Analyses to Demonstrate the Thermal Performance of the CASTORÒ KN12

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INTRODUCTION

The CASTOR® KN-12 is a new cask design of GNB for dry and wet transportation of up to 12 PWR spent nuclear fuel assemblies in Korea. It complies with the requirements of 10 CFR 71 [1] and IAEA ST-1 [2] for TYPE B(U)F packages. It received its transport license from the Korean Competent Authority KINS in July 2002 and is now in use in South Korea.

Demonstration of the cask's compliance with the regulatory requirements in the area of thermal performance has been carried out by a combination of testing carried out by Korea Atomic Energy Research Institute and analyses carried out by Arup.

This paper describes the analyses to demonstrate the thermal performance of the cask and compliance with regulatory requirements under normal and hypothetical accident conditions of transport. Other aspects of the design of the CASTOR® KN12 are presented in other papers at this conference.

DESCRIPTION OF THE CASK

The containment vessel consists of a cylindrical thick-walled forged carbon steel body, closed by a stainless steel lid with thirty-seven M48 studs with nuts and three M48 cap screws and sealed by an elastomer O-ring. The cask cavity and the O-ring seating surfaces are covered by a welded stainless steel cladding for corrosion protection.

In the lid, a vent and drain opening are integrated and closed by a closure plug with an elastomer O-ring seal and covered by the bolted closure lid also sealed with an elastomer O-ring.

Neutron shielding is provided by a polyethylene plate at the bottom side of the cask and two rows of thirty six polyethylene rods residing in longitudinal bore-holes in the cask wall.

Fuel assemblies are located within a fuel basket which consists of rectangular stainless steel receptacles, in a grid work of borated aluminium sheets and spacer units. The borated aluminium plates provide efficient heat removal, and the boron content of these plates assures nuclear criticality safety under normal transportation and under hypothetical accident conditions.

Two pairs of trunnions are attached for lifting, manoeuvring and also tie-down during transportation.

Energy absorption and control of deceleration during hypothetical accident 9m drop scenarios are provided by a pair of impact limiters, one at each end of the cask, attached to the cask by bolts during transportation. They are manufactured from a carbon steel inner structure and a stainless steel outer shell filled with wood. The outer steel shell is welded water tight to protect the wood against humidity. The steel shell was designed to fully utilise the energy absorbing capacity of the wood.

The cask has been designed to carry up to twelve PWR fuel assemblies of various configurations: 17x17, 16x16 or 14x14, in dry or wet transportation – i.e. with helium or water as backfill.

The cask is intended for road transport. During transport, the cask will be horizontally oriented and sheltered from solar radiation by a transport hood.

METHODOLOGY TO DEMONSTRATE REGULATORY COMPLIANCE

Demonstration of the cask's compliance with the requirements of 10 CFR 71 and IAEA ST1 in the area of thermal performance were carried out by a combination of tests and analyses. Finite Element (hereafter, FE) analyses were conducted to evaluate its performance in the normal and hypothetical accident conditions of transport. Tests of a select set of the scenarios were then carried out using a 1/8 slice model which consists of 1/8th the height of the cask and with insulated ends. Besides itself being a demonstration of the thermal design of the cask, the tests were also used to validate the FE analyses of the tests which were carried out before the tests. Since the same modelling methodology was used in the analyses of the full scale cask and the slice model, validation of the FE analyses of the tests also served to validate the methodology of the FE analyses of the full scale cask.

TEMPERATURE LIMITS

Under the normal conditions, the cask must lose the heat generated by the fuel to the environment without exceeding the operational temperature limits of the cask components important to safety.

In order to avoid melting of the fuel pellet, the temperature of the pellet centreline must not exceed 2593 °C (2866 K) for normal operating conditions and hypothetical accident conditions.

To avoid failure of the fuel cladding from accelerated oxidation, the maximum temperature of the fuel rod cladding should be limited below 398 °C (671 K) for normal operating conditions and 426 °C (699 K) for hypothetical accident conditions. These are the same as the design criteria for the fuel assemblies in the reactor core.

