transport frame. There are cases in which the equipment should be considered as part of the package and be included in the safety demonstration for the package. In every case all the safety functions of these parts have to be identified and shown in the safety assessment [20].

If for example transhipping is only possible utilising the transport frame then an additional consideration of the transport frame and the effects on the safety of the package under the IAEA test conditions could be necessary.

DROP TESTS AND COMPONENT TESTS

In general for new construction principles of package design the implementation of experimental tests in the approval process, for example of drop tests concerning the IAEA test conditions under normal and accident transport conditions, is necessary. Additionally, component tests could be important depending on the safety analyses concept. For example, such an additional component test could enable an evaluation of the impact limiter behaviour in the whole temperature range.

Whether and to what extent drop tests are necessary, depends on the individual construction of the packaging, the materials used and implemented and identified safety margins in the package design. The procedure needs to be sufficiently justified by the applicant in the safety analyses concept.

According to IAEA regulations [2] the possibility exists for using reduced-scale models. If the drop tests with such models are carried out, attention needs to be paid to following fundamental points:

- Guarantee of the transferability of the test results of the reduced-scale model to the original design (geometry and loads, materials, lid system, leak tightness, seal behaviour etc.)
- IAEA consistent realization of the drop tests under observation of the special properties of scale models, for example taking into account drop height corrections [17].

NUMERICAL CALCULATIONS

Numerical calculations by means of the finite element method are currently part of safety analyses concepts of different package design approvals in Germany. The calculations can be carried out according to the particular loading situation (strain rate dependant) statically or dynamically.

Detailed finite element analyses may be necessary to:

- justify a drop test program outline
- transfer drop test results with a scale model to the original package, for example with design modifications or changed material properties,
- calculate local stresses and strains that are inaccessible for a direct measurement as for example of notches or areas within the cask body wall,
- analyse drop test scenarios at other boundary conditions that are different to the test conditions. For example at a temperature of -40°C or at maximum operating temperature.

The verification of the numerical calculations is essential. Depending on the influence to the safety of the package the individual components of the numerical model need a partial verification, e.g. impact limiter, basket for the fuel elements etc.

BAM has defined basic conditions for the preparation, checking and evaluation of numerical calculations in SAR in a guideline [13] mainly to assure the correct performance of numerical simulations according to the state-of-the-art and to optimise and to clarify the examination of these reports.

The SAR itself has to fulfil formal requirements (layout) and must include all data essential for the understanding and checking of the modelling (completeness) and the discussion of the results. This includes the documentation of the software and input data used. The modelling (simplification of the technical problem, discretization, element types, material data, initial and boundary conditions, loads etc.) must be discussed in detail.

Essential are also presentation (data processing, graphic and tabular presentation) and evaluation (checks, precision and discussion) of the results [18].

MATERIAL QUALIFICATION

Within the package design assessment all materials used, need to be qualified with regard to the relevant mechanical, thermal and chemical properties for the design and the manufacturing process. For the manufacturing process BAM requires for each safety relevant component a sheet for the specification of the material (e.g. mechanical and thermal properties) and a sheet of testing to meet these properties during manufacturing.

The proofs of the properties can occur either through references or through reports of the applicant to their own qualification procedures. The property values of standard materials can be justified on basis by references.
But if the material or the manufacturing/assembling process used is not standard or if the IAEA conditions exceed the boundary conditions which are defined in standards (e.g. operating temperature) then additional material investigations and/or a comprehensive qualification procedures are necessary. The BAM cooperates closely with the TÜV Rheinland Group to ensure appropriate material and manufacture qualification processes and their correct practical realization as well as over matters of quality assurance.

ASSESSMENT OF THE THERMAL DESIGN

BAM is faced with the situation to evaluate the thermal design at increasingly higher heat inventories coupled with higher temperatures. This results in a higher utilization of materials combined with reduced safety margins. It also leads to critical consequences in the design analysis for both the calculation approaches and for the evaluation of material behaviour. Therefore, generally a more precise thermal test analysis on the basis of complex Finite Element models with detailed illustration of the thermal sources becomes necessary.
By inclusion of concrete canopies designed for the transport operation, the thermal analysis outside of the package can include estimates of circumferential effects on the horizontal package position.
Increased heat inventories need extended qualification steps for high temperatures such as materials like polyethylene and resins which are used for the shielding.

