MECHANICAL/THERMAL PACKAGE DESIGN SAFETY ASSESSMENT AND MANUFACTURING QUALITY ASSURANCE OF SPENT FUEL TRANSPORT CASK NCS 45

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ABSTRACT

The NCS 45 package is designed for a variety of radioactive contents ranging from irradiated PWR, BWR and FBR fuel rods, parts of fuel rods as well as non-fissile radioactive material. BAM assessed the applicants safety analysis concept and the appropriate report with respect of requirements according to transport regulations under routine, normal and accident transport conditions related to mechanical design and thermal design, activity release and quality assurance aspects.

The assesment concept of the safety report was a combination of drop test program, analytic and numerical calculations as well as various components tests. The paper will give details of BAM activities in the official safety assessment that had been summarized in the BAM design examination certificate which was a prerequisite for the Package Design Approval Certificate issued by the German competent authority.

INTRODUCTION

The Federal Institute for Materials Research and Testing (BAM) is the responsible German authority for the design assessment with respect to mechanical and thermal testing, activity release, material qualification and all aspects of transport packeges for radioactive materials.

The quality management system for manufacture and operation of the package NCS 45 is approved by BAM. BAM checks applicants proof in their safety analysis reports and assesses the conformity to the applicable legal regulations based on the Regulations for the Safe Transport of Radioactive Materials (TS-R-1) [1].

BAM assessed the applicants safety analysis concept and the appropriate report for NCS 45 with respect of requirements according to transport regulations under routine, normal and accident transport conditions related to mechanical design and thermal design, activity release and quality assurance aspects.

The applicant included a drop test program as part of the mechanical safety evaluation concept. BAM performed the drop test program finished in an appropriate test documentation. The applicant used experimental drop test results for verification of analytical and numerical calculations as part of the safety analysis report. Overall 19 drop tests with a small scale model (1:3) were performed.

Concerning further verification of the analysis of several components of the packaging, the following accompanying investigations contracted by the applicant were carried out:

- Investigation and evaluation of the energy absorbing capacity of wood as part of the impact limiting devices,
- Behavior of the special steel material NITRONIC 50HS for the bolts used under the aspect of long term behavior,
- Investigation and evaluation of thermal conductivity of the thermal insulation.

The applicant confirmed the regulatory requirements concerning thermal package design aspects under routine, normal and accident transport conditions with numerical calculations carried out with an appropriate validated software. The correct modeling and approach for the material behavior of the thermal insulation was assessed in a material qualification procedure. BAM assessed applicants analysis by independent numerical finite element model and evaluation by means of the commercial software ANSYS [2].

Leakage rates measured after drop tests were taken into account to determine the leakage rates for the appropriate transport conditions fulfilling regulatory requirements. The function of the sealing barriers of the scale model was analyzed during drop tests by means of leak tightness tests before and after every drop test.

After the design approval the first serial cask was manufactured according to a quality assurance program accepted by BAM. This presentation will finish with details from manufacturing and competent authority controls of that process.

DESIGN OF NCS 45 PACKAGING

The NCS 45 package is designed for a variety of radioactive contents ranging from irradiated PWR, BWR and FBR fuel rods, parts of fuel rods as well as non-fissile radioactive material. The cask body is made of a sandwich construction stainless steel-lead layer stainless steel. The package has a total mass of 22 660 kg. Designer, manufacturer and approval holder of the NCS45 is Nuclear Cargo + Service GmbH (NCS) a German company belonging to the DAHER group. For details see also in [3].