EVALUATION BY ANALYSIS

The thermal conditions specified by 10 CFR 71 and IAEA ST1 are summarised as follows:

	Ambient Temperature	**Insolance**	**Decay Heat Generation**
Normal Conditions			
Hot Condition	38 °C (311 K)	✓	Maximum
Cold Condition	-40 °C (233 K)	×	Maximum
Minimum Temperature Condition	-40 °C (233 K)	×	None
Hypothetical Accident Condition			
Initial Conditions	38 °C (311 K)	✓	Maximum
30 minute Fire Phase	800 °C (1073 K)	×	Maximum
Cool Down Phase	38 °C (311 K)	✓	Maximum

Only the cask with the 17x17 PWR fuel assemblies was analysed, as this represents the worst case, in terms of temperatures in the cask and in the fuel assemblies and also in terms of pressure. And among the normal conditions of transport, only the Hot Condition was analysed for the same reasoning. The analyses considered both water and helium as backfill mediums.

One basic three-dimensional FE model was used for the analysis of all the normal and hypothetical accident conditions, by applying different sets of boundary conditions and material properties. The explicit non-linear FE code LS-DYNA [3] was used for the analyses.

The model is shown in Figure 1. It consists of all significant components of the whole package. The model consisted of only half a cask taking advantage of symmetry. Different material properties, corresponding to the wet cask or the dry cask, were applied to the model to simulate the two backfill cases.

As the cask is to be transported horizontally, the basket was modelled to rest on one side of the cask inner wall with a maximum gap on the opposite side.

The transport hood was not modelled. Instead, air temperature between the hood and the cask was obtained by a separate analysis and applied as boundary condition here.

In the analyses, convection and radiation boundary conditions were defined for all the exposed surfaces of the package to simulate exchange of heat with its surrounding via convection and radiation.

Emissivities used in the radiation boundary conditions are: 0.93 for painted package surfaces under normal conditions and 0.8 for package surfaces under accident conditions.

During fire, the correct heat input is given by the following equation stated at Nelsen [4]:

$$q_{in} = s \{ e_{fire} \, a_{surf} \, T_{fire}^{4} - e_{surf} \, T_{surf}^{4} \}$$

where s = Stefan-Boltzmann constant

e_{fire} = emissivity of the fire = 0.9 (IAEA Regulations)

a_{surf} = surface absorbtivity = 0.8 (IAEA Regulations)

T_{fire} = temperature of the fire = 800°C (IAEA Regulations)

e_{surf} = emissivity of the cask surface = 0.8 (IAEA Regulations)

T_{surf} = temperature of the cask surface

Due to a limitation in the analysis software, this flux input was actually given by the following equation

$$q_{in} = s\,\{0.8T_{fire}^{\;4} - 0.8T_{surf}^{\;4}\}$$

where 0.8 is the emissivity specified for the surfaces of the package during the hypothetical accident condition. This conservatively overestimates the heat flux input into the cask in a fire.

During normal conditions of transport, the cask itself will not receive any insolation, as it is shielded by the transport hood. However the air between the hood and the cask will be higher than the normal ambient temperature.

During the fire phase of the hypothetical accident condition, the cask will not be heated by insolation. However, during the cool down phase, the cask will no longer be covered by the transport hood and the exposed surfaces will be subjected to insolation.

IAEA ST1 specifies insolation on exposed curved surfaces to be 400 W/m² for 12 hours per day and on vertical surfaces, 200 W/m² for 12 hours per day. These values of insolation were applied to the package surfaces during the cool down phase of the hypothetical accident conditions. They were conservatively applied as constants, i.e. for 24 hours per day.

MODELLING OF THE FUEL ASSEMBLIES

The fuel assemblies were not modelled explicitly in the thermal analyses of the cask. Instead, the “effective thermal conductivity method” as presented by Bahney [5] was adopted. The fuel assemblies were modelled as solids with homogeneous “smeared” (or “effective”) properties making no distinction between the different properties and heat transfer characteristics of the various components of the assembly. The “effective conductivities” through a traverse section were calculated from a detailed two-dimensional slice model of the cross section of the fuel assembly using the FE code, MSC/NASTRAN [6]. The axial conductivity and densities of the homogeneous fuel assembly region were calculated from the volume-averaged properties of the different material in the assembly. The heat capacity was calculated from the mass-averaged heat capacities of the different material in the assembly.

The two-dimensional model of the fuel assembly cross section is shown in Figure 2.

Four-noded shell elements were used to model the cross section. These shell elements allowed heat transfer across the elements by conduction. Boundary conditions were imposed on the edges of the elements to model the radiation between surfaces of the components.

