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NUMERICAL SIMULATION OF HI-STAR 63 WITH POLYURETHANE FOAM IMPACT LIMITER DURING HYPOTHETICAL FIRE ACCIDENT

Abrar H. Mohammad and Indresh Rampall
Holtec International
Marlton, NJ, USA

ABSTRACT

The Holtec International Storage, Transport, and Repository (HI-STAR 63) package is a type B(U), radioactive package containing commercial Spent Nuclear Fuel (SNF) designed for the transportation of the SNF. The HI-STAR 63 cask is installed with Polyurethane (PU) foam impact limiters primarily because of its capacity for energy absorption under hypothetical drop accidents and thermal insulation under fire accidents. The thermal response of the HI-STAR 63 cask when exposed to a high temperature fire of 1475^{o}F (802^{o}C) for a period of 30 minutes, based on the 10CFR71 Hypothetical Accident Conditions (HAC), has been evaluated. A fire safety test was conducted in a high-temperature furnace at the Southwest Research Institute (SwRI) to ensure the safe transport capability of the HI-STAR 63 package. Numerical simulations of the HI-STAR 63 1/3 scale model subjected to the furnace test fire have been carried out using Computational Fluid Dynamics (CFD) code FLUENT. A three-dimensional CFD model is constructed to model the packaging with the PU foam-filled impact limiters and transient numerical simulations are carried out to predict the temperatures of safety-significant HI-STAR 63 cask components. The CFD results were compared with the fire test results near the seal region of the containment boundary. The CFD results for the scale model bounds the measured test data in respect of temperatures and reliably predicts the time at which the seal temperatures peak. CFD simulations of the 1/3-scale HI-STAR 63 tests therefore provide additional assurance of the capability of the CFD methodology deployed to evaluate the thermal performance of transport packages.

INTRODUCTION

HI-STAR 63 (acronym for Holtec International Storage, Transport, and Repository) is the model name of a transport cask engineered to serve as a Type B(U)F-96 packaging for transporting radioactive material (including commercial spent fuel or CSF) under exclusive or non-exclusive use shipment pursuant to transport regulations. The HI-STAR 63 System consists of a sealed, metal multi-purpose canister, herein abbreviated as the "MPC", contained within an overpack with impact limiters. Figure 1 provides a pictorial view of the HI-STAR 63 cask. This design concept is same as the multi-purpose canister concept articulated in the U.S. Department of Energy (DOE) [1, 2].

The HI-STAR 63 Cask containment system boundary is engineered similar to the anatomical design and construction of the containment boundary of the HI-STAR 100 certified for transport [3] and for storage [4]. More specifically, the containment boundary materials, welding joint details, NDE requirements, gasket joint configurations, and Code of design and fabrication for the HI-STAR 63 containment boundary, etc., are identical or more robust than those of the HI-STAR 100 (certified by the United States Nuclear Regulatory Commission, USNRC, and deployed at nuclear plants since the late 1990s). The protection against release of radionuclides for the cask closure is achieved by the use of a bolted closure lid equipped with two concentric annuli seals providing two independent barriers against leakage. As with HI-STAR 100, a multi-layer steel shell construction surrounds the containment boundary to provide a natural barrier against crack propagation and a significant portion of the gamma shielding. The steel thickness of the cask also provides sufficient neutron shielding from the design basis fuel contents and therefore no special neutron shielding material is required.

The HI-STAR 63 Package accommodates a fuel basket within its storage cavity. Except for the integral lid carrier housing and remotely operated closure lid carrier, the design embodiment, construction, and structural materials (except where stainless steel materials are determined to be suitable options) employed in the HI-STAR 63 are identical to that used in the HI-STAR 100. Figure 2 provides a pictorial of the HI-STAR 63 Packaging. The cask is engineered with polyurethane (PU) foam impact limiters on each side.

