Thermal Modelling of the SAFESHIELD 2999A Package

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1. Introduction

The SAFESHIELD 2999A is a general purpose container, designed by Croft Associates, for transporting small volumes of radioactive materials that require heavy shielding. It is intended for carrying materials as diverse as source capsules and accelerator targets.

An experimental heating test to determine temperatures under normal conditions of transport (NCT) has previously been performed. A pool fire test has also been carried out in order to demonstrate the temperature of the package during hypothetical accident conditions (HAC). Finite Element modelling of the container has also been performed, however, in order to extend the test data to regulatory conditions by including, for example, the effect of solar insolation.

2. Description of the SAFESHIELD 2999A

The SAFESHIELD 2999A container is shaped like an upright cylinder, 1.4m high and 1.0m diameter. The design of the container is shown in Figure 1. It consists of a shielded flask which sits inside a protective casket. The flask is constructed from stainless steel and has thick, lead-filled walls to provide shielding. A bolted lid provides the containment boundary. The outer casket is constructed from mild steel. The walls, lid and base all contain a cavity which is filled with foam to provide protection against both impact and fire under accident conditions. Additional impact protection is provided both above and below the flask by four layers of aluminium honeycomb. The sides and top of the casket are bolted down onto the base. Four vertical plates around the sides of the casket provide holes for lifting the package. A transport frame is also available which enables the SAFESHIELD 2999A container to be easily handled by fork-lift truck.

3. Description of the Finite Element Model

The SAFESHIELD 2999A package is generally axi-symmetric apart from the lifting plates on the casket and some small fins on the flask. The fins on the flask were not considered significant to heat transfer and it was judged that the presence of the lifting plates could be represented via modified boundary conditions. It was therefore judged reasonable to model the package as being axi-symmetric. The Finite Element model of the SAFESHIELD 2999A package is shown in Figure 2. This model, which was generated using the FEMGV pre-processing package [1], contains 6,500 elements and 20,000 nodes and explicitly represents:

- The flask
- The casket
- The lead
- The foam
- The aluminium honeycomb shock absorbers
- The aluminium and steel plates between the layers of honeycomb

4. Calculations Performed

Calculations were first performed to model the experimental heating tests carried out on the SAFESHIELD 2999A package. The results of these calculations were compared against the measured temperatures to demonstrate the validity of the Finite Element model for predicting temperatures under NCT. Following the comparison against the heating test, calculations were performed which modelled the SAFESHIELD 2999A package during normal conditions of transport (NCT) as specified in the IAEA Regulations [2].

A calculation was next performed which modelled the experimental pool fire test which had been performed upon the SAFESHIELD 2999A package. The results of this calculation were compared against the measured temperatures to demonstrate the validity of the Finite Element model for predicting temperatures under HAC. Calculations were then performed modelling a thermal test (pool fire test) as specified in the IAEA Regulations [2].

The calculations were all performed using the FEAT general purpose Finite Element analysis package [3]. FEAT has been developed, and is owned, by British Energy and BNFL. It is well validated and used extensively by British Energy and BNFL to support the safety cases for their nuclear power stations.

5. Material Properties

Measured values or reliable sources were used for all the material properties. Reliable sources were used for the stainless steel, mild steel, lead, aluminium sheet and aluminium honeycomb.

The foam, a material called TISAF, is proprietary to Croft Associates. Measured values of thermal conductivity were available up to temperatures of 108°C but no data was available at the high temperatures experienced by the foam during the fire test. Data from other insulating materials suggests that the thermal conductivity will increase with temperature and that the rate of increase will also increase with temperature. The TISAF foam was therefore assumed to have a component of thermal conductivity which is proportional to the fourth power of absolute temperature (i.e. is proportional to the strength of the thermal radiation). The magnitude of this additional conductivity was then adjusted in order to give good agreement with both the low temperature conductivity measurements and the observed temperatures in the experimental pool fire test.

