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BEHAVIOUR OF METALLIC SEALS IN CASTOR®-CASKS UNDER NORMAL AND ACCIDENT CONDITIONS OF TRANSPORT: QUALIFICATION REQUIREMENTS

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ABSTRACT AND INTRODUCTION

The Federal Institute for Materials Research and Testing (BAM) is the responsible German authority for the design assessment of mechanical and thermal aspects of transport casks for radioactive materials. BAM checks applicants' proof in their safety reports and assesses the conformity to the applicable modal regulations based on the Regulations for the Safe Transport of Radioactive Materials (TS-R-1) [1].
Containment components are classified at the highest level "No. 1" according to the German regulation for quality assurance and control of packagings for transport of radioactive materials - TRV 006 [2]. This means that comprehensive quality assurance and control are required for these components. BAM has developed quality assurance and assessment criteria for seals as an important component of containment systems. These criteria include qualification of the manufacturer, fabrication of test seals, a full qualification program for the mechanical, thermal, short- and long-term behavior of the seals, quality assurance during fabrication of original seals, arrangements after assembling and loading casks and re-inspection tests of the containment system during their usual operation.

The Gesellschaft für Nuklear-Service mbH (GNS) applied for qualification of the design and the properties of metallic double jacket spring seals as components of containment systems for CASTOR®-casks. As a result, some modified design criteria for the behavior of a system consisting of metallic seals, lids, bolts and cask body have been developed. These design criteria concern the elastic compression and expansion behavior and the standard-helium-leakage-rate.

This paper presents BAM requirements for a sealing qualification process and gives advice for implementation based on qualification tests performed by GNS. The results of special research by GNS were used as proof concerning tightness behavior of seals with aluminium and silver outer jackets under the influence of mechanical loading, particles and corrosion.

SEALS

Double jacket metal seals are used as a component of the closure system in transport and storage casks. The seals are inserted and compressed in lid flange grooves. The configuration of double jacket metal seals (see Figure 1) consists of a circular spiral spring encased in two jackets. The outer material is normally aluminium or silver and the inner is stainless steel.

Figure 1. Configuration of a Double Jacket Metal Seal

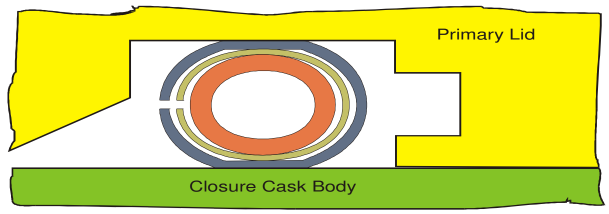

Figure 2. Metal Gasket under Installation Conditions

This type of metal seal functions as follows: During installation of the lid the generated pre-load forces deform the outer jacket. Due to the higher deformability of the outer jacket compared to the inner jacket material, the outer jacket adapts very closely to the structure of the sealing flange surfaces. The inner jacket causes that the compression force of the spiral spring, generated by the compression, to be constantly distributed to the outer jacket (see Figure 2). This configuration shows high sealing quality in accurately designed and assembled casks. For metallic seals in transport and storage casks a standard-helium-leakage-rate ($Q_{He/St}$) of $\leq 1 \cdot 10^{-8}$ Pa·m^3/s after lid assembling is specified.

REQUIRED PROOF FOR QUALIFICATION OF METALLIC SEALS

The IAEA transport regulations TS-R-1 [1], specify different transport scenarios, termed as routine conditions of transport (RCT), normal conditions of transport (NCT) and accident conditions of transport (ACT), and define limits for the loss of radioactive contents (e. g. in § 657 [1]) under these transport conditions. The applicant has to demonstrate the effect of mechanical loadings on the containment system including seals as proof of safety for RCT, NCT and ACT.

BAM has to evaluate possible lid movement and component displacement or deformation. The ability of the seal to meet the leakage-rate-criterion under the specified mechanical loadings, causing axial or radial lid movement or repeated compression, has to be demonstrated by

1. drop tests on full-scale casks or reduced-scale models in a drop test program of approved cask design type (the reliability has to be assured by statistical confirmation) or
2. component test program with simulation of lid and seal displacements and involvement of specific drop tests.

Additionally, the applicant has to consider the conditions during loading and unloading operation of the cask. In the case of lid set-up on the cask in a storage pool, BAM requires consideration and investigation of corrosion behavior and the influence of particles in the seal contact area on tightness.