METHODOLOGY

As mandated by Transport Regulations [5], the HI-STAR 63 package is subjected to a sequence of hypothetical accident conditions. The objective is to determine and assess the cumulative damage sustained by the package. The accident scenarios specified in order are: (i) a 30 foot free drop onto an unyielding surface; (ii) a 40-inch drop onto a mild steel bar; (iii) exposure to a 30-minute fire at 800°C (1472°F) and (iv) immersion under a 3 ft head of water. The initial conditions for the fire accident specify steady state at an ambient temperature between –40°C (-40°F) and 38°C (100°F). This paper discusses the effects of hypothetical accident (iii). The initial condition prior to fire accident is the hot ambient environment for normal transport and a heat load inside the fuel basket. The fire accident is evaluated assuming an adverse combination of factors that overestimate heat input during fire and underestimate heat rejection to the environment after the fire.

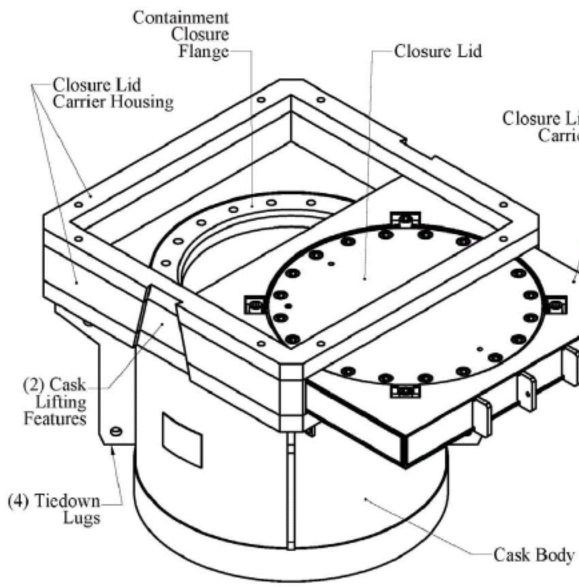


Figure 1. Exterior View of the HI-STAR 63 Cask

SCALE MODEL TEST PACKAGE

The HI-STAR 63 scale model used for the physical test was based on a 1/3 scale representation (to the extent practical) of the full scale HI-STAR 63 cask design. The physical test was carried out on a 1/3-geometrically scaled HI-STAR 63 cask with 1/3-scale top impact limiter and dummy loaded basket. However, the crush material and crush strengths of the impact limiter remain unchanged with the scale of the physical dimensions. The bottom impact limiter shown in Figure 2 was not modeled as a separate component but as a dummy impact limiter integral to the cask with appropriately simulated weight and CG since the most damaging cask drop orientation to be top end down. The diameter of the seals and its seal grooves were essentially 1/3 scale. Of most critical importance was the scale modeling of the top PU impact limiter and the cask closure system (closure lid, bolts and seal materials). These components were precisely modeled due to their high importance to fulfilling the test objectives.

A one-third scale test model of the HI-STAR 63 transportation package was subjected to a 9-meter "free drop test on an essentially unyielding surface in the most vulnerable configuration" at the Sandia National Laboratory in Albuquerque, New Mexico. The package survived the fall with its impact limiter deformed but firmly attached.

Subsequent to the impact, the package was subjected to the 1-meter drop-on-a-penetrant-column test. After enduring the 9-meter drop and 1-meter puncture tests, the package was taken to the Southwest Research Institute in San Antonio, Texas where it was subjected to an 800°C (1472°F) thermal test. The sequence of tests was carried out in strict accordance with the 10CFR71 regulations [5]. The series of tests provided the physical proof that all performance demands on the package under the hypothetical accident conditions postulated in 10CFR71.73 are satisfied; namely, the package maintained its leak-tightness and its shielding effectiveness. The tests indicated no need for any design change.