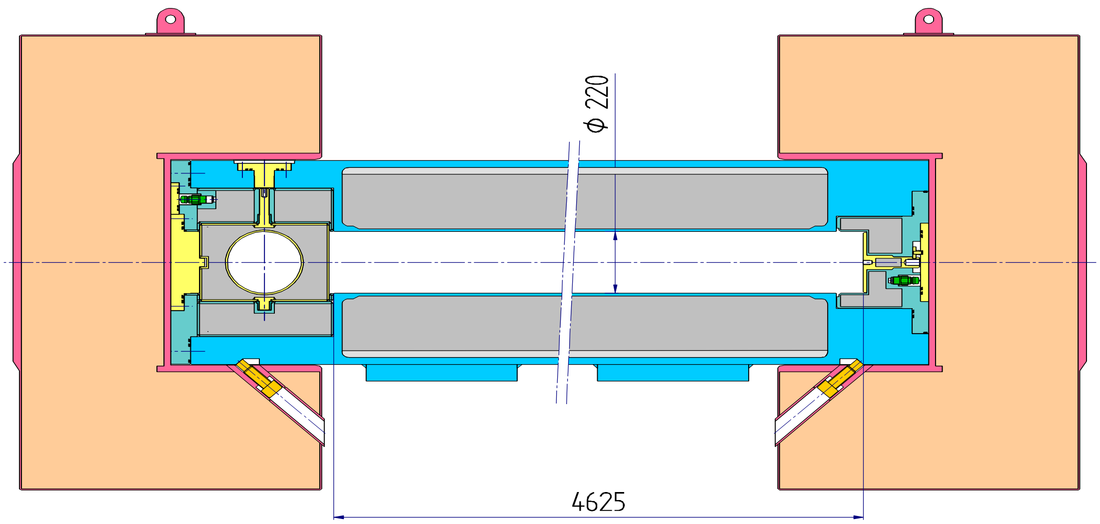

Fig. 1 Design of the NCS 45 Packaging (courtesy NCS)

The cask design Transport cask NCS 45 (shown in Fig.1) consists of the following design subgroups:

- Cask main body,
- Lid plug (incl. lid of the rotary lock, lid of the coupling, rotary lock drive lid),
- Bottom plug (incl. discharge plug lid)
- Trunnions,
- Impact limiters and
- Interior components.

All lids and plugs have double O-Ring EPDM gaskets. Cylindrical impact limiters are placed over the lid and bottom ends of the cask. They surround the front sides and parts of the mantle surface. The shock absorbers consist of a welded metal sheet casing, reinforced on the inside and filled with balsa and spruce wood.

Design NCS 45 has four trunnions to assure handling of the cask. These are attached in pairs, at the lid and bottom end, to the trunnion base plates, each by means of 12 screws, with a transition fit. Package NCS 45 is used to transport uranium oxide fuel rods, fuel rod segments, pellets and pellet debris, which must be transported in different baskets, due to their geometrical dimensions, physical forms and burn-ups. Currently comprised the approval of NCS 45 five several versions.

ANALYSIS CONCEPT

The applicant has carried out the safety proofs by means of experimental testing, analytical and numerical calculation procedures, as well as based on the following standards:

AD 2000 [4], VDI 2230 [5], DIN 18800-2 [6] and FKM 2003 [7].

Furthermore BAM carried out a drop test program, which is documented in the test report. The aim of the drop test program was to verify analytically or numerically single proofs.

A total of 19 drop tests with a 1:3 model of the NCS 45 cask were carried out, from which three of these tests were repetitions.
The global analysis concept is shown in Fig. 2.

