THE INFLUENCE OF THERMAL EXPANSION ON PACKAGE TIGHTNESS DURING FIRE

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ABSTRACT

Packages for the transport of radioactive materials are subjected to a fire test of thirty minutes at 800°C according to TS-R-1. As a result of the fire test, significant temperature gradients usually occur within the package. This is supported by thick walled designs of those packages, in particular. Temperature gradients lead to different thermal expansion, which results in displacements as well as stresses. This has an impact on the package wall but also on the leak tightness because of different influences of thermal expansion on the package wall and the lid.

The paper provides approaches based on analyses. Starting with well known analytical correlations for thin and thick walled pipes, a finite element model will be developed to analyse the problem on a numerical basis also. After the verification of the numerical model with respect to the results of the analytical approaches, the finite element model will be adjusted to be nearer to real package designs. In particular, the link to the lid system and the evaluation of leak tightness will be made. Finally, design aspects will be included in the finite element model. Results of the analyses are presented and conclusions are drawn.

As a result, shock absorber design and the design of the lid system are important aspects to improve the safety of the package with respect to leak tightness. The effects of thermal expansion during fire test can be analysed numerically. Analytical approaches are suitable for basic estimations and to support first design steps. Experimental verification is a difficult task because the event will occur during the fire test and the leak tightness could be rebuilt after the fire test is done and the measurements take place. Nevertheless, the opening of the package can last a significant time. Therefore, analyses are important to explore this effect and to demonstrate safety.

INTRODUCTION

As required by the regulations [1], Type B (U) packages have to be subjected to a fire test of thirty minutes at 800°C with the boundary conditions provided by para. 728 in [1]. Reference [2] gives additional advisory for test conditions. In addition to other requirements, the loss of radioactive

material shall meet the A_2/week-limit of para. 657 if subjected to the test. Thus, for a design with a lid sealed onto a shell flange, sufficient leak tightness has to be ensured.

During a fire test, significant temperature gradients will be induced in the containment wall and cause inhomogeneous thermal elongations. These elongations have an effect on the displacements at the shell flange. The lid has also a potential for temperature gradients and resulting deformations. Deformations of lid and shell flange in combination influence the seal behaviour and introduce additional stresses in the bolts. Due to a change of the configuration of lid and shell flange, a seal torus expansion till seal detachment due to gap formation in the seal area can occur. In particular for the highly sensitive metallic seals, this could result in an increased helium leak rate, or as worst case scenario, in an opening of the seal seat and thus an increased release of radioactive material. After the fire test is finished, the sealing area will be reconstituted during the cooling phase. But nevertheless, the described effect can take place for a significant duration. Thermal processes take extensively more time than highly dynamic processes as drop tests, for which the reconstitution will happen faster, if it happens at all.

The reconstitution process avoids the full exploration of the effect by common leak tightness pre- and post test measurements. Due to the special fire test conditions, the possibility for any data acquisition by measurements is highly restricted. Therefore, analysis is the main way for demonstration, which is also the method used in this paper.

In this paper, the effect is developed firstly by simple analytical and numerical considerations, followed by intensively and more detailed finite element analyses. The effect is explained in detail and the leading parameters will be identified. Finally, design issues will be addressed.

THERMAL EXPANSION OF THICK WALLED STRUCTURES
As a first step, the thermal expansion of thick walled structures will be examined. Therefore a thick walled pipe is considered, which should represent the shell body of a cask for radioactive material. Shock absorber and lid design is neglected at first. Fixed temperatures on the inside and the outside of the wall are analysed with respect to steady-state conditions. Simplified calculation approach is used for the one based on the formula provided by Roark [3].

The thick-walled pipe was loaded by temperatures with a significant gradient regarding the wall thickness. The highest temperature is at the outside and the lowest at the inside of the pipe as usually obtained during the fire test of TS-R-1 [1]. For steady-state conditions, you will get a logarithmic temperature characteristic regarding the wall thickness [4]. Temperature gradient and wall thickness are varied in this analysis to identify their influence on the results.

