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COMPUTATIONAL MODELLING TO PREDICT WASTE PACAKGE PERFORMANCE UNDER FIRE ACCIDENT CONDITIONS

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ABSTRACT

In the UK, NDA is developing a design safety report for the Standard Waste Transport Container (SWTC) for the transport of intermediate level waste. The approach for confirming the protection afforded to the contents (waste packages) is nested modelling: a model of the SWTC is used to predict the internal temperatures during a fire. These temperatures are then applied to a separate model of the external surface of waste packages to predict possible releases.

The thermal test, for demonstrating ability to withstand accident conditions in transport, specifies an external temperature of 800^{o}C for 30 minutes. Heat transfer considerations mean that the contents of the SWTC will experience temperatures which are much lower than 800^{o}C, but over a longer period than 30 minutes.

The main focus for demonstrating safety are first to ensure that the lid / body gap opening remains small, second that the local temperatures are within the design limits of the seal and third that the internal pressure can be contained throughout the fire conditions. The safety of the SWTC against all these loadings is discussed in this paper.

INTRODUCTION

In the UK, NDA is developing a series of transport flasks for transporting a range of standard waste containers. The waste containers themselves have relatively thin walls and are not intended to provide any shielding. Shielding is instead provided by the walls of the store or geological disposal facility (when the waste is being stored) or the transport flask (during transport). Because different wastes have different shielding requirements, standard transport flasks with a range of wall thicknesses (75mm, 150, and 285mm) are being created. The Standard Waste Transport Container with a wall thickness of 285mm, known as the SWTC-285, is the first that will be built. It is this flask which is the topic of this paper.

The thermal assessment of a preliminary design of the SWTC-285 has previously been performed [1]. The design has subsequently evolved and the thermal performance of the flask has recently been re-assessed to provide input to the Design Safety Report.

DESIGN OF THE SWTC-285

The SWTC-285 is designed to transport various types of standard waste container:

- one compact stillage containing four NDA standard 500 litre Drum waste packages;
- one NDA standard $3m^3$ Box waste package;
- one NDA standard $3m^3$ Drum waste package.

The container is a cuboid steel vessel with a 285mm thick wall, base and lid. The general arrangement of the package is shown in Figure 1 and a photograph of a scale model of the package in Figure 2. A significant change between the preliminary design and the current design of the SWTC-285 is that, in the preliminary design, the body of the container was constructed from forged type 304 stainless steel whereas, in the current design, it is constructed from cast type CA6NM steel. The lid, however, is still constructed from type 304 stainless steel.

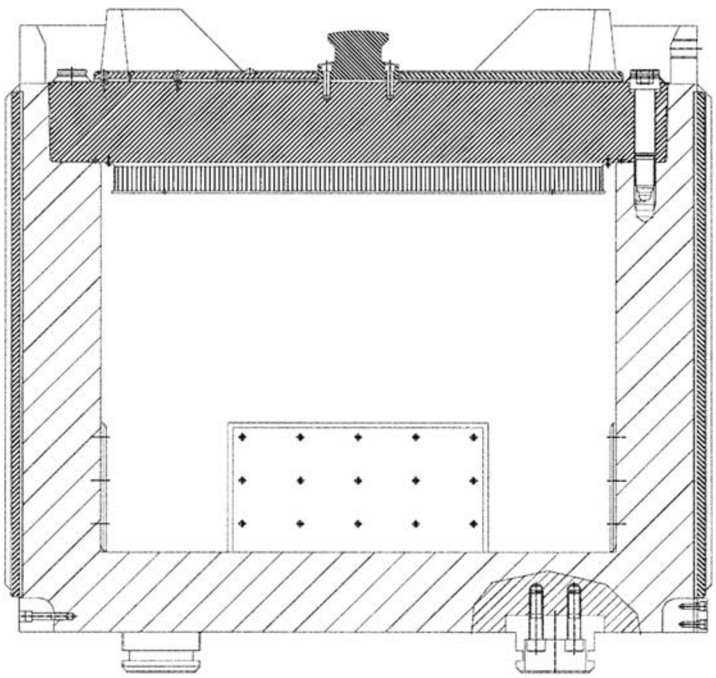

Figure 1: General arrangement of the SWTC-285

Figure 2: The SWTC-285 1/3 scale model

The container is 2.3m high and 2.4m square and has an internal enclosure 1.4m high and 1.8m square. It has a 285mm thick lid, constructed from type 304 stainless steel, which is fixed to the body by 40 M68 studs and nuts. The container has up-stands on the top of the body and lid which act as energy absorbers in an impact. Ribs up the side of the container, around each corner, provide additional impact protection. A sheet of aluminium honeycomb is attached to the underside of the lid to act as a cushion between the lid and the waste container in the event of an impact.