The elements representing the fuel rods were modelled as heat generating. A uniform temperature boundary condition was imposed on the boundaries of the model.

The transverse “smeared” conductivity of the fuel assembly was calculated from the two dimensional model using the equation;

$$k_e = \frac{Q}{4L(T_o - T_s)}(0.2497)$$

where k_e = Effective thermal conductivity (W/mK)

Q = Assembly heat generation (W)

L = Assembly active length (m)

T_O = Assembly centre temperature (peak cladding, K)

T_S = Surface temperature (K): temperature at the boundary of the model

The equation is the analytical solution of the heat diffusion equation for a steady temperature in a rectangle generating heat.

To obtain temperature dependent effective conductivities, the model was analysed with a range of different boundary temperatures.

TEMPERATURES IN THE NORMAL CONDITIONS OF TRANSPORT

Figure 4a and 4b show the temperature distribution in the cask - top frame shows the complete package, bottom frame with the content blanked from view to highlight the temperature contours in the containment and the impact limiters. Figure 5a and 5b shows the temperature distribution of the hottest cross section of the cask.

The maximum fuel cladding/pellet was predicted to be 227 °C for the case with helium as a backfill medium and 201 °C with water as a backfill medium. The temperatures were below the allowable temperatures of the components.

The maximum temperature of the cask exterior surface was predicted to exceed 85 °C. The IAEA Regulations requires a personal barrier to be used to prevent access during transport should surface temperatures exceed 85 °C. However, the transport hood prevents access during transport, and from a separate analysis, the temperature of the hood was predicted to be around 64 °C. Therefore CASTOR® KN-12 does not require a personal barrier.

Temperatures of all safety related components were found to be below their maximum safe operating temperatures.

Because the gas volume was not modelled in the analysis of the wet cask, it is possible that the upper two fuel assemblies which are not totally immersed in water will have a higher temperature. To obtain a very conservative upper bound on what the temperature of these upper fuel assemblies might be a separate analysis was carried out for a dry cask with nitrogen as the cooling medium. This analysis showed that the maximum fuel pellet/cladding temperature was 261 °C – a pessimistic upper bound estimate for the temperature of the upper assemblies in the wet cask. This temperature is below the allowable temperature, and therefore acceptable.

PRESSURES IN THE CASK IN THE NORMAL CONDITIONS OF TRANSPORT

The internal pressure in the cask was calculated from the contribution of pressure from:

1. Fuel rod backfill gas from failed fuel rods
2. Fission gas from failed fuel rods
3. Cask backfill gas
4. Water vapour pressure (for the wet cask only)
5. Partial pressure of hydrogen for half a year (for the wet cask only)

Using the recommendations given in NUREG 1617 [7], the pressures were calculated assuming that 3 % of the fuel rods failed due to cladding breaches, and that the failed fuel rods released only 30 % of their fission gas but all of their fuel rod backfill gas.

The calculated maximum pressure in a dry cask for normal conditions of transport with the Westinghouse 17x17 fuel assembly is 155 kPa (absolute pressure). The calculated maximum pressure in a wet cask for normal conditions of transport with the Westinghouse 17x17 fuel assembly is 360 kPa (absolute pressure).The internal pressure of the dry and wet cask do not exceed the 700 kPa (relative pressure) as specified by the requirements of the IAEA.

TEMPERATURES AND PRESSURES IN THE HYPOTHETICAL ACCIDENT CONDITIONS OF TRANSPORT

The maximum fuel cladding/pellet was predicted to be 272 °C for the case with helium as a backfill medium and 225 °C with water as a backfill medium. The temperatures do not exceed the maximum allowable temperatures of the components. Apart from the moderator rods and plates, the safety related components were found to not exceed their maximum safe operating temperatures.

The method used to calculate the maximum internal pressure in the cask under normal conditions was used to calculate the maximum pressure of the cask under the hypothetical accident condition. Using the recommendations given by NUREG 1617, the pressures were calculated assuming that 100 % of the fuel rods failed due to cladding breaches, and that the failed fuel rods released only 30 % of their fission gas but all of their fuel rod backfill gas.

The calculated maximum pressure in a dry cask for hypothetical accident conditions of transport with the Westinghouse 17x17 fuel assembly and backfill gas of helium, was 398 kPa (absolute pressure). The calculated maximum pressure in a wet cask for hypothetical accident conditions of transport with the Westinghouse 17x17 fuel assembly, was 2271 kPa (absolute pressure).