The strength in the middle of the pipe, inside and outside, as well as the angle between shell flange and lid at the end of the pipe will be evaluated (Figure 1). Because there is not any fixation, it will be considered a free elongation at the neutral diameter of the pipe. Pipe length is not important for this analysis.
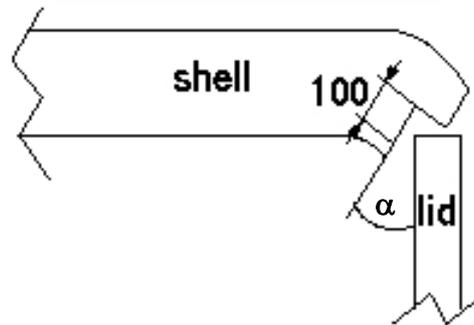
Figure 1. Deformed end of pipe and evaluated angle α

The resulting stresses at the inside and the outside of the pipe are provided by table 1. The inside temperature is always 200°C and the interior diameter 1500 mm. Common steel is considered with a Young's modulus of 205 GPa, a Poisson's ratio of 0.3 and a thermal expansion coefficient of 13.0E-6 K^{-1}.

Table 1. Resulting minimum and maximum stresses using [3]

Temperature Gradient	Wall Thickness	Stresses outside	Stresses Inside
K	mm	MPa	MPa
100	200	-175	205
200	200	-351	411
300	100	-547	595
300	200	-526	616
300	300	-508	635

Looking at the results in table 1 we can consider compression at the outside and tension at the inside of the pipe. Secondly, the influence of the temperature gradient seems to be more significant than the influence of wall thickness. These influences can also be assumed for the deformation at the free end of the pipe.

If we assume a distance of the lid edge to the trace of the seal of about 100 mm, the resulting angle will be within the range of the useful elastic recovery of a common metallic seal. This would be a significant safety issue for the potential release of radioactive material during the fire test (Figure 1).

APPLYING FINITE ELEMENT ANALYSIS AND CONSIDERING MATERIAL INFLUENCE

Similar to the analytical approach, a finite element model is developed using ANSYS [5]. Geometry is adjusted to an interior diameter of 1400 mm and an exterior diameter of 2200 mm, which gives a wall thickness of 400 mm. Additionally, the base material is changed to ductile cast iron with a Young's modulus of 162 GPa, a Poisson's ratio of 0.274 and a thermal expansion coefficient of 11.0E-6 K^{-1}.

The analytic approach by Roark [3] provides a sufficient similarity with the FEA results (Table 2). In addition, table 3 provides a comparison of different pipe or shell materials as steel and cast iron.

Due to the higher Young's modulus and the higher thermal expansion coefficient as well as the lower Poisson's ratio, the stresses and also the deformations for a steel shell are higher than for a cast iron one with the same geometry.

Table 2. Resulting minimum and maximum stresses using [3] and FEA

Temperature Gradient	Wall Thickness	Stresses outside	Stresses Inside	Method
K	mm	MPa	MPa	
100	400	-119	139	FEA
100	400	-104	141	[3]
200	400	-237	278	FEA
200	400	-209	282	[3]
400	400	-447	557	FEA
400	400	-418	564	[3]

Table 3. Resulting stresses using [3] for steel and cast iron

Temperature Gradient	Wall Thickness	Stresses outside	Stresses Inside	Material
K	mm	MPa	MPa	
200	400	-209	282	Cast iron
200	400	-324	437	Steel

TEMPERATURE FIELDS USING TRANSIENT ANALYSIS

Now the boundary conditions for the FE analysis are enlarged by considering the whole fire test cycle. The cask is modelled with solid elements and represents a quarter of the whole body. Using a quarter model instead of an axisymmetric one offers the possibility to extend the model with features like holes for moderating material. The outside cooling fins are not explicitly modelled. The heat load at the inner wall consists of a homogeneous applied heat flux due to the power of 40 kW provided by the inventory. The heat load at the outer surface is given by a fire of 800°C over a time of 30 minutes which represent the scenario outlined by the IAEA regulations. The calculation is carried out as a transient calculation over a time of 2 hours which includes a phase of cooling down of 90 minutes.