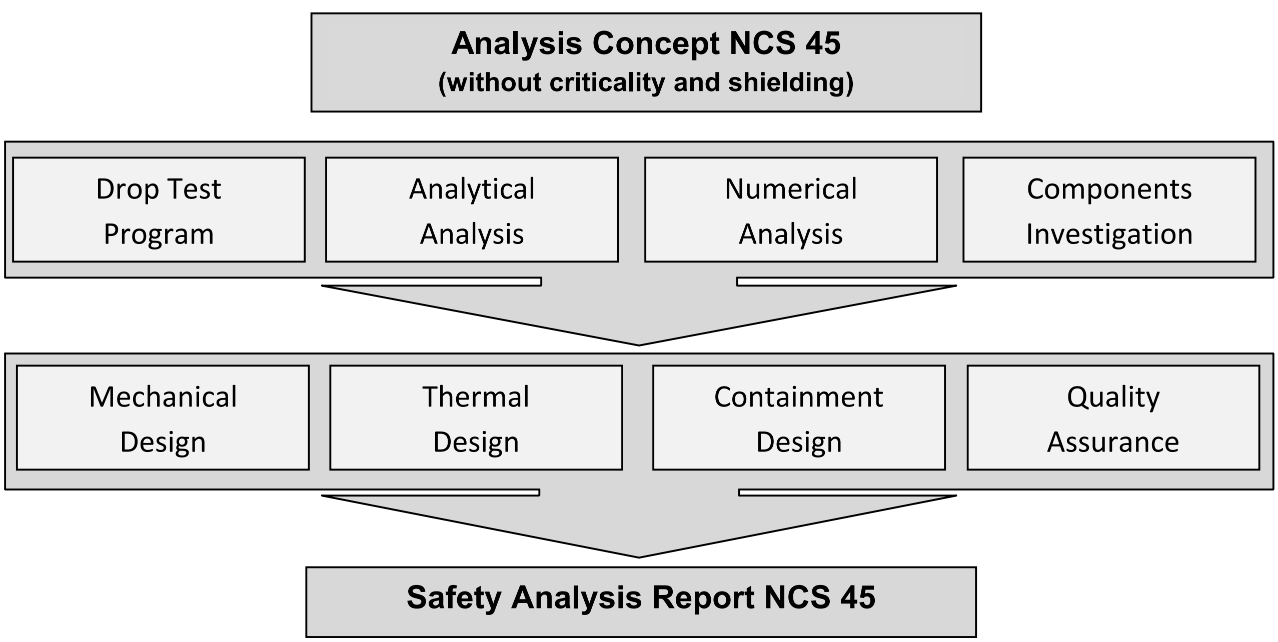

Fig. 2 Analysis concept NCS 45

The accompanying investigations, mentioned in the introduction were an important part of the safety analysis. BAM checked the integration and suitability of the test results in the corresponding proofs of the single components.

DROP TEST PROGRAM

The analytical and numerical safety proofs presented by the applicant for the mechanical tests under the accidental transport conditions required according to [1] No. 727, were primarily verified through the results of drop tests with a 1:3 scale model.

When transferring the results of small-scale model tests to the design model NCS 45, the laws of similarity mechanics were taken into account. The integration of the results of these investigations in the safety analysis report has to be supported and completed by additional calculations to analyse package behavior under other safety relevant conditions as by the drop test

Drop No.	Height	Orientation	Investigation objectives
1	0.3 m	Vertical (impact on front surface, lid end)	1,2,3,4,5,6,8
3	9 m	Vertical (impact on front surface, lid end)	1,2,3,4,5,6,7
11	1 m	1 m drop onto a bar, 86° angle (impact on rotary lock lid)	6,7,10
9	9.3 m	Vertical (impact on front surface, bottom end)	1,2,3,4,5,6,7
17	1.0 m	1 m drop onto the bar, 90° angle (impact on discharge plug lid)	6,7,10
1	0.3 m	Vertical (impact on front surface, lid end)	1,2,3,4,5,6,8
7	9 m	Drop on the edge of the lid, 80° angle	1,2,3,4,5,6,7
15	1.2 m	1.2 m drop onto a bar, 80° angle (impact on discharge plug lid)	6,7,10
8	9.3 m	Drop onto the bottom edge, 84° angle	1,2,3,4,5,6,7
16	1.22 m	1.22 m drop onto a bar, 84° angle (impact on cask edge)	6,7,10
5	9.3 m	Drop onto mantle surface line	1,2,3,7,9,12,13
13	1 m	1 m drop onto a bar, 30° angle (impact on cask mantle)	9,11,12
2	0.3 m	Drop onto mantle surface line	1,2,3,6
6	9 m	Slap-down, 20° angle	1,2,3,6,7,9, 12,13
14	1 m	length of the bar was 1940 mm, stripping off lid shock absorber	2
8	9.3 m	Drop onto the bottom edge, 74° angle	1,2,3,4,5,6,7
16	1.3 m	1.3 m drop onto a bar, 74° impact on cask edge	6,7,10
10	9.3 m	Vertical (impact on front surface, lid end) at 96 °C	1,7,11,12
11	1.3 m	1.3 m drop onto a bar, 86° angle (Repeated test from sequence 1)	10