The foam was also observed to shrink during the experimental pool fire test. This effect was included in the model by modifying the density and thermal conductivity of the foam, as a function of time, to represent those of a sheet of reduced thickness. The rate of shrinkage was assumed to be constant during the fire and to give the measured amount of shrinkage at the end of the fire.

6. The NCT Heating Tests

The principal experimental heating test was carried out at a constant heat load of 250W and in an average ambient temperature of 18°C. The container was sat, on a wooden board, on a concrete plinth in an open room.

The heat input was provided by an electric heater inside an aluminium block in the centre of the flask. The temperature of the package was measured by six thermocouples and ten sets of temperature sensitive strips (which record, within a given rage, the maximum temperature reached). An additional thermocouple measured the ambient temperature and a hand-held probe was also used to make measurements of the temperature of the exterior of the casket.

An earlier heating test, at a heat load of 480W, had also been performed. This test had only been instrumented with three thermocouples.

In common with most heating tests, it was not possible to maintain a constant ambient temperature during the period of several days required to establish equilibrium conditions. Diurnal variations in both ambient and container temperatures were measured by the thermocouples. To minimise the effect of the variations in ambient temperature, the transient temperature measured by each thermocouple during the final 24 hours of the test was averaged to provide the best estimate of the ‘steady state’ temperatures. The magnitude of the diurnal temperature variation at each location, as measured by the thermocouples, was also used in assessing the ‘steady state’ temperature experienced by each of the temperature sensitive strips (which only record the maximum temperature achieved).

The equilibrium temperature inside the flask during the 250W test was 83°C, 65°C above the ambient temperature. The outside of the casket was only about 4°C above ambient.

7. Modelling the NCT Tests

In the model the 250W heat load was, in the absence of any experimental information, applied uniformly over the inner surface of the flask cavity and underside of the lead plug. The sides and top of the casket were modelled as losing heat by natural convection and radiation. Well established correlations were used to derive the appropriate heat transfer coefficients. The bottom of the casket was not perfectly insulated. Heat loss by conduction through the wooden board on which the container was sat was therefore included in the model.

An air space exists, between the sides and top of the flask and the casket, across which heat is exchanged by radiation and natural convection. The surface to surface radiation was modelled using the inbuilt radiation heat transfer capability of FEAT. Natural convection in the enclosed air spaces was modelled using an appropriate correlation for natural convection coefficient.

In the SAFESHIELD 2999A package, narrow air gaps exist between a number of different components and these can produce a significant thermal resistance. The most significant of these are around the lead in the flask and between the sheets of aluminium honeycomb and the load plates that separate them. In the heating test the container was mounted vertically, with the weight of the lead-filled flask supported by the bottom sheets of honeycomb. The effective width of the air gaps between the honeycomb sheets below the flask would therefore be expected to be much less than that between the sheets above it, which are only supporting their own weight.

Because the width of these narrow air gaps is unknown, they were adjusted to give the best agreement between the predicted temperatures and those measure in the experimental heating test. Good agreement was achieved between the predicted and measured temperatures. The maximum difference between measured and predicted temperature was 4°C and the average difference was just 2°C. In particular, the temperature of the O ring seals in the lid of the flask were predicted correctly to within 1°C.

8. Modelling of Regulatory NCT Conditions

Having validated the F.E. model against the experimental results from the heating test, the temperature distribution under regulatory conditions was determined. Two calculations were performed, one without any solar insolation and one with insolation included. When solar insolation was included, a transient calculation was performed, covering a period of ten days, with the heat flux from insolation included for 12 hours each day.

The differences in the boundary conditions between these regulatory conditions calculations and those used to model the heating tests were:

- Increase in ambient temperature to 38°C
- No heat assumed to be lost through the bottom of the casket
- Solar insolation included (in the second calculation).

The rate of solar insolation was taken from the IAEA Regulations [2], with a heat flux of 800W/m^2 being applied to the top and 200W/m^2 to the sides of the casket for 12 hours each day. The flux on the sides corresponds to the value for ‘flat surfaces not transported horizontally’ in the Regulations. This was considered to be more appropriate than the value for ‘curved surfaces’ which is intended to be applied to horizontal cylinders..