For long term behavior of seals in transport casks, BAM requires proof of thermal behavior, the influence of radiation to the material properties, corrosion behavior of both jackets because of water possibly enclosed after seal compression, and effects of radiolysis from enclosed water on sealing integrity.

The qualification program including specification of component tests have to be developed by the applicant. BAM evaluates and accepts this program, and partly supervises the performance of tests. Such programs have to contain the following main issues for double jacket metal seals:

- Material specification
- Load-Deformation-Curve (one-time compression)
- Tightness under axial loading (repeated compressions)
- Tightness under radial loading (flange/seal displacement)
- Influence of maximum and minimum temperatures under NCT and ACT
- Particle test (influence of particles of different sizes between seal and contact surface on tightness)
- Corrosion
- Long term performance.

Special equipment has to be constructed and manufactured for the performance of mechanical tests. The test equipment has to meet the requirements regarding variation of axial compression, radial displacement of flanges and measurement of the standard-helium-leakage-rate. Within such a program cask technical specification has to be taken into account, especially test flange material, groove depth and roughness of sealing contact area. BAM requires measuring of the standard-helium-leakage-rate immediately after displacement and a few days after displacement when the leakage rate trend indicates an ending of the test (standard values are: least 7 days after axial lid displacement and 20 days after radial lid displacement).
The long term leakage rate measurement should show how the seal works. Normally the seal can compensate a loss of tightness directly after displacement or of particles incorporation by creeping of the outer jacket material.
After each seal disassembling the width of the sealing contact should be measured.

Tightness under axial mechanical loading (one-time and repeated compressions)

The determination of the load-deformation-curve of a seal after one-time compression is the basic test to describe and analyze the mechanical behavior in relation to the standard-helium-leakage-rate. Figure 3 shows a standard characteristic curve showing essential points important for lid system design and quality assurance:

- Y_0 - *Achievement of* $Q_{He/St}$ *during pressing process*
- Y_1 - *Exceeding* $Q_{He/St}$ *during load relieving*
- Y_2 - *Optimal operation point according to manufacturers specification*
- r_u - *usable resilience.*

This test with a reference seal from each production batch is a standard for quality assurance during fabrication.

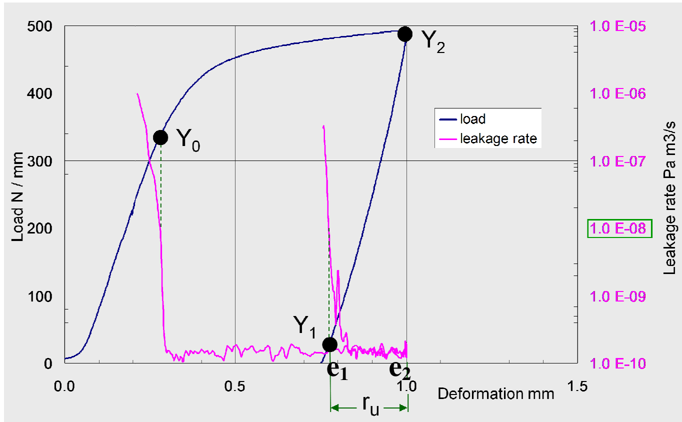

Figure 3. Example of a Load Deformation Curve of a Double Jacket Seal with Outer Jacket of Silver including Measurement of the Leakage Rate

An additional mechanical loading in the axial direction to the lid for ACT results from vertical drop tests of casks onto the lid or bottom. Repeated compression in a component test simulates a short-term axial lid coming off followed by complete closing in a drop test event. This behavior has to be assumed e. g. for a lid during a 9 m vertical drop test if the maximum strain of the lid bolts remains within the elastic range. From BAM's point of view the repeated compression has to distinguish between

a) *repeated compression without seal displacement* because of sufficient high clamping load (around Y_1) and
b) *repeated compression including seal displacement* to simulate a complete seal resilience and, hence, repositioning. The seal is rotated by 45° between each compression.

The GNS tests in [3] show the achievement of $Q_{He/St} \leq 1 \cdot 10^{-8}$ Pa·m^3/s for *repeated compression without seal displacement* for seals with *silver* as well as seals with *aluminium* outer jacket after up to five times compression and load relieve.