Most of the top and sides of the container is covered by a 25mm thick layer of cork, clad in stainless steel. This acts as a heat shield in the event of a fire Around the nuts, up-stands and ribs there is no insulation. Neither is there any insulation on the base of the container.

The lid / body seal is achieved with a 15 mm diameter EPDM-30H O-ring fitted in a dovetail groove in the lid. This gives the seal a nominal 25% compression.

There is a valve mounted on the lid of the container which will be used to both vent the container before unloading and establish the atmosphere inside the container before transport.

OVERVIEW OF THE ANALYSIS

The SWTC-285 is designed to be a type B(M) package. Under normal transport conditions the ambient air temperature is therefore assumed to be 38°C and subject to solar insolation, as specified in the IAEA Regulations [2]. Under accident conditions it must withstand a 9m drop test and 1m drop onto a punch followed by a 30 minute 800°C pool fire.

Various aspects of the performance of the SWTC-285 were covered in the analysis:

- The temperature of the SWTC-285 during normal transport
- The temperature of a waste package inside the SWTC-285 during normal transport
- The temperature of the SWTC-285 during the regulatory thermal test
- The mechanical distortion of the SWTC-285 during the regulatory thermal test
- The temperature of a waste package inside the SWTC-285 during the thermal test
- The pressure generated inside the SWTC-285 during the thermal test

The analysis did not include an impact assessment because a 1/3 scale model of the SWTC-285 had already been subjected to the IAEA regulatory drop and punch tests. Further impact assessment by modelling was therefore unnecessary. However, the damage sustained by the flask during the impact tests was included in some of the thermal models.

The SWTC-285 flask will be used to transport a select number of different waste package types with a wide range of different radioactive waste materials and thermal properties. To ensure that the assessment bounded all possible waste package types, the SWTC-285 was modelled as being empty. This represented the minimum possible thermal capacity for the combination of flask and contents which will result in the maximum possible temperatures in the SWTC-285 during the thermal test. However, this approach might not be pessimistic if the heat generated by the waste itself were neglected. The maximum design heat load (200W) was therefore included in the calculations, modelled as a uniform heat flux on the inner surfaces of the flask.

To determine the temperature of the waste in any given waste package inside the SWTC-285, either during normal transport or during the thermal test, the temperature of the inner surface of the flask calculated in the SWTC-285 model is used as a boundary condition in a separate model of the waste package. In the current assessment a stillage holding four 500 litre drums has been modelled. From the calculated temperature of the waste both the potential release of radionuclides and water vapour into the flask cavity can be determined. The release of water vapour contributes to the pressure inside the flask.

DESCRIPTION OF THE SWTC-285 F.E. MODEL

The Finite Element model of the SWTC-285 flask is shown in Figure 3. Because of the symmetry of the flask design, only a 1/8 segment of the whole flask is represented. The model includes:

- The flask body
- The flask lid
- The up-stands on the top of the body and lid
- The ribs on the side of the body
- The studs and nuts which fasten the lid to the body
- The thermal shields on the side of the body and top of the lid
- The feet
- The lid pintle

The model contains approximately 45,000 elements and 95,000 nodes. Because of the complexity of the geometry, tetrahedral elements were used to mesh most of the model. Hexahedral elements were used to model the thermal shields, however, as this shape of element is better suited to modelling the thin steel cladding around the cork and ensuring that there are several elements across the thickness of the cork, where large temperature gradients were expected. The mesh in the insulation panel and flask body are illustrated in Figure 4.