In a first approach the FE-analysis is done with a cylindrical cask modelled with a constant cross-section and homogeneous material (cast iron). It is calculated with a heat load up to the free edge. Gradients of temperature are shown in figure 2 and correspond in quality with the ones used for the analyses before.
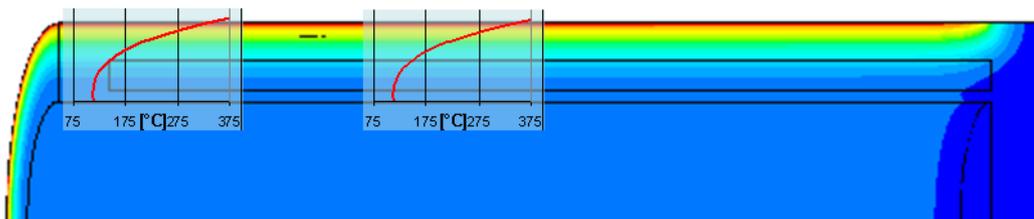

Figure 2. Temperature fields and gradients of the cylindrical cask after 30 minutes fire

LID AND SHOCK ABSORBER DESIGN

Effects discussed above have not considered the presence of end shock absorbers and the lid. If the shock absorber is lost during the drop test, a temperature gradient will also be present over the lid. This effect, which we have not considered before, would lead to a deformation of the lid in a way, that the release of the seal will be increased. This effect is reinforced by a significant thickness of the lid due to shielding reasons.

On the other hand, if the shock absorber is still present after the drop test, the temperature gradient for the covered area of the cask will be significantly lower. The deformation of the lid is usually not important any more.

But the transition area between the shell part, which is covered by the shock absorber, and the area which is not, has a significant influence. To explore this effect, adiabatic boundary conditions are applied to the locations of the shock absorbers as shown in figure 3. Preliminary calculations have shown that the assumption of an adiabatic boundary condition instead of modelling the shock absorber leads to a slight underestimation of the deformation. However the difference is small enough to assume an adiabatic boundary condition for further calculations. In further approaches the lengths of these areas will be varied to simulate different lengths of the overlapping of the end shock absorbers. The overlapping is a frequently used design feature for the type B packages considered here. For reference purpose the length of this adiabatic area at the shell flange would be chosen to be 0.4 m. With respect to the models used before, the inner heat load is applied to a more realistic distance to the flange as well. Additionally, the cask is modified with a cut out at the shell flange to fit the primary lid.
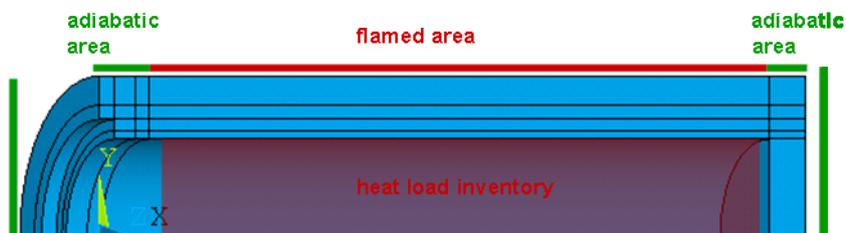

Figure 3. Boundary conditions for the shock absorber

Looking at the results of the analysis described above, the radial temperature gradient will change along the shell length due to the adiabatic boundary conditions shown in figure 3. At the beginning of the fire test, the temperature gradient in the cask wall will only be slightly different (figure 4). A significant change can be identified at the end of the fire test (figure 5). The gradient of the average wall temperature stays constant up to the adiabatic area, where it rapidly falls down.
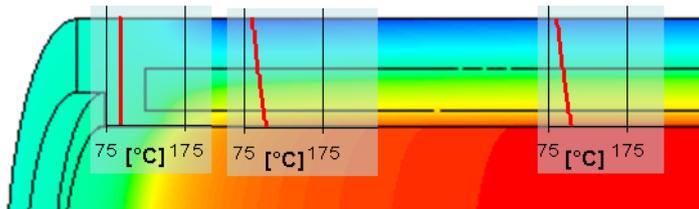