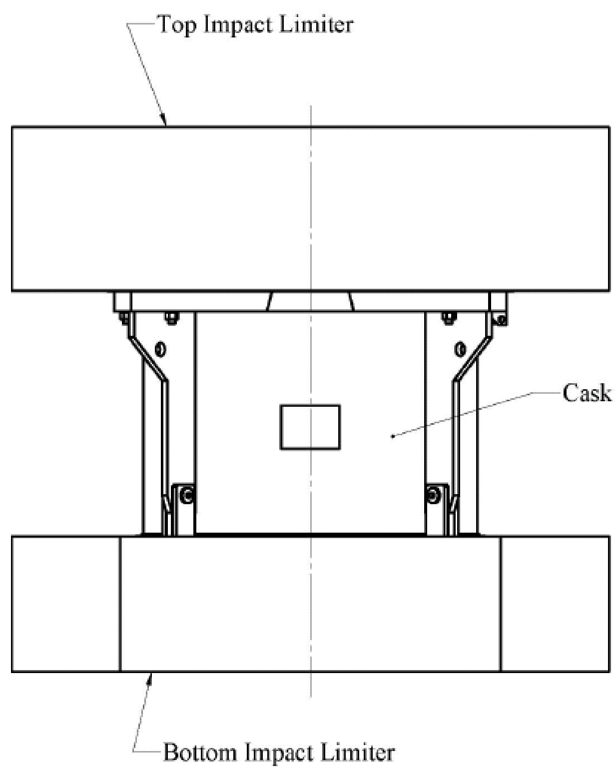


Figure 2. Exterior View of HI-STAR 63 Packaging

HIGH-TEMPERATURE FURNACE TEST

The post-test condition of the package following the puncture test was the pre-test condition for the high-temperature furnace test. The test cask was instrumented with 25 thermocouples. These thermocouples were located on the cask lid, the cask side, between the cask and the impact limiter, on the impact limiter skin, inserted in four of the closure bolts to a depth equal to that of the sealing surface, and one on the cask contents. After installation of the thermocouples, which were spot welded to the cask body using nickel strips, the cask body was re-painted with high-temperature paint.

The furnace test was conducted at Southwest Research Institute (SwRI). The information from the test is used to determine the thermal environment the cask experienced during the test, the spatial and temporal distribution of temperatures within the cask, and the ability of the cask to maintain containment following the test. To conduct the test, the unit was first thermally conditioned by allowing it to sit in an insulated temperature conditioning box for approximately 20 hours. The temperature of the conditioning chamber was adjusted several times during that period to assure the cask temperature, as measured by the thermocouples in the closure bolts, was at 92°C (198°F) when the cask was lowered into the furnace. The preheating ensures that the overpack initial temperature is equal to or greater than the HI-STAR 63 cask transport temperatures. The furnace is pre-heated for period of at least 30 minutes before the cask was removed from the temperature conditioning chamber.

The required duration for the test is determined by comparing the scale model heat input to the full-scale cask regulatory specific heat input. For the full-scale cask the specific heat input can be calculated by:

$$Q_F = \left(\pi DL + \frac{\pi D^2}{2}\right)\sigma F\left(\varepsilon_F, \varepsilon_P\right)\frac{\left(T_F + 273\right)^4}{M_P}\tau_F, \quad (1)$$

where:
Q_F is the full-scale specific heat input J/kg,
D is the full-scale package diameter = 3.889 m,
L is the full-scale package length = 2.516 m,
σ is the Stefan-Boltzmann constant = 5.67 x 10-8 W/m^2K^4,
$F(\varepsilon_F,\varepsilon_P)$ is the view factor for a fully engulfing fire, which is calculated by:

$$F\left(\varepsilon_F, \varepsilon_P\right) = \frac{1}{\frac{1}{\varepsilon_P} + \frac{1-\varepsilon_F}{\varepsilon_F}\left(\frac{A_P}{A_F}\right)} = 0.5625 \quad (2)$$

ε_F is the regulatory flame emissivity = 0.9,
ε_P is the package surface emissivity = 0.6,
A_P/A_F is the surface area ratio of the package to the fire = 1 for an opaque fire,
T_F is the fire temperature = 800°C,
M_P is the mass of the full-scale package = 25,589 kg,
and τ_F is the regulatory fire duration = 1800 sec.