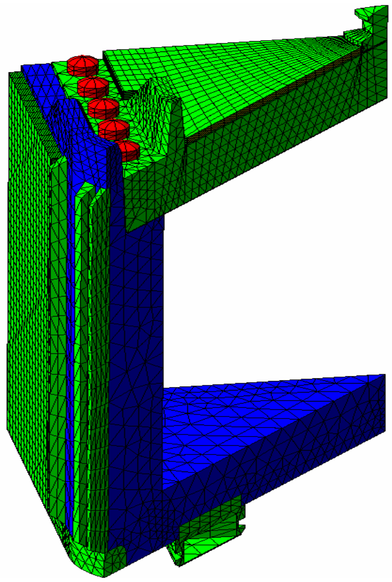

Figure 3: The finite element model of the SWTC-285

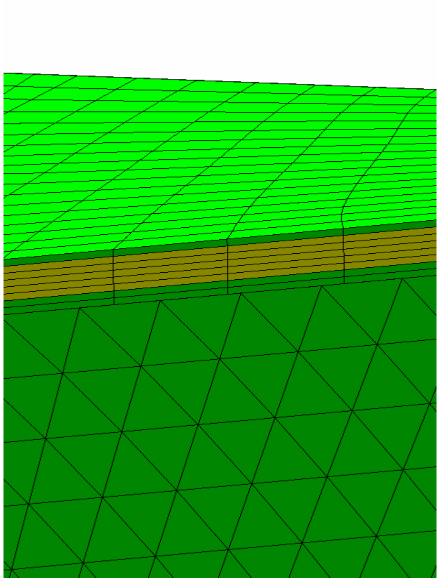

Figure 4: Detail of the finite element model of the SWTC-285 showing interface between the lid and thermal shield

The meshes on either side of the boundary between the thermal shields and the flask do not match. Instead the faces on either side of this boundary were thermally connected using boundary conditions. In reality there is a narrow air gap between the thermal shields and flask body or lid. The boundary conditions joining the thermal shields to the flask represented heat transfer by conduction and radiation across this air gap plus conduction down the fastening studs.

Detailed consideration was given to heat transfer between the lid and the body of the flask. During normal operation the studs and nuts hold the lid firmly in contact with the body. Good thermal contact is therefore to be expected at the seal face. The model therefore represented no thermal resistance between the body and the lid at the seal face, under normal transport conditions. However, during the thermal test, which is assumed to follow an impact it would be optimistic to assume good heat transfer between the body and lid. An air gap is therefore assumed to exist at the seal face and, pessimistically, only heat transfer by radiation is modelled. Heat transfer by conduction down the studs was, however, still explicitly represented.

The heating phase of the thermal test represents the flask being enveloped for 30 minutes in a pool fire at a temperature of 800°C, as specified in the IAEA Regulations [2]. These regulations specify that the fire should be assumed to have an emissivity of 0.9. Reflection of radiation from the fire is unphysical. Therefore radiation was modelled as from a box surrounding the flask with black surfaces at a temperature of 772.3°C, obtained from the equation:

$$T_{eff}^4 = 0.9 \times T_{fire}^4 + 0.1 \times T_{amb}^4$$

where T_{eff}, T_{fire}, and T_{amb} are the absolute temperatures of the effective black body source, the fire and the ambient respectively. The absorptivity of the surface of the flask was assumed to be 0.8, as specified in the IAEA Regulations.

A pessimistically high forced convection coefficient of 15W/m/K was assumed during the heating phase. During the cooling phase heat transfer coefficients based on engineering correlations for natural convection were applied.

The thermal shields contain cork to provide insulation against the heat from the fire. In the model this cork is represented as a solid material through which heat transfer occurs by conduction only. In practice cork dries out, chars, and shrinks upon exposure to a fire. Its effective thermal conductivity upon exposure to a fire may therefore be different to its conductivity measured at room temperature. Data from experiments performed around 30 years ago [3, 4], in which various insulating materials, including cork, were tested for suitability as thermal insulation materials in transport packages, has been used to determine the effective thermal conductivity. It was found that, in order to adequately bound the heat transfer measured during heating in a 800°C furnace, the thermal conductivity of the cork needs to be increased from 0.055 W/m/K, its value at room temperature, to 0.1 W/m/K. In the SWTC-285 model, the cork was pessimistically assumed to have the lower thermal conductivity both during normal operation and during the cooling phase of the thermal test and to have the higher value during the heating phase of the thermal test.