As an example, *repeated compression including seal displacement* in [4] gives the following results for both seal design types, *with silver and aluminium outer jacket:*

- After one-time compression a standard-helium-leakage-rate of high quality ($1 \cdot 10^{-11}$ Pa·m^3/s) was measured for all specimens.
- The standard-helium-leakage-rates measured directly after twice performed compression were in the range to meet the requirements of IAEA TS-R-1 [1] concerning the loss of radioactive contents at ACT relating to the given radioactivity of the cask content.

Tightness under radial mechanical loading

Mechanical loading in the radial lid direction can result from horizontal cask drop test when the lid is displaced into radial direction.

Simulation of this scenario has to be done by an appropriate test equipment (see Figure 4). BAM requires a minimum specific radial seal displacement as conservative value for NCT and ACT. Before relieving of radial mechanical loading, the maximum displacement has to be kept 30 min. After relieving the test lid flanges can be taken out the test set-up for long-term measurement outside. The standard-helium-leakage-rate has to be measured periodically for a minimum 20 days to get information about long-term behavior.

The test report should also contain the following items, which have to be documented after disassembling of flanges:

- Photo documentation of the seal in the groove
- Deformation of seal
- Rolling of seal
- Radial rills
- Roughness measurement
- Measurement of sealing contact area width

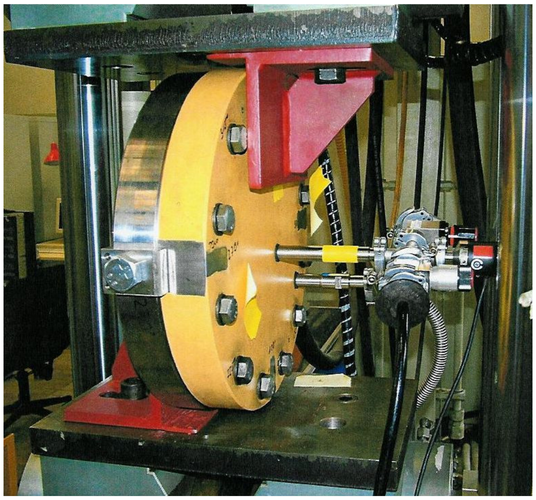

Figure 4. Test Set-Up for Simulation of a Radial Displacement of the Lid Flange

GNS tests [5] with *aluminium* and *silver* outer jacket seals showed the following results directly after relieving:

- *Seals with silver outer jacket*

  There was no significant increase of initial standard-helium-leakage-rate ($Q_{He/St}$ *and lower)* after displacement.

- *Seals with aluminum outer jacket*

  The standard-helium-leakage-rate increased compared to the initial value about a one order of magnitude maximum 30 to 40 minutes after radial displacement. However the initial value could be achieved with an extended test period. The flange surface roughness measurement and the macroscopic visual inspection gave no details of aluminium adherence on the flanges' sealing surface. No aluminium tearing occurred either.

Further displacement effects were noticed at visual inspection of all seals and flange contact surfaces used:

1. Seal sliding was observed in the seal section approximately in parallel to the displacement direction.
2. The seal (limited by the shape of the groove) was observed rolling in the section vertical to displacement direction.
3. The seal showed a mixture of both aforementioned effects in the section approx. 45° to displacement direction.

Influence of particles in the seal/flange contact area on tightness

During cask loading operations in the storage pool it may occur that particles can fall on the flange surface before compression of the seal. BAM requires a “particle test” for information about the influence of particle size and texture on tightness.

The GNS tests [6] were performed with corundum grains (Al_2O_3). They were arranged at the seal/flange contact area as shown in Figure 5. The same arrangement had to be considered at the seal’s opposite side. Ten corundum grains, five each side, were pressed into the sealing contact area. Tests with two different particle sizes were carried out and the leakage rate was measured.

The result was that smaller particles had no influence on the leakage rate of either *silver* or *aluminium* seals. Visual inspection showed the grains completely enclosed in the outer jacket material (see Figure 6).

Larger particles showed different tightness behavior on both seal design types. *Aluminium* outer jacket seals achieved good sealing quality directly after compression and leakage rate values decreased during long term measurement.