Solving equation (2) gives a specific heat input of 162,000 J/kg.

The required scale model fire duration to obtain an equal specific heat input can be calculated by:

$$\tau_{\min} = \frac{Q_F M_S}{\left(\pi D_S L_S + \frac{\pi D_S^2}{2}\right)\sigma F\left(\varepsilon_{tc}, \varepsilon_S\right)\left(T_{tc} + 273\right)^4} \quad (3)$$

where:
D_S is the scale model diameter = 1.293 m,
L_S is the scale model length = 0.758 m,
T_{tc} is the furnace temperature = 800°C,
M_S is the scale model mass = 973 kg,
$F(\varepsilon_{tc},\varepsilon_S)$ is the view factor for a package in a furnace, which is calculated by:

$$F\left(\varepsilon_{tc}, \varepsilon_S\right) = \frac{1}{\frac{1}{\varepsilon_S} + \frac{1-\varepsilon_{tc}}{\varepsilon_{tc}}\left(\frac{A_S}{A_{tc}}\right)} = 0.9 \quad (4)$$

ε_{tc} is the furnace surface emissivity = 0.58,
ε_S is the scale model package surface emissivity = 0.95,
A_S is the surface area of the scale model = 5.7 m^2
A_{tc} is the interior surface area of the furnace = 70.65 m^2

Solving equation (4) gives a required fire duration of 409 seconds. After the desired test duration of 409 seconds, the cask was lifted out of the furnace and transferred to the indoor cooling area. It is observed that the PU foam impact limiter catches fire locally. This fire is referred to as secondary fire. After the secondary fire died, the package is allowed to cool down to ambient conditions. The temperature history of the closure bolts at the lid seal location is monitored during the furnace test and thereafter.

TEST RESULTS

The principal results from this test are the post-test leak rate, the seal temperature (as measured by the thermocouples in the closure bolts), and the peak canister temperature. Figure 3 shows a sequence of photos from furnace test and cool-down. The temperature of the seal region, as measured by the thermocouples inserted in the closure bolts to the depth of the seal, peaked between 170 and 182°C, depending on the gage. This temperature is below the manufactures recommended maximum long-duration operating temperature of 204^{o}C (400^{o}F). Figure 5 shows the temperature history for the closure bolts during the furnace and cool-down periods. The fastest acting thermocouples on the package were those on the exterior skin of the impact limiter. Figure 7 shows the temperature history for the thermocouple that bounds the other thermocouples. Overall, the cask performed as intended and its ability to contain its radioactive contents and perform its shielding requirements were not compromised.

Open furnace ready for cask

Furnace closed

Cask being removed from furnace

Cask in cool-down area

Fire from foam burning almost out

Figure 3. Sequence of High-Temperature Furnace Test

THERMAL MODEL

A thermal transient simulation model to determine the fire condition temperature response is developed on the FLUENT CFD code [6]. This model incorporates time dependent thermal loads on the exposed surfaces of the HI-STAR 63 System for determining transient responses of the 1/3 scale HI-STAR 63 cask.

Numerical simulations are carried out using FLUENT to predict the thermal behavior of the cask components during fire (furnace test) and post-fire conditions (cask cool down). The HI-STAR 63 package 1/3-scale tests are utilized to demonstrate the validity of the CFD analysis approach by comparing the FLUENT predictions against the experimentally measured test data i.e. closure lid temperatures at the elevation of the seal. Critical information such as the furnace temperature, duration of fire and ambient temperature are obtained from the tests.