Objectives of investigation

1	Deformation of shock absorbers	3	Rigid body deceleration cask	5	Rigid body deceleration lid
2	Functionality of shock absorber fastening	4	Rigid body deceleration contents	6	Load on lid screws
7	Containment leakage	9	Load on cask body (DMS)	11	Form and position of lead shielding
8	Shock absorber leak rate	10	Puncture protection against bar in shock abs.	12	Form and position of thermal insulation
13	Form and geometry of contents				

Table 1 Drop Test Program with 1-3 model of NCS 45 package

For the drop tests one test sample was used. Parts which were damaged during the drop tests were replaced (e. g. impact limiter) or repaired (e.g. the load dummy). The program and the investigation objectives are shown in Table 1.

The test sample represents all essential characteristics of the NCS 45 design. Outer and inner dimensions were scaled down accurately. Plates and bolts were scaled down accurately as well wherever possible. If certain dimensions were not available, a conservative approach was taken. In total, 19 drop tests in 8 sequences were carried out. The results of the drop tests can be transferred to the original scale with sufficient precision, especially concerning integrity and sealing function.

The test aims and conditions of the drop tests (configuration of containment, model orientation, measuring points, length of the puncture bar, etc.) were defined in a test program of the applicant, which was approved by BAM.

The drop tests were conducted with continuous monitoring of strains and accelerations at appropriate locations on the cask body, lids and lid bolts to get the impact responses of the specimens. The leak tightness of the containment system was usually determined with a tracer gas method. For this procedure a Helium leak detector was used.

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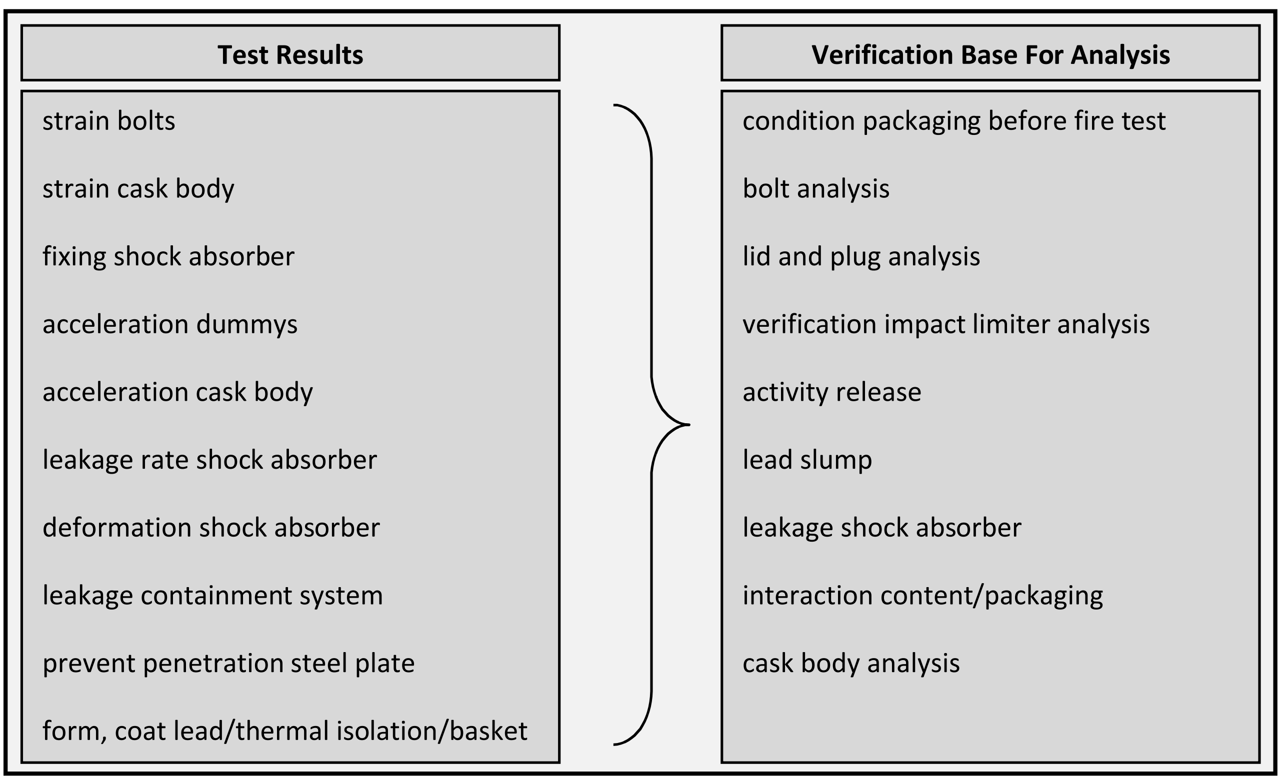