The thermal test calculations need to include the effect of damage sustained during the impact tests. From the results of the drop and punch tests performed on the 1/3 scale model, it was concluded that the damage which should be represented in the model was the removal of the lid pintle and the removal of a section of the lid insulation panel. In the thermal test calculation the finite element model was modified to include this damage.

RESULTS FROM THE SWTC-285 F.E. MODEL

The thermal calculations were performed using the FEAT [5] finite element code. FEAT, a commercially available code, has been developed and is owned by British Energy and has been used extensively to support the safety cases for the British Magnox and AGR nuclear reactors.

a) Normal transport

Because the SWTC-285 has thick steel walls, and hence a large thermal capacity, it is expected that diurnal variation in temperature during normal transport will be very small. A steady state calculation was therefore performed to determine the temperature of the flask under normal transport conditions. The solar insolation values which were applied were the average over 24 hours. The predicted temperature distribution during normal transport showed that the solar insolation has a more significant effect upon the flask temperature than the internal heat load (200W) does. The maximum temperature of 59°C occurs on the lid of the flask, where the solar insolation is greatest, while the minimum temperature of 43°C occurs at the bottom where there is no solar insolation. In the absence of any solar insolation the maximum surface temperature is only 40°C.

b) Regulatory thermal tests

During the heating phase of the thermal test, the combination of the large thermal capacity of the flask and the insulation provided by the insulation panels work effectively to limit the rise in temperature. The predicted temperature distribution at the end of the heating phase is shown in Figure 5. It can be seen that the hottest regions at this time are the unprotected extremities: the lid pintle, the up-stands and the feet. The inside of the flask, however, remains cool.

The 1/3 scale impact tests resulted in the lid pintle being removed and part of the thermal insulation on the lid being removed. The removal of insulation resulted in an increase in the heat transmitted from the fire to the lid during the thermal test. However, the magnitude of this increase was modest and the region of the lid which consequently became hotter was relatively remote from the lid seal.

During the cooling phase of the thermal test, heat continues to be conducted from the hot outer regions of the flask to the cooler inner regions. Inside the flask the hottest region is the base. Here the average temperature reaches 143°C (2¼ hours after the start of the fire) and the maximum temperature reaches 168°C. At the top of the flask the maximum temperature experience by the inner lid seal is predicted to be 156°C. This is comfortably below the upper temperature limit for this elastomeric material (about 200^{o}C over the timescale of the fire event).

The analysis of the 1/3 scale impact tests is still on-going. Hence the interpretation of the impact distortion at the lid / body seal location is not yet available for application to a combined impact and fire analysis.

Thermal expansion of the flask during the thermal test will cause distortion. It needs to be demonstrated that the gap between the lid seal faces remains sufficiently small for containment to be maintained. The temperatures predicted using the FEAT code were transferred to an ABAQUS model in which the thermal distortion at was calculated. It was shown that the studs and nuts are effective in holding down the lid during the thermal test and the maximum increase in the gap between the seal faces caused by thermal distortion is only 0.8 mm.

DESCRIPTION OF THE 500 LITRE DRUM F.E. MODEL

The SWTC-285 is designed to transport a range of different standard waste packages. The package which was selected to be modelled in the current study was a 500 litre Drum. The SWTC-285 can hold four of these packages, sat inside a frame known as a stillage.

The Finite Element model of the 500 litre Drum is shown in Figure 6. Because of the symmetry of the waste packages inside the SWTC-285, only one half of one drum is represented. The model contains approximately 13,000 elements and 60,000 nodes. The drum is modelled as being filled with ILW encapsulated in a cementitious grout. This waste was given a volumetric heat generation rate corresponding to a total heat output of 50W from each drum. The stillage was not included in the model as it was not expected to have any significant effect upon heat transfer to and from the drum.