The HI-STAR 63 1/3-scale package is a cylindrical container equipped with an impact limiter to simulate the scaled weight and dimensions of the HI-STAR 63 package. A geometrically accurate three-dimensional half-symmetric representation of the 1/3-scale HI-STAR 63 package was constructed using the FLUENT pre-processor GAMBIT [6]. An isometric view of the model is presented in Figure 4. The dynamic model features several conservative assumptions to bound temperature excursions during the heat up and cooldown phases of the accident. An overview of the principal features of the 3D thermal model is provided in the following:

i. The basket assembly is a hollow cylinder placed in the cask to simulate the basket mass during the tests.
ii. The 1/3 scale HI-STAR 63 containment baseplate, closure lid and containment shell are explicitly included in the 3D model.
iii. The 1/3 scale HI-STAR 63 package is heated to an initial temperature of 92^{o}C (198^{o}F). All the cask components are at 92^{o}C (198^{o}F) prior to beginning the furnace test.
iv. To evaluate the hot furnace condition, an external ambient temperature of 809^{o}C (1488^{o}F) is applied to simulate the furnace temperature during the fire test. The temperature of the furnace during the furnace test was conservatively higher than the minimum regulatory requirement of 800^{o}C (1472^{o}F).
v. Surface to surface thermal radiation heat transfer is modeled using the Discrete Ordinates (DO) radiation model in FLUENT.
vi. The thermal solution employs all three modes of heat transfer – conduction, radiation and convection.
vii. The Sandia laboratories reported forced convection heat transfer coefficient during large pool fires is adapted to model convection heat input [7].
viii. The 1/3 scale HI-STAR 63 package is positioned upside down which is consistent with the test configuration (i.e. the impact limiter is positioned towards the ground as shown in Figure 4).
ix. The duration of furnace fire was summarized in the previous section.
x. To evaluate the post-fire cooldown condition, an external ambient temperature of 28^{o}C (83^{o}F) was applied on all external surfaces of the cask.
xi. Natural convection and radiation heat transfer from the surface of the cask to the ambient was conservatively understated in the thermal model during post-fire cooldown.

The principal assumptions used in the analyses are presented below:

i. The temperature of the furnace is an average of the temperatures measured using the thermocouples kept at four different locations inside the furnace. This assumption ensures that the total heat input to the 1/3-scale model is the same as that during the actual furnace-test.
ii. As mentioned earlier, it was observed during the course of the furnace tests that the PU foam crush material combusts during the fire-test and it continues to do so locally after it is taken out of the furnace. The temperature of the foam-fire is conservatively assumed to be 600^{o}C (1112^{o}F) [8].

iii. The package outer surface was painted black to maximize the heat input into the package. To maximize the fire heating of the cask inside the furnace, an all engulfing fire with a high flame emissivity of 0.9 and a theoretically bounding package absorbtivity are assumed.

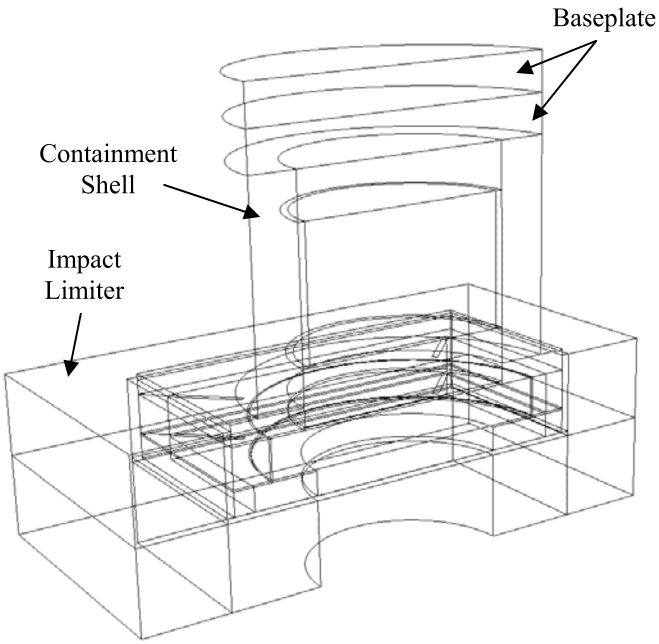


Figure 4. Isometric View of the 1/3 scale HI-STAR 63 Half-Symmetric Thermal Model