The predicted temperature distribution for the case with insolation included is shown in Figure 3. This temperature distribution does not correspond to a particular time during the transient calculation but is instead the maximum temperature achieved at each location. It can be seen that there are significant drops in temperature between the flask and the casket and across the foam insulation and aluminium honeycomb sheets. The average temperature on the inside of the flask cavity is 100°C and the temperature of the seals is 83°C. This is well below their NCT temperature limit of 125°C.

9. The Pool Fire Test

The pool fire test on the SAFESHIELD 2999A container was performed by AEA Technology at Winfrith in England. The test complied with the requirements of the IAEA Regulations [2]. The pool of kerosene fuel was 6m square. The SAFESHIELD container was mounted horizontally on a steel support frame. Good flame cover was achieved and the fire lasted for 36½ minutes. The flame temperature was measured on each side of the container. The maximum flame temperature recorded was 1130°C and the average flame temperature was 962°C.

Instrumentation of a package in a pool fire environment is difficult, especially when the package is to be first subjected to impact tests (as was the case for the SAFESHIELD 2999A). Temperature sensitive strips were therefore the main method of temperature measurement. A few thermocouples were, however, attached to the exterior of the package and pushed through a hole in the casket into the space between the casket and flask.

Although the outside of the casket reached temperatures approaching that of the fire itself, the foam performed its insulating function well and the temperature sensitive strips showed that the seals in the lid of the flask reached a maximum temperature of only between 110°C and 116°C.

10. Modelling of the Pool Fire Test

During the 36½ minute duration of the fire, all the exterior surfaces of the casket were modelled as being exposed to a fire at the measured average temperature (962°C). The emissivity of the fire was assumed to be unity and the convection coefficient to be $10W/m^2/K$. The surface of the casket was assumed to have an absorptivity of 0.8. During the cooling phase the exterior of the casket looses heat by radiation and natural convection. An established correlation was used to derive the natural convection heat transfer coefficient. There was no heat source inside the flask during the experimental test. No internal heat source was therefore modelled.

The thickness of the narrow air gaps were assumed to be same as during normal transport (these thicknesses having been adjusted to give good agreement to the experimental heating test data). The only exceptions were the air gaps between the sheets of aluminium honeycomb below the base of the flask. Since the container was mounted horizontally in the fire test, the weight of the flask was no longer pressing the sheets together and the gaps were therefore assumed to be larger than they were when the container was mounted vertically.

When the SAFESHIELD 2999A container was inspected after the pool fire test, it was found that in inner surface of the casket and outer surface of the flask were coated in a black deposit. It was concluded that this was caused by the products of decomposition of the foam venting into the casket through the holes drilled for the thermocouples. The presence of this deposit will have significantly increased the emissivity of the surfaces which it coated. In order to model this, the emissivity of these surfaces was modelled as being unity.

As described above, the thermal conductivity of the TISAF foam was unknown at high temperatures and was adjusted to give good agreement between the predicted and measured temperatures.

Figure 4 shows the agreement between the predicted and measured temperature on the outside of the casket. The agreement is seen to be good during both the heating and cooling phases. The predicted maximum temperature experienced at the flask lid O ring seals was 112°C, in good agreement with the measured range of between 110°C and 116°C. The internal cavity of the flask was predicted to reach a maximum temperature of 111°C. This is again in good agreement with the measured temperature range of between 104°C and 110°C.

11. Modelling of Regulatory HAC Conditions

Having validated the F.E. model against the experimental results from the pool fire test, the temperature distribution under regulatory accident conditions was determined. The presence of the black deposit on the outside of the flask and inside of the casket which was observed in the experimental test is not expected to occur under accident conditions (since no holes for thermocouples are drilled on operational packages!) but could not be demonstrated to be impossible. Two transient calculations were therefore performed, one with a black deposit on the inner surfaces and one without.