Fig. 3 Test results and verification base of drop test program

After each drop test sequence measurements and inspections of the test specimen were carried out. Measured dimensions were the deformation of the impact limiter, deflection of the lids and plugs, as well as deformation of the cask body and the basket

After the completion of the drop test program the cask body and the impact limiter was cut across the longitudinal axis to allow visual and dimensional control of the lead shielding and the wood compression. The implementations of the test results of drop tests in the proofs concerning the single components of assembly are shown in Fig.3.

MECHANICAL AND THERMAL ASSESMENT

Impact Limiter

The NCS 45 package has two impact limiter filled with balsa and spruce wood, one at each end. The function of shock absorber is the reduction of loads to the package components under test conditions according to [1] Paragraph 722 and 727.

The design calculations of the impact limiter carried out by the applicant for drop test I according to [1] Paragraph 727 with analytical calculation. There are based on the law of conservation of energy. The kinetic energy of the cask is completely absorbed by the deformation energy of the wood filling. The applicant verified this calculating algorithm by means of drop tests. To verify the relevant wood characteristics (specific deformation energy, stress-upsetting-relation), the applicant used static and dynamic compression tests performed by BAM on cylindrical wood samples.

The analytic calculations are carried out in two steps.

1.) Assuming that the specific deformation energy remains constant are during the deformation of the impact limiter determined the deformed volume of the shock absorber and evaluated against the penetration of the cask. } verification against penetration

$$E_{Kin} \leq E_{spruce/balsa}$$

2.) Multiplication of the shock absorber inter-sections of different wood areas with the yield stress of wood. } calculation decelerations

$$a = \frac{\sigma_F}{m} A$$

The correct mathematical application of this method was checked by BAM with independent calculation tools.

Because of dynamic effects during the beginning of deformation very large deceleration occurred. The applicant took these structural material characteristics into account by subdividing the assessment in beginning and plateau of the deceleration. The derivation of the material characteristics are based on drop test results and the accompanied material investigation.

In Fig. 4 shows an example for the analysis for the vertical drops. For the impact two deformation mechanisms of the impact limiter were taken into account:

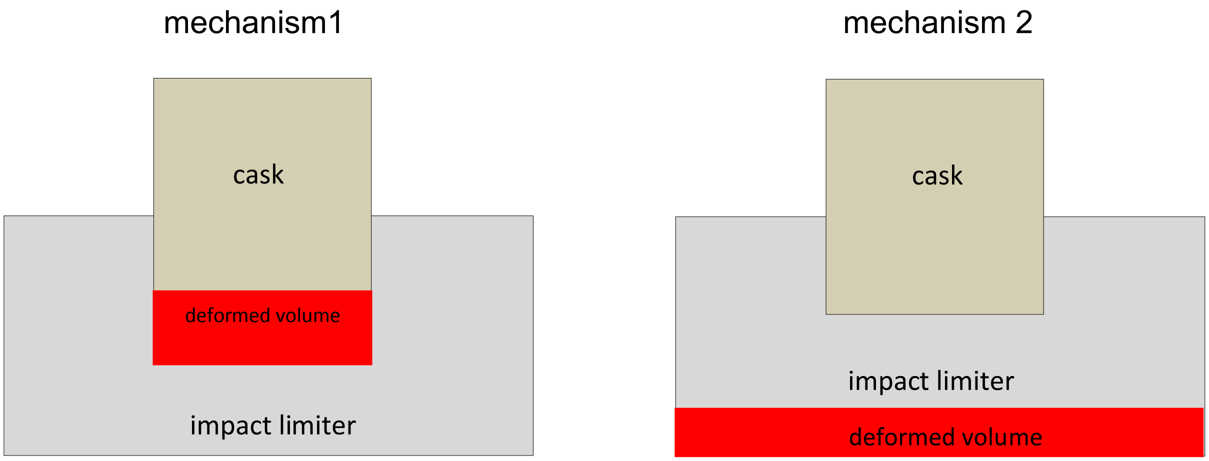

Fig. 4 Deformation mechanisms for vertical impact drops

Mechanism 1

it is assumed for the proof that the interior shell of impact limiter remains rigidly connected to the cask body and plunges together with the latter into the impact limiter.

Mechanism 2

for the second proof it is assumed that the deformation occurs on the front surface of the shock absorber, and that furthermore the whole exterior area of the shock absorber is implicated in the deformation procedure.

Conservatively, deformation mechanism 1 is used for the verification aim safety against puncturing and for the boundary conditions for the thermal analysis. The mechanism 2 was used for the design of cask body, of the lid system and for the contents deceleration. In order to verify the calculation assumptions, the applicant compares the results assessed analytically with the results of drop tests.

Cask Body

The drop test program a drop onto the horizontal shell line (side drop) and a drop on the shell line with a 20° angle (slap-down drop) were performed for the verifications of horizontal drops for the cask body. For the transfer of the test results to package NCS 45, analytic calculations (bent beam model) and FEM calculations carried out with the Dyna3D code were presented. The test results and the presented FEM calculations for both horizontal drop tests showed that for the central area of the cask body, maximum loads occur for the 0° drop on the mantle line. The maximum loads for the welding seam area between cask mantle and head or foot piece occur during the slap down drop test. The remaining bending of the cask of approximately 23 mm (69 mm for the original package) measured during the drop test, was reduced by change the material of the interior and exterior shells of package NCS 45 from stainless steel (no. 1.4541) to stainless steel (no. 1.4565), in order to minimize remaining deformations.

Lids and Plugs

The assessment for the lid systems were performed by analytic calculations. There are based on elastic theory of plate. A circular plate with a free bearing or a fixed plate and in each case a circular cut out is assumed as calculation models. Because of interaction with impact limiter, content, dynamic effects and compression behavior of wood there were used different load systems. The 1 m free drop test onto a steel bar is not relevant for the lid or the bottom plug, due to the puncture protection.

Screws

The relevant loads under routine transport conditions represent the stresses on lid and trunnion screws. The applicant carried out calculations for the assembly status on basis of German Guideline VDI 2230 [5]. Tightening torques for the containment screwed connections were defined taking into account the results of the drop tests. It was not possible to achieve an exact scaling of the containment components (screws, gaskets, grooves in the lids). Therefore, a simple transferring of the tightening torques and screw forces to the original package is not possible. A conversion transfer of the bolt tightening torques was carried out according to the following scheme:

- Analysis of the pretension forces measured during the drop tests in the lid and bottom plug screws and definition of the average friction coefficient.

- Calculation of the average pretension force of the small lid screws with the average friction coefficients defined in the 1st step (not result from drop tests).

- Conversion of the minimum and maximum pretension forces in the lid and bottom plug and small lid screws to the „equivalent“ pretension forces required for the screws in the original scale.

- Checking and determining of the tightening torques for design type NCS 45 by applying criterion according to which the joint of the corresponding lids in the model and in the original scale are relieved under exterior forces, which are related to each other according to a relation defined in the modeling laws.

The verifications for the trunnion systems were performed according to the German standard KTA 3905 [8]. The operating and long term characteristic values were assessed according to AD 2000 [4]. For the trunnions and their screws the applicant specified a load cycle number of $N_\sigma = 2*10^5$. Furthermore for the trunnion support plate and its welding fatigue strength was assessed. As a result of the numbers of load cycle number N_σ, the utilisation of the trunnions and of the trunnion screws was limited to a maximum of 100 transports. For the calculation of the trunnions the Finite Element Method (FE-Program MSC/NASTRAN) was used and an analytical calculation procedure was applied for the trunnion screws. For the evaluation and the testing of the applicant's design calculations BAM carried out own FE calculations.