The 1/3 scale HI-STAR 63 package is pre-heated to 92°C and is then placed inside the furnace maintained at 809°C. The HI-STAR 63 package is exposed to a furnace fire for 409 seconds (primary fire). During the test, the foam material combusts. To predict the temperatures accurately, the numerical simulations incorporated the secondary fire effects due to foam combustion. The combustion heat input to cask continues for about 13 minutes after the package is removed from the furnace. The various steps in the analyses are presented below:

i. Furnace fire – The HI-STAR 63 package with an initial temperature of 92°C is placed inside the furnace maintained at a temperature of 809°C. This event lasts for 409 seconds.
ii. Post-furnace combustion heat input – The post-furnace heat input is applied to the FLUENT model in three steps as follows:
    a. Secondary Fire (SF) 1 - Heat input to entire cask outer surface and top of the impact limiter surface for 4 minutes.
    b. SF2 - Heat input to cask outer surface restricted to short height and on top of the impact limiter surface. This event lasts for 1.5 minutes.
    c. SF3 - Heat input to a small region of the cask and a part of the impact limiter surface. This event lasts for 7.5 minutes.
iii. Post-fire cooldown – The HI-STAR 63 package is allowed to cool down under ambient temperature of 28°C (83°F) for sufficient time to reach peak temperatures.

Heat input to the HI-STAR 63 cask while it is engulfed in a fire is from a combination of radiation and forced convection heat transfer to all cask/impact limiter exposed surfaces. This can be expressed by the following equation:

$$q_F = h_{fc}(T_F - T_s) + \sigma\,\varepsilon\,[(T_F + 460)^4 - (T_s + 460)^4] \qquad (5)$$

where:

q_F =	surface heat input flux (Btu/ft^2-hr)
T_F =	fire condition temperature 809°C (1488°F)
T_S =	transient surface temperature (°F)
h_{fc} =	forced convection heat transfer coefficient [Btu/ft-hr-°F]
ε =	surface emissivity = 0.9 (per 10CFR71 [5])
σ =	Stefan-Boltzmann Constant (0.1714×10^{-8} Btu/ft^2-hr-°R^4)

For conservatism, the Sandia laboratories reported forced convection heat transfer during large pool fires (h_{fc} = 25.5 W/m^2-°K (4.5 Btu/ft^2-hr-°R) [7]) is adopted.

After the fire event, the ambient temperature is restored to 28°C (83°F). The HI-STAR 63 System cools down during this post-fire cooldown phase. Heat loss from outside exposed surfaces of the cask is determined by the following equations:

$$q_S = 0.18\,(T_S - T_A)^{4/3} + \sigma\,\varepsilon\,[(T_S + 460)^4 - (T_A + 460)^4] \qquad (6)$$

where:

q_s=	surface heat loss flux (Btu/ft^2-hr)
T_S =	transient surface temperature (°F)
T_A =	ambient temperature (83°F)
ε =	surface emissivity
σ =	Stefan-Boltzmann Constant (0.1714×10^{-8} Btu/ft^2-hr-°R^4)

During this entire transient event (fire and post-fire cooldown), the temperature history of closure lid bolts at the seal location in the HI-STAR 63 System is monitored.

NUMERICAL RESULTS AND CONCLUSION

A transient analysis was performed to simulate the fire test conditions and the post-fire cooldown of the HI-STAR 63 1/3-scale package using FLUENT. The variation of maximum temperature of the closure lid bolts at seal elevation is plotted against time and is shown in Figure 5. The predicted temperatures of the closure bolt from the CFD simulations are compared with the temperatures from the 1/3-scale tests. The CFD results conservatively bound the test data. Figure 6 shows the temperature contour on the outer surface of the HI-STAR 63 package for the sequence of events described before. Figure 7 shows the variation of maximum temperature on the exterior skin of the impact limiter. The numerical results bound the test data.