The differences in the boundary conditions between these regulator conditions calculations and those used to model the experimental pool fire test were:

- Increase in ambient temperature to 38°C
- Heat source (250W) represented inside the flask
- Solar insolation included during the cooling phase
- Initial temperature distribution increased to correspond to NCT conditions (with insolation).
- Duration of fire reduced to 30 minutes
- Temperature of fire reduced to 800°C
- Emissivity of fire reduced to 0.9

Figure 5 shows the maximum temperatures reached at each point on the container during the regulatory fire test. The exterior of the casket reaches temperatures close to 800°C but the flask experiences temperatures only moderately above 100°C. The peak temperatures in the flask are reached around 7 hours after the start of the fire. The maximum temperature experienced by the flask lid O ring seals is 132°C, well below their short term upper temperature limit of 200°C. The maximum seal temperature predicted for the ‘no blackened surfaces’ case is slightly below that predicted when the effect of blackening is included. The lead in the flask is predicted to reach a maximum temperature of 139°C, well below its melting point of around 290°C. The inner cavity of the flask reaches a maximum temperature of 148°C.

12. Conclusions

A Finite Element analysis has been performed of the thermal performance of the SAFESHIELD 2999A container. This analysis complemented the experimental heating and fire tests performed upon the container. The tests provided validation of the F.E. model while the analysis enabled the effect of regulatory requirements (such as a 38°C ambient and solar insolation) to be accurately determined. The thermal analysis of the SAFESHIELD 2999A demonstrates how a combination of testing and F.E. analysis can be used to determine the maximum temperatures that may occur under normal and accident conditions of transport. Neither testing nor F.E. analysis alone are capable of accurately determining these temperatures with any confidence.

The SAFESHIELD 2999A container was successfully shown to meet all the requirements of the IAEA Regulations, with respect to thermal performance, for a type B(U) package.

References

1. ‘FEMGV User Manual’, Release 6.3, Femsys Ltd, 2002.

2. ‘Regulations for the Safe Transport of Radioactive Material’, IAEA Safety Standards Series, 1996 Edition (Revised), ST-1, IAEA, Vienna.

3. ‘FEAT User Guide’, Rel

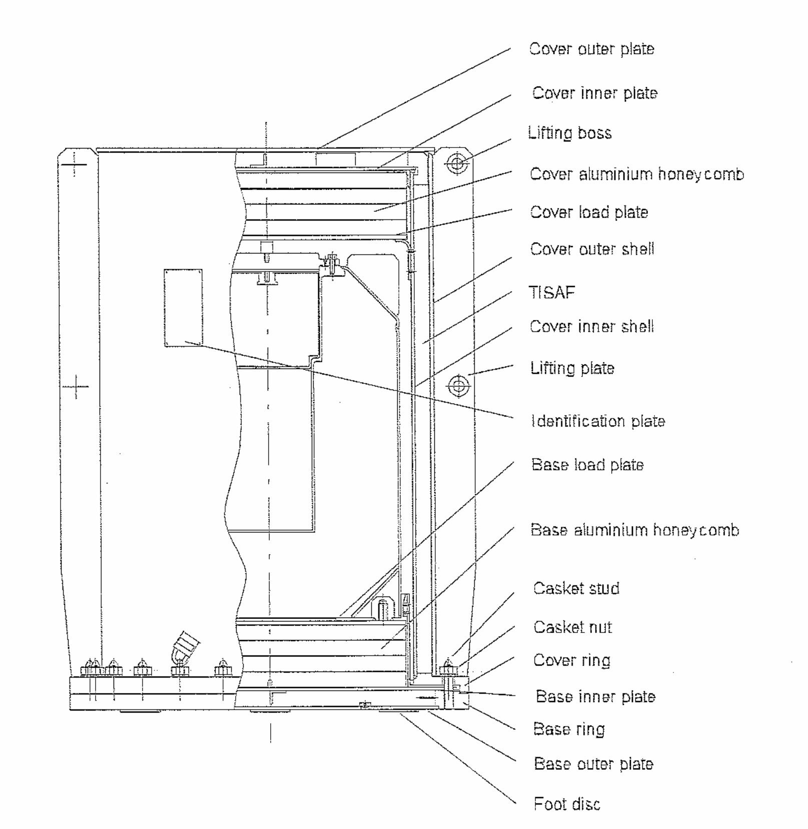

Figure 1 – The SAFESHIELD 2999A Package

Materials

Blue - Stainless steel
Red - Low carbon steel
Orange - Lead
Yellow -Foam
Green - Al honeycomb
Violet - Foam/support