FINITE ELEMENT ANALYSIS OF THE THERMAL TESTS

Thermal tests were designed to verify the numerical tool and analysis methodology used for the safety proof of the CASTOR® KN-12. A test model which consisted of a 1/8 slice of the cask was built and tested. FE analyses of this model and the tests carried out were analysed. These analyses were validated against the test results.

The test programme included Environmental Tests, i.e. hot condition and cold condition of the normal conditions of transport, and Fire Test which correspond to the conditions of the Hypothetical Accident Condition.

The FE model of the 1/8 slice model is shown in Figure 3. It exploits the symmetrical nature of the test model and consists of a half of the test model.

Figure 6a shows the temperature distribution from the analysis of the 1/8 slice model in the hot condition test at three sections: Section C (lower frame) at mid-length and Sections A and B (upper frame) nearer the end caps. Figure 6b shows the temperature distribution in the cold condition test at the same cross sections.

Results from the FE analyses of the thermal tests were compared with the test results. The correlation between them showed that the numerical tool and the analysis methodology used in the analysis of the Hot Environmental Test are robust and sufficient. Since the same numerical tool and analysis methodology was also used in the thermal analysis of the real full scale cask, the test-analysis correlation also showed that the numerical tool and modelling methodology used in the thermal analysis of the real full scale cask were also robust and sufficient.

CONCLUSIONS

The thermal behaviour of CASTOR® KN-12 have been evaluated against the conditions specified in 10 CFR 71 and IAEA ST1.

The analysis demonstrates that

- Under normal conditions of transport, the operational temperature limits of the cask components important to safety will not be exceeded
- The maximum temperature of the fuel rod cladding will stay below 398 °C in normal operating conditions and 426 °C in hypothetical accident conditions, hence ensuring no failure of the fuel cladding from accelerated oxidation.

The tests and the FE simulation of the tests

- Demonstrated directly that the cask performs satisfactorily under the cases tested, and
- Demonstrated that the method and assumptions used in the analyses of the "real cask" are valid and reliable.

REFERENCES

[1] Title 10 of the Code of Federal Regulations Part 71, Packaging and Transportation of Radioactive Materials, April 1996

[2] International Atomic Energy Agency, Regulations for the Safe Transport of Radioactive Material, ST-1, 1996 Edition

[3] Livermore Software Technology Corporation, LS-DYNA Keyword User’s Manual Version 950, May 1999

[4] Nelsen, J. M., Vigil, M. G., Diggs, J. M., Trujillo, A. A., Analytical / Experimental Program to Assess Thermal Response of Geometrically Simulated Cask to Engulfing Fires, PATRAM '83: 7th International Symposium on Packaging and Transportation of Radioactive Materials, 1983

[5] Bahney III, R. H., Lotz, T. L., Doering, T. W., Effective Thermal Conductivity Method for Predicting Spent Nuclear Fuel Cladding Temperatures in a Dry Fill Gas, PVP-Vol. 348, Transportation, Storage and Disposal of Radioactive Materials, ASME, 1997

[6] MacNeal-Schwendler Corporation, MSC/NASTRAN Thermal Analysis User's Guide, 2001

[7] U.S. Nuclear Regulatory Commission, Standard Review Plan for Transportation Packages for Spent Nuclear Fuel: Final Report, NUREG-1617, March 2000