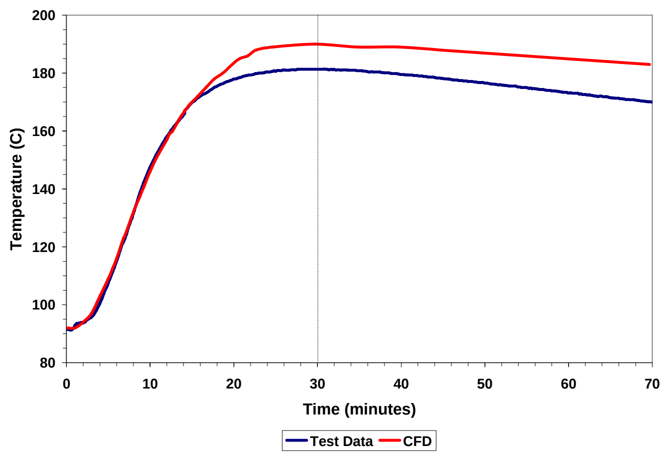
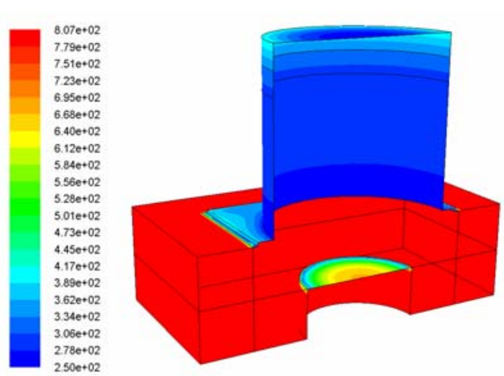


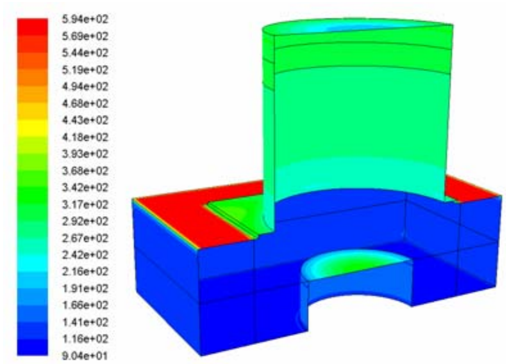
Figure 5. Comparison of CFD Results and Test Data for Closure Lid Bolt Temperature

Following specific observations can be made from the results:

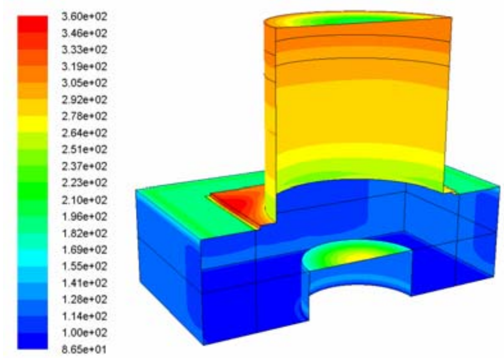
1. The temperature of the closure bolts reach the peak temperature at essentially the same time (approximately 30 minutes after the start of furnace fire) for the CFD results and test data.
2. The CFD results are in good agreement with the test data. The maximum temperatures of the closure bolts from the CFD simulations are slightly higher than the test data during the furnace fire (about 1-3 degree Celsius).
3. The CFD results bound the measured test temperatures (See Figure 5).



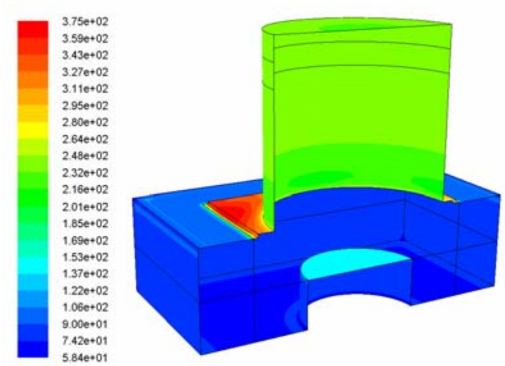
(a) At the end of furnace fire - after 409 seconds