Figure 4. Gradients in the cask wall before fire test, t = 0 min, length of adiabatic area: 0.4 m
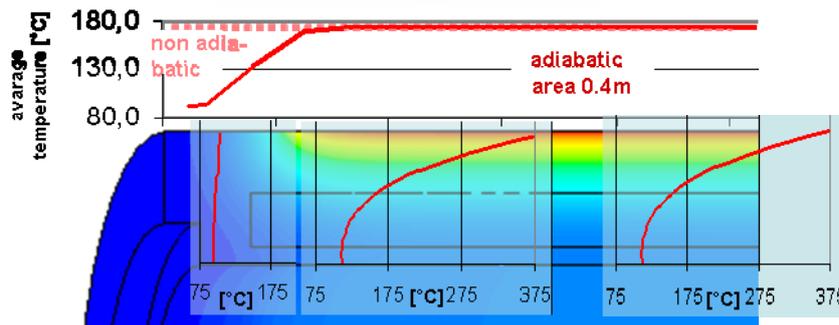
Figure 5. Temperature gradients in the cask wall and gradient of the average wall temperature at the end of the fire test

If the adiabatic area is increased to 0.7 m, the change of temperature gradient will move towards the bottom (figure 6) and therefore away from the flange area.
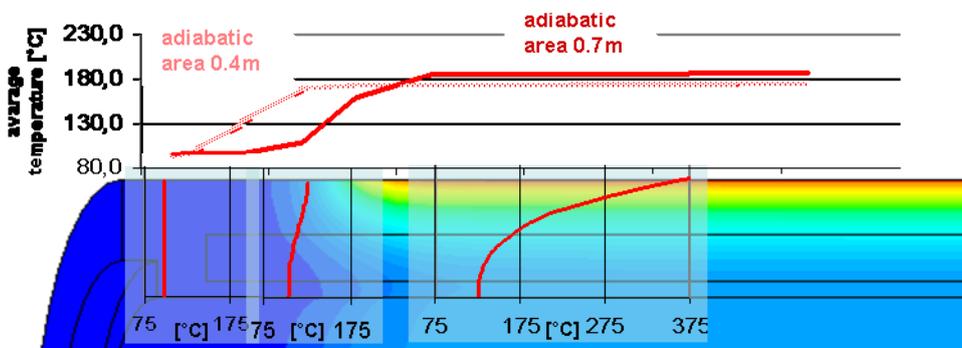

Figure 6. Gradients in the cask wall and averaged gradient for an adiabatic area of 0.7 m

EVALUATION OF LEAK TIGHTNESS

To evaluate the leak tightness, deformations at the flange area will be considered first. If shock absorbers are lost during drop tests, the deformation of the flange area results from the different axial thermal elongation over the wall thickness as described at the beginning of the paper.

If there are adiabatic areas due to the end shock absorber design, the situation will be quite different. As seen in figure 5, there should not be an angle at the shell flange since there is hardly a radial temperature gradient. However, concerning the change of radial thermal gradient over the length the higher gradient in the directly fire engulfed area leads to a larger diameter of the cask due to thermal expansion. The smaller diameter of the cask in consequence of the lower temperature level at the adiabatic area forces the cask wall to an inwards rotation.

Therefore the angle at the shell flange is the immediate consequence of the angle that occurs in the axial direction to reach the smaller diameter at the adiabatic end of the cask. This kind of deformation is shown in figure 7 for an adiabatic area of 0.4 m. Also in figure 7, it can be seen that the "rotating point" moved inwards and the last 0.3 m approx. is an almost linear slope.

With an adiabatic area of 0.7 m the "rotating point" actually moves further away from the shell flange so that there is not even a longer linear slope, there is also a kind of backwards rotation. This causes a smaller angle at the shell flange.
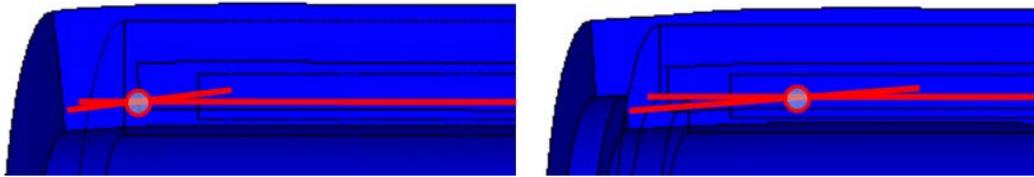
Figure 7. Deformation at shell flange, t = 30 min, non adiabatic (left) and adiabatic area of 0.4 m (right)

To quantify the influence, the angles are calculated and provided by table 4. The resulting angles support the thesis of the influence of the adiabatic area. Additionally, gap values at seal position are analysed considering a distance of the lid edge to the trace of the seal of about 100 mm. Assuming a useful recovery for a metallic seal of about 0.3 mm, special designs can be within this range and provide a significant safety issue for the potential release of radioactive material during the fire test.