ASSESSMENT OF THE CONTAINMENT SYSTEM AND ACTIVITY REALAESE

The proof of the containment system (closure system, seals etc.) under the relevant IAEA tranport conditions can be carried out by drop tests or by separate additional experiments on the mechanical design of the lid system.
The use of experimental tests on full-scale or reduced-scale models or by component tests has to illustrate the ability of the containment system to meet the leakage-rate-criterion under deformation or axial or radial movement of the lid. Concerning this matter BAM developed quality assurance and assessment criteria. The criteria include the qualification of the manufacturer, the fabrication of test seals, a full qualification program for the mechanical, thermal and long-term behaviour of the seals, quality assurance during fabrication of original seals, arrangements after assembling and after loading the cask as well as recurrent inspections of the seals and sealing surfaces during their usual operation.
The regulations, e.g. TS-R-1 [2], specify the different transport scenarios, termed as routine, normal and accident conditions of transport, and define limits for the loss of radioactive content (e.g. in §657 [2]) under these transport conditions. BAM has to check the loadings to the containment system which result from the defined transport conditions in the safety proofs. Additionally, the applicant has to consider the conditions during loading and unloading of the cask. According to the German guideline for quality assurance and quality control of packagings for transport of radioactive materials (TRV 006 [12]) components of the containment are classified in the highest level – No. 1. This means that for these components a comprehensive quality assurance and quality control is required which has to be developed under supervision of BAM for design, manufacturing, documentation and operation.
Before a metallic or elastomeric seal can be used in series casks BAM has to qualify the manufacturing process regarding stability and the compliance of specific design values of the seals which are derived from experimental tests, by component tests or from practical investigations with loading and unloading conditions of the cask.

INPUT CONDITIONS FOR THE SHIELDING DESIGN

In Germany the BfS is responsible for the assessment of the design of radiation shielding within the SAR. However, BAM checks the necessary analyses for stability of all materials, relevant for the shielding design under the given boundary conditions (pressure, temperature, cyclical loading, long-term behaviour).

With regards to this increasing attention in the future will be placed upon the long-term stability. For example effects such as degassing caused by radiation will be of interest.

INPUT CONDITIONS FOR THE DESIGN OF THE CRITICALITY SAFETY

The BfS is responsible for the assessment of the criticality safety too. However, the geometrical input conditions for the analysis are examined by BAM. For this Finite Element calculations for the simulation of the basket and inventory behaviour are generally used. The BAM has to evaluate the calculated deformations and loads including the considered real material behaviour under the given IAEA transport loading conditions.

With regard to higher burnups of the fuel elements to be transported the requirements of the numerical models used are increased to realistically account for the fuel element and basket behaviour. In order to better understand the behaviour of the fuel elements under mechanical loadings, there are various research activities (e.g. in Germany BMU-GRS research project "Experimental investigations of the behaviour of high-burnup fuel rods under mechanical accident loads") in which the BAM is involved.

QUALITY MANAGEMENT SYSTEMS; QUALITY ASSURANCE

Within the type testing of tranport packages for radioactive material the quality assurance system is examined by BAM. Here the quality assurance and a combined fully aligned program for manufacturing, assembling, operation and maintenance are important.

The system of quality assurance is based on the liability of the approval holders and manufacturers themselves, and is supplemented by a comprehensive official monitoring.

The surveillance of the quality assurance in the manufacture of the packaging is BAM's responsibility. The basis of this process is the German guideline TRV 006 [12]. It defines requirements for production and testing to ensure that the series sample conforms to the approved design. The main steps of the official supervision are:

- Examination of the manufacturer's qualification including his sub-suppliers,
- Qualification of materials and specific fabrication processes,
- Examination of the specific quality assurance program adapted to the scope of production,
- Approval of master documents like specifications and manufacturing and test plans,
- Technical inspections during the manufacturing of components and final inspections before commissioning,
- Assessment of non-conformities,
- Final check of the documentation for correctness and completeness and issuing an acceptance certificate for the packaging.

As consulted experts of BAM, employees of TÜV Rheinland Industrial Service are entrusted to perform to a great extent the official surveillance. Details of the surveillance system as well as examples and experience with a multiplicity of suppliers and several hundred manufactured casks will be presented in [19].

CONCLUSIONS

BAM checks the mechanical and thermal safety analysis, the safe containment of the radioactive material and the quality assurance program during manufacturing, operation and maintenance.

The state-of-the-art approach in the field of safety analysis including associated assessment criteria and procedures has been developed rapidly in recent years. BAM quantifies the value of drop tests for licensing procedures of new package designs. BAM has extensive experiences with drop test programs. The mechanical safety analysis concepts in SAR often include numerical Finite Element analyses. For the acceptance of such kinds of calculations BAM requires good qualifications of the CAE engineers of the applicant, the modelling and the discussion of the results and the documentation of the input data (material data etc.).
In the field of general requirements the function of impact limiters, of canopies and of transport frames has been introduced or increased in the assessment. All relevant chemical, physical and technical properties of the materials are assessed in detail on the basis of a comprehensible and clear documentation of the sources with respect to the qualification.
BAM expects in every case the clear and detailed description of the evaluation concepts and requires that the most important mechanical and thermal aspects are clearly demonstrated. The consequences of the safety concept choice on the package design safety analysis must be clear at the beginning of the assessment. The concept influences significantly the depth of an experimental or calculation proof.
All relevant boundary conditions with respect to TS-R-1 [2] must be taken into account, e.g. the assessment of stresses and brittle fracture analysis from -40°C through to maximum operational and thermal accident temperature.
In the containment analysis BAM requires detailed and comprehensive qualification of seals as well as a calculation of an activity release based on well specified release values depending on the radioactive contents.
Concerning quality assurance, a fully aligned program for manufacturing, assembling, operation and maintenance is necessary to get the compliance control with the SAR before starting any manufacturing process.

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