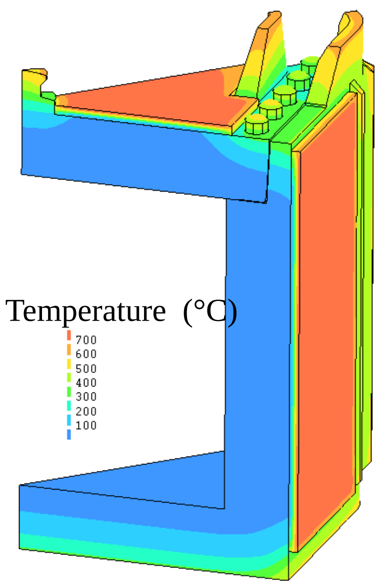

Figure 5: Temperature of the SWTC-285 at the end of the heating phase of the thermal test

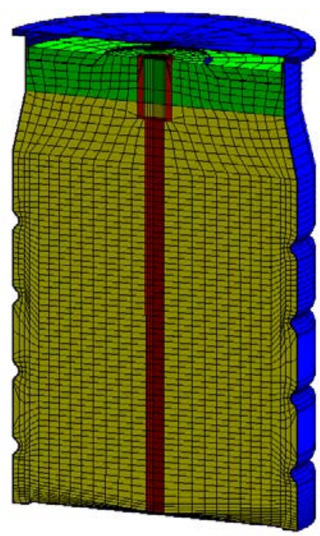

Figure 6: The finite element model of a 500 litre Drum. Materials: Blue- stainless steel; Green- capping grout; Yellow- wasteform; Red- steel paddle

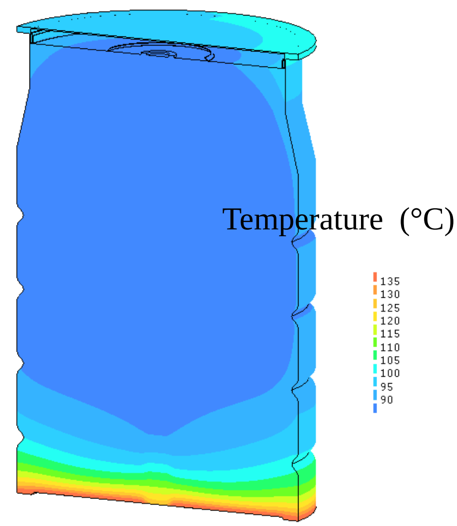

Figure 7. Maximum temperature of the 500 litre Drum experienced during the thermal test

During normal transport the annular foot of the drum will be in good thermal contact with the base of the SWTC-285 while the sides and top of the drum will exchange heat with the SWTC-285 by natural convection and radiation. The temperature of the drum foot was therefore fixed to the base temperature calculated by the SWTC-285 model. Walls representing inner surfaces of the SWTC-285 were included in the model so that the exchange of heat between the drum and the SWTC-285 by radiation and convection could be properly modelled. The temperature of these walls was set to the inner surface temperatures calculated by the SWTC-285 model.

RESULTS FROM THE 500 LITRE DRUM F.E. MODEL

a) Normal transport

It was found that, during normal transport, the temperature of the drums is largely controlled by the temperature of the annular foot in contact with the body of the SWTC-285. The internal heat generation causes the maximum temperature to occur in the centre of the drum but this is only 6°C greater than the temperature of the base.

b) Regulatory thermal tests

To model the temperature of the 500 litre Drum during the thermal test a transient calculation was performed. The fixed temperature of the drum annular foot and the walls representing the inner surfaces of the SWTC-285 were varied as a function of time, following the transient inner surface temperatures predicted in the SWTC-285 thermal test calculation. It was pessimistically assumed that the punch and drop tests prior to the thermal test had resulted in some deformation of the 500 litre Drums such that the whole of the base, and not just the annular foot, is in good thermal contact with the base of the SWTC-285.

Figure 7 shows the predicted maximum temperature that is predicted to occur throughout the 500 litre Drum. The whole drum, and its contents, are predicted to exceed 81°C. The maximum temperature of 141°C occurs at the bottom of the drum where it is in contact with the base of the SWTC-285.

From the predicted distribution of maximum temperature throughout the 500 litre Drum both the release of radionuclides and the internal pressurisation of the SWTC-285 can be calculated. The radionuclide release will depend upon the nature and content of the wasteform. The release of water vapour from the waste package during the thermal test was predicted to produce a maximum pressure of 3.7bar inside the SWTC-285. When added to the pressure from the heating of the gas inside the flask, this gives a maximum total pressure of 13.1bar which the SWTC-285 is easily able to withstand.

CONCLUSION

The thermal performance of the SWTC-285 waste transport container has been assessed. It is concluded that the flask is capable of meeting all the requirement relating to thermal performance specified in the IAEA Transport Regulations for Type B(M).

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