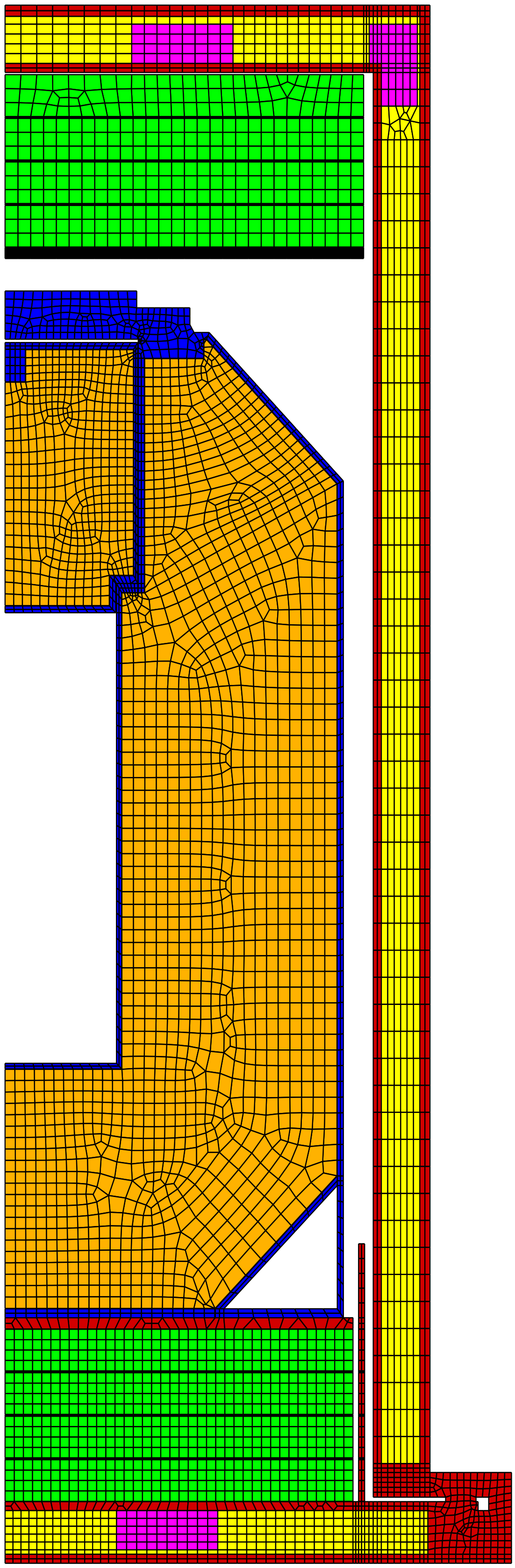

Figure 2 – The Finite Element Model

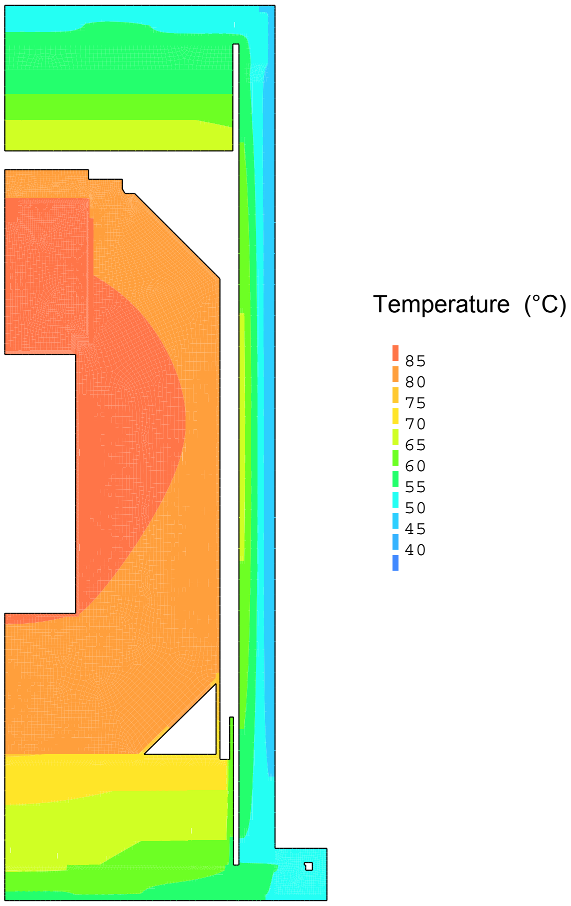

Figure 3 – NCT Temperature Distribution – With Insolation