Thermal Design

Package design NCS 45 has a multiple layer cask wall. This includes a layer of lead which mainly serves for shielding purposes. The thermal insulation based on cement, which mainly is supposed to protect the cask against excessive heat during the fire test. Variable contents with different radioactive inventories are foreseen. The applicant has presented the thermal verifications for design model NCS 45 for routine transport conditions, normal transport conditions and accidental transport conditions. Verifications are based on numerical calculations carried out with the HEATING code. Furthermore, the software for the material of the thermal insulation was assessed during qualification tests. BAM has no objection against using the HEATING 7 code. Going beyond the applicant's calculations, BAM carried out own analyses with the ANSYS 11code [2], and can thus confirm the reliability of HEATING 7 for the verifications which must be performed here, based on these analyses.

The calculating model has the following characteristics:

- two dimensional,
- axially symmetric related to the longitudinal cask axis,
- strong simplification of the trunnions, and
- further simplification in the bottom and lid areas.

BAM carried out calculations with three dimensional models, which confirmed the results obtained by the applicant with two dimensional models, with only very slight deviations.

ACTIVITY RELEASE LIMITATION

For Type B(U) packages the following activity release values are observed limits:

- Normal transport conditions $G_{A,NCT} \leq 1*10^{-6}$ *[A_2/h]*

- Accident transport conditions $G_{A,ACT} \leq 1$ *[A_2/week]*

To determine the leakage for the testing conditions which must be assumed according to Sections 722 and 727 in [1], the leakage measured in the drop test program were taken into account. During drop sequences 1 and 2, the total leakage from capillary leaks and permeation rates were measured. In drop test sequences 3 to 7, only capillary leaks were assessed through limitation of the measuring times.

BAM concluded from drop tests result the relevant helium standard leakage only is constituted by the permeation rates of single elastomere gaskets installed in the lids. Capillary leaks which must be assumed for the 1:3 model due to the testing conditions according to Section 727 in [1] lead to a total leak rate due to capillary leakages and to the permeation rate of 3,0 x 10^{-6} Pa*$\frac{m^3}{s}$. The results of the drop tests show that the leakage after the drop tests did not increased.

To transfer the measured leakage to package NCS 45, the applicant assumes an influence of the permeation rate which is proportional to the perimeter of the gasket, and deduces the following leak rates for the transport conditions which must be verified:

- Normal transport conditions 10^{-5} Pa $\frac{m^3}{s}$.
- Accident transport conditions 10^{-5} Pa $\frac{m^3}{s}$.

By ensuring these Standard-Helium leakage rates the regulatory limits of activity release are met.

QUALITY ASSURANCE MEASURES

The evaluation of quality assurance measures through BAM is based on the Technical Guidelines concerning Quality Assurance Measures [QM] and Quality Assurance Supervision (QU) for packagings used to transport radioactive materials - TRV 006 - of the German Federal Ministry of Transport [9].

The Nuclear Cargo + Service GmbH Company has a quality management system which fulfils the requirements of DIN EN ISO 9001 [10] according to the certificate of Deutsche Gesellschaft zur Zertifizierung von Managementsystemen mbH (DQS) (German Company for Certification of Management Systems). The Quality Management Manual contains definitions for the development and operation of transport casks.

Quality characteristics given through drawings, materials and standards are guaranteed through the definition of working and testing steps in Manufacturing and Test Follow-up Plans (FPPs). For this, corresponding structural material test sheets and testing instructions are mentioned as binding conditions in the FPPs.

According to TRV 006 [9] a corresponding FPP must be presented by the applicant to BAM for preliminary inspection, to allow for tests before starting operation. According to TRV 006, an independent inspector, charged by BAM, will establish an acceptance certificate assuring the conformity of every series sample, and present it to BAM.

For testing during operation, as well as for the corresponding plans and instructions which must be established, the points determined in TRV 006 (Utilization and Maintenance, Periodic Inspections) are valid. Fig. 5 shows the first manufactured NCS 45 package.

Fig. 5 NCS 45 package

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