Table 4. Resulting angles at the shell flange

Case	Angle	Gap values at seal position
Non-adiabatic area	0.186°	0.325 mm
Adiabatic area of 0.4m	0.143°	0.250 mm
Adiabatic area of 0.7m	0.073°	0.127 mm

Transient mechanical calculations over time based on the temperatures of the thermal analysis determine the time length of a relevant deformation. Figure 8 shows the calculated angle at the shell flange over time. The material of the whole cask is still assumed to be cast iron. If it has to be assumed that the critical angle is 0.1°, in case of an adiabatic area of 0.4 m, this angle would be exceeded for 20 min approximately. For an adiabatic area of 0.7 m, this angle would not be reached at all. Finally all calculations indicate a reconstitution of the displacements at the shell flange after the fire.
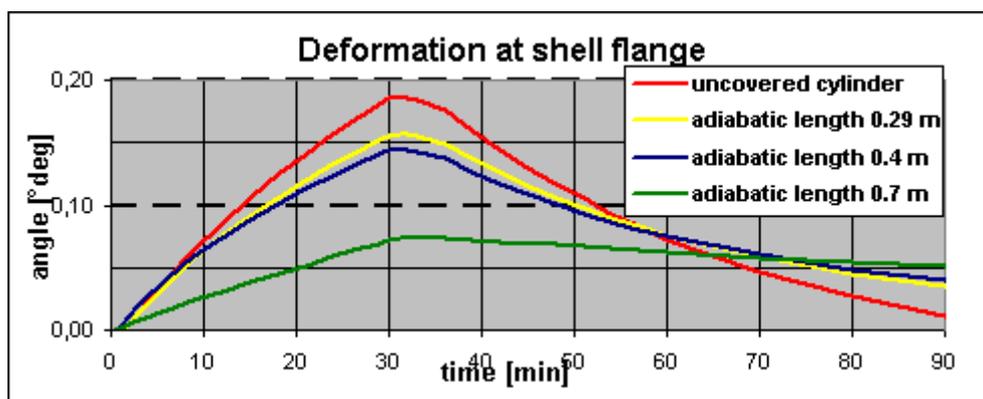

Figure 8. Angle at shell flange over time for different lengths of the adiabatic area

Besides the length of an adiabatic area, some additional factors can influence the dimension of the deformation:
- Mass of the cooling fins: Fins with their additional specific heat capacity lower the surface and the average temperature of the cask wall; leading to a decrease of deformation

- Drilled holes for moderating material: Holes weaken the cask wall; leading to a increase of deformation (effect includes the smaller heat conductivity of this area)
- Heat load: Fewer heat loads of the inventory cause larger deformations due to larger radial gradients; in opposite higher heat loads cause lower deformations

CONCLUSIONS

The paper provides an investigation of the parameters, which can influence thermal expansion of the cask wall during the fire test. The effects on potential release of radioactive material and the duration of this situation during the test are discussed. In particular, design features influence the geometry of sealing system components after fire impact like wall thickness, temperature gradient across the wall, lid thickness, used materials and lid as well as shock absorber design. These design features have to be thoroughly considered for packages, which have to suffer the fire test according to para. 728 in [1]. A very significant design feature is the overlapping length of the end shock absorber and the potential loss of the lid end shock absorber during the previous drop event according to para. 727 in [1]. The paper is far from completeness. Special designs can have features which are not considered here. Therefore, each special design has to be evaluated separately. But the discussed influence of thermal expansion of containment components on the leak tightness should be part of the assessment. This paper can give some advice for designers, engineers and experts investigating this issue. Moreover, only transport conditions are addressed. Thermal expansion problems for interim storage scenarios are discussed in [6].

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