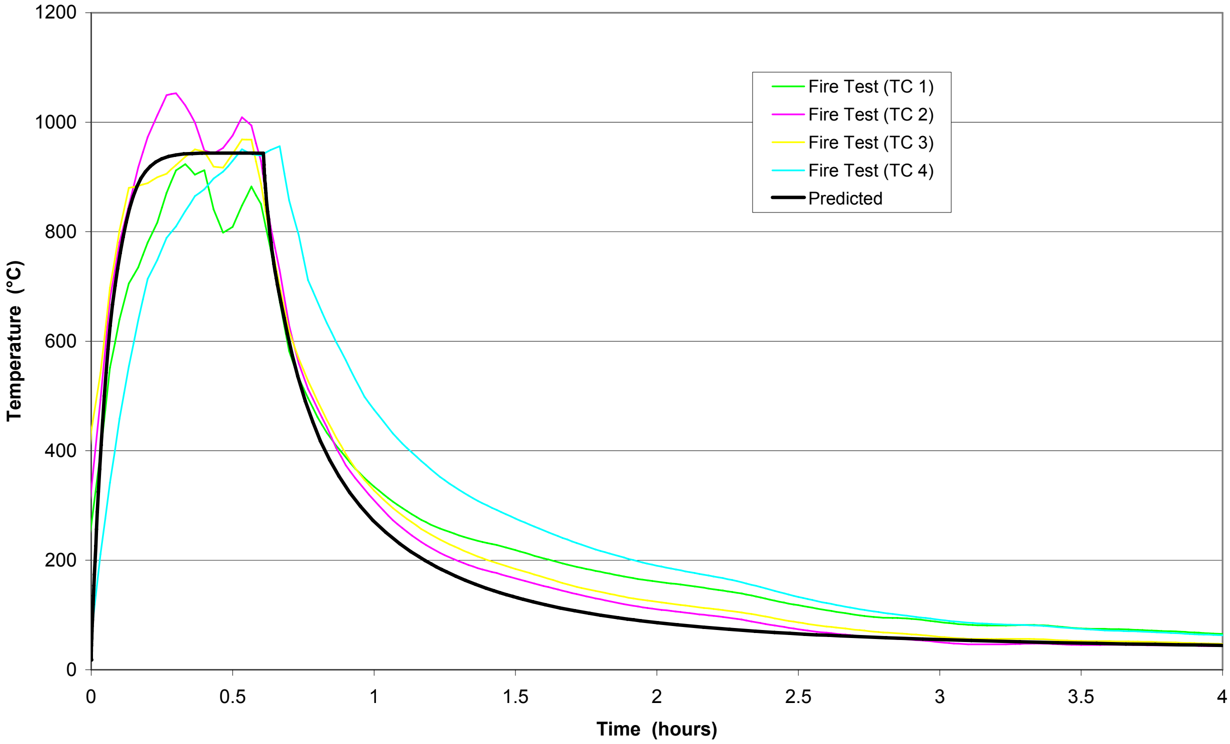

Figure 4 – Predicted and Measured Casket External Surface Temperature during the Experimental Pool Fire Test