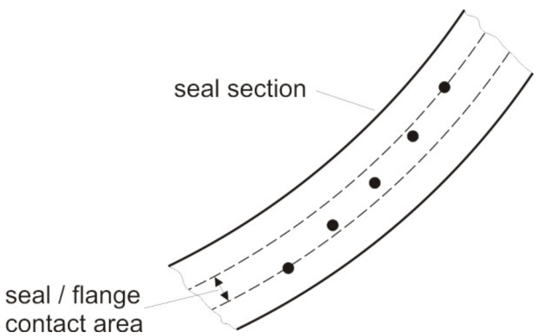

Figure 5. Arrangement of Corundum Grains on Seal/Flange Contact Area

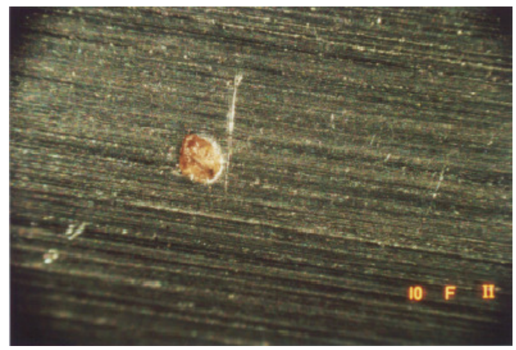

Figure 6. Aluminium Seal with Pressed in Corundum Grain

Chemical Resistance and Corrosion

If the cask has to be loaded under water, chemical resistance and corrosion effects have to be considered. BAM requires proof regarding the water-resistance of each sealing material. Corrosion behavior from contact with different materials has to be evaluated too.

The storage pool water contains 2500 ppm boron as boric acid. Moreover, impurities of ions from chloride, iron and copper can be found. Research on *aluminium* outer jacket seals showed that these impurities can produce local elements with pitting effects.

Based on the water composition, corrosion tests have to be performed in different concentrations and combinations of test solutions, e.g. contamination liquid + boric acid with realistic and higher concentrations or contamination liquid + boric acid + compounds with the above mentioned ions.

For the GNS corrosion tests [7] two different solutions were used which were supposed to conservatively cover the composition of storage pond water (see Table 3). Operation maximum temperature also had to be taken into account.

Table 3. Qualitative Composition of Corrosion Test Fluids

Solution	*1*	*2*
Boron[1]	*>2500ppm*	*>2500 ppm*
Chloride[2]	*no*	*yes*
Copper[3]	*no*	*yes*
Ferreous content[4]	*no*	*yes*
Soluted in	*Deionat*	*Deionat*
pH-value	*4.1 … 4.5*	*4.3 … 4.7*

1)H_3BO_3; 2)$NaCl$; 3)$CuSO_4*5H_2O$; 4)$FeCl_3$

Flat sheets of sealing jacket material (*stainless steel* and *silver*) were provided and arranged so that electrical contact was guaranteed to evaluate short term corrosion behavior. These sheets were immersed in the solutions for one, two and a maximum three weeks.

- *Test results with solution 1*

  The tests showed no surface corrosion for *stainless steel* exceeding the gravimetric measurement. A scanning electron microscope found either no local corrosion.
  The *silver* samples also showed a very low surface corrosion. Pitting corrosion was not found on the *silver* samples.

- *Test results with solution 2*

  The tests showed no surface corrosion for *stainless steel* exceeding gravimetric measurement. A scanning electron microscope found either no local corrosion.
  Surface corrosion of *silver* samples provided a little higher value than in solution 1. Pitting corrosion was also not found on the *silver* samples.

CONCLUSIONS

BAM requires proof of compliance of leakage rate criteria under mechanical loadings from RCT, NCT and ACT for use of double jacket metal seals in transport casks. In general, since there is only a small number of drop tests with full-scale casks or reduced-scale models additional tests are necessary to show the statistically confirmed ability of the containment system to meet the leakage-rate-criterion. Therefore, BAM requires a qualification program prepared by the applicant containing all relevant mechanical, corrosion and particle tests. Long term effects also have to be investigated. These tests are assessed and partially witnessed by BAM.

In addition to the above described mechanical tests, the effect of loading in the oblique direction to the lid system and also focused in a point has to be considered by the applicant. In the case of oblique and puncture drop tests, proof may be an analytical demonstration comparing the loadings and their effects on the containment system with horizontal and vertical drop tests.

The applicant also has to demonstrate transferability of leakage rate results from tests with reduced-scale models or component tests to the original dimensions.

Based on the results of all mechanical tests, the applicant has to determine seal design values for the standard-helium-leakage-rate in relation to effects on containment systems under RCT, NCT and ACT, direction of mechanical loading and duration of the leakage rate measurement.

ACKNOWLEDGMENTS

BAM thanks GNS allowing to publish test results from their test reports.

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