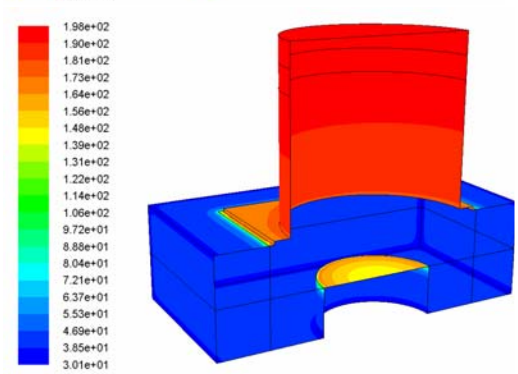
(b) At the end of SF1 - after 649 seconds



(c) At the end of SF2 - after 739 seconds



(d) At the end of SF3 - after 1189 seconds



(e) Post-fire cooldown - after 4200 seconds

Figure 6. Temperature (in ^{o}C) Contours of the 1/3 scale HI-STAR 63 Package Outer Surface

The results of the FLUENT simulations for the scale model test bounds the measured test data in respect of temperatures. The temperature of the closure lid seals from the test data are well within the temperature limit of 204°C (400°F). In conclusion, simulation results of the 1/3-scale HI-STAR 63 tests provide additional assurance of the capability of the CFD methodology deployed to evaluate the thermal performance of the HI-STAR 63 package.

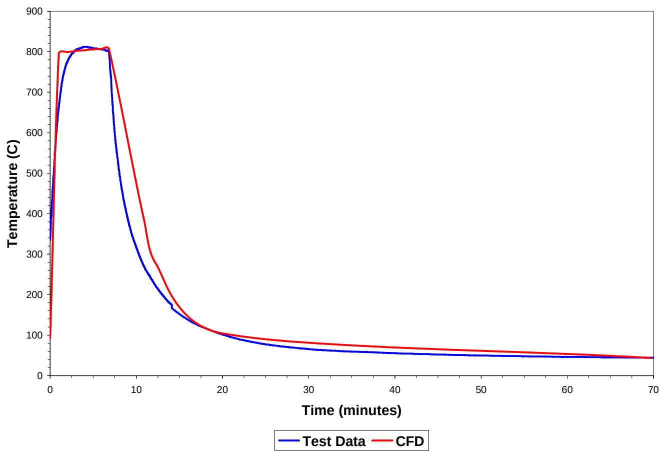


Figure 7. Comparison of CFD Results and Test Data for Impact Limiter Exterior Skin

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REFERENCES

[1] U.S. Department of Energy, "Multi-Purpose Canister (MPC) Subsystem Design Procurement Specification", Document No. DBG000000-01717-6300-00001, Rev. 5, January 11, 1996.

[2] U.S. Department of Energy, "MPC Transportation Cask Subsystem Design Procurement Specification", Document No. DBF 000000-01717-6300-00001, Rev. 5, January 11, 1996.

[3] HI-951251, Latest Revision, "Storage, Transport, and Repository Cask System (HI-STAR 100 Cask System) Safety Analysis Report", USNRC Docket 71-9261.

[4] HI-2012610, Latest Revision, "Final Safety Analysis Report for the Holtec International Storage, Transport, And Repository Cask System (HI-STAR 100 Cask System), USNRC Docket 72-1008.

[5] 10CFR Part 71, "Packaging and Transportation of Radioactive Materials", Title 10 of the Code of Federal Regulations, Office of the Federal Register, Washington, D.C.

[6] FLUENT, Computational Fluid Dynamics Software (Fluent Inc., Centerra Resource Park, 10 Cavendish Court, Lebanon, NH 03766).

[7] "Thermal Measurements in a Series of Large Pool Fires", Sandia Report SAND85 – 0196 TTC – 0659 UC 71, (August 1971).

[8] Prager, F. H. and Rosteck, H., "Polyurethane & Fire – Fire Performance Testing under Real Conditions", 2006.