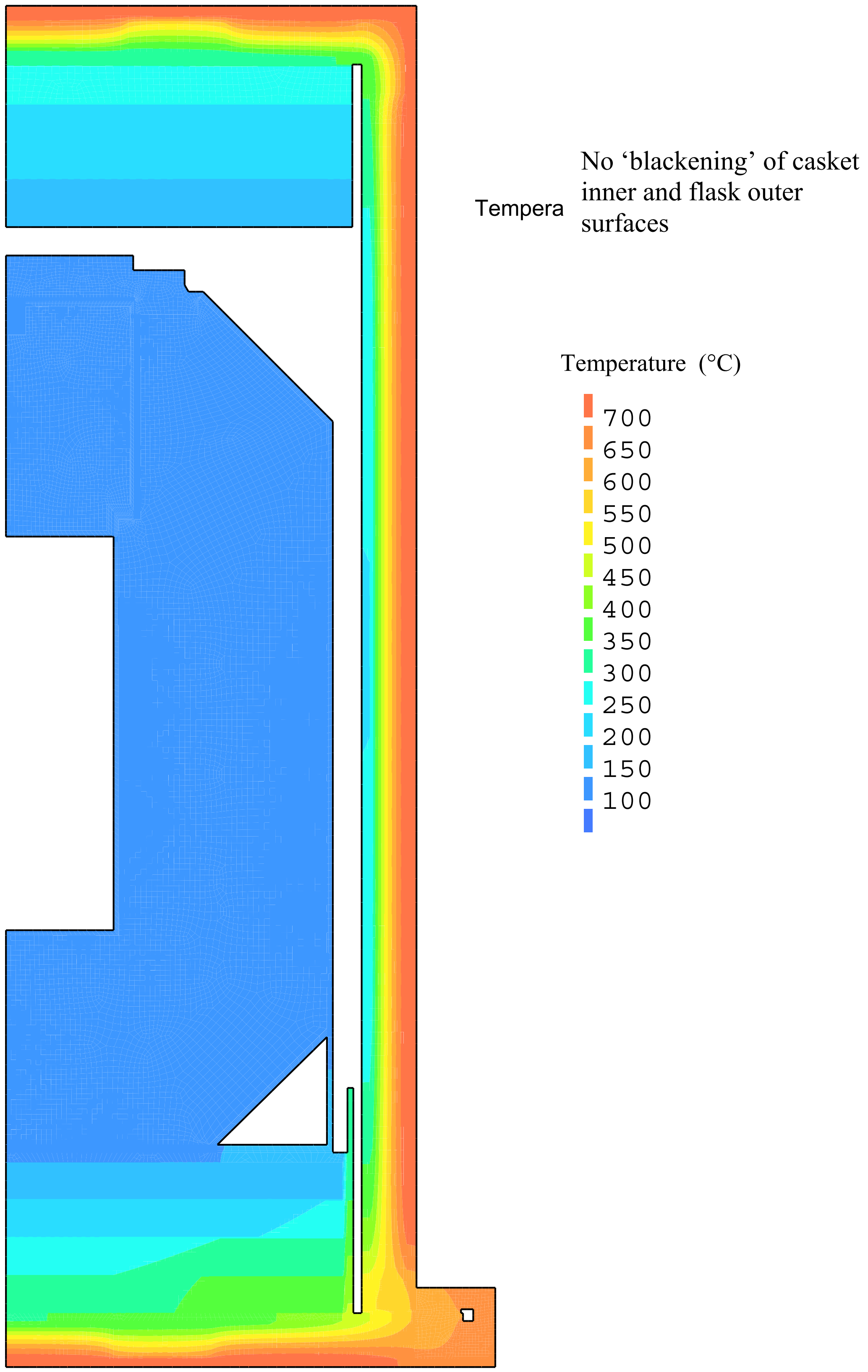

Figure 5 – HAC Temperature Distribution – Maximum Temperatures Reached During Transient