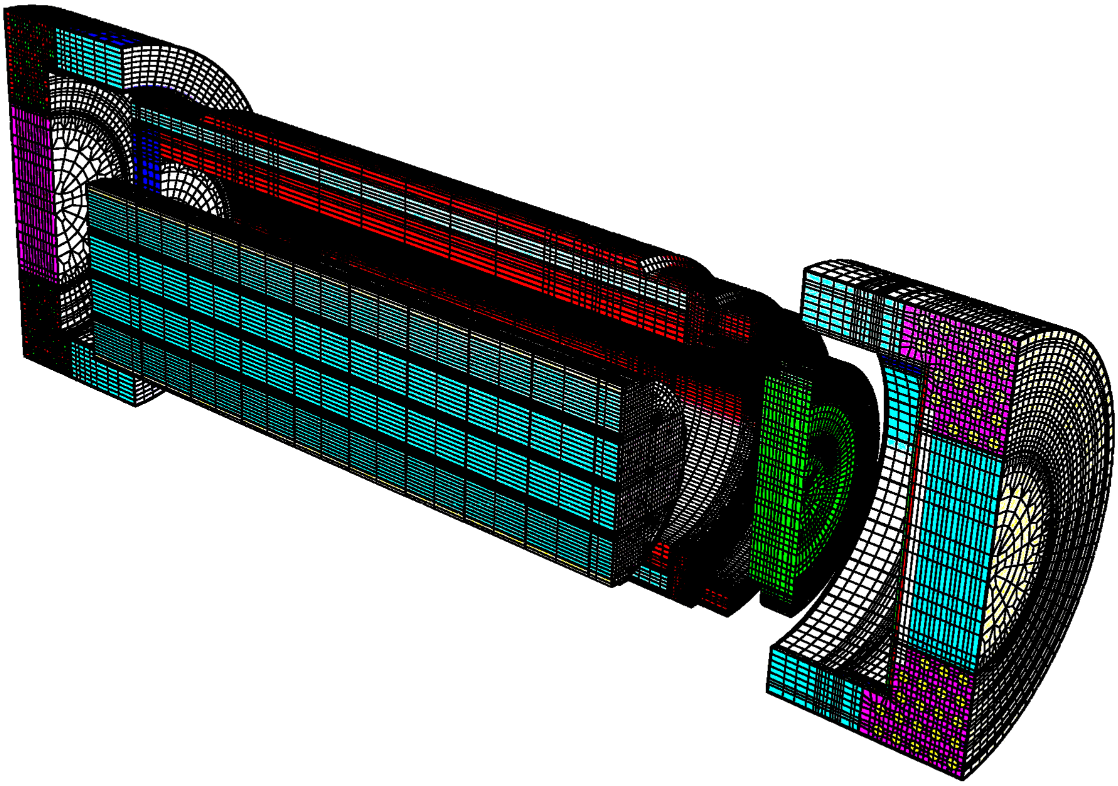
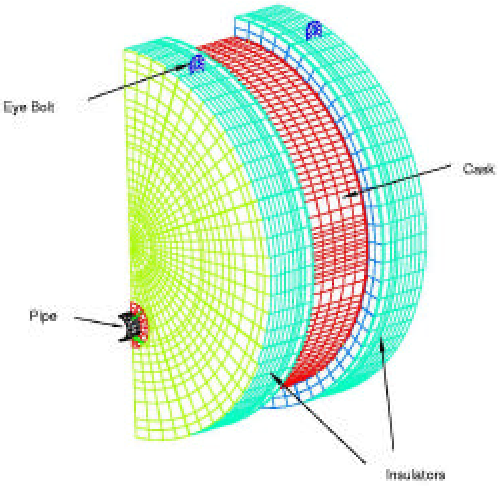


Figure 1. Three-dimensional FE model of the CASTOR® KN-12 cask for thermal analyses



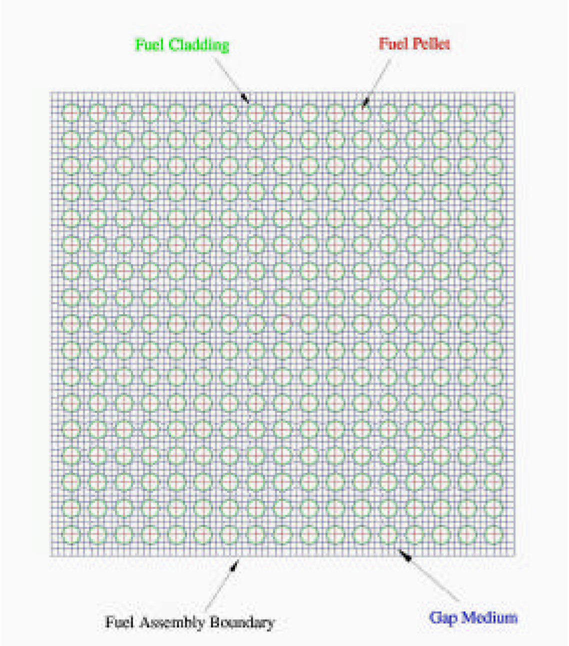


Figure 2. Two-dimensional FE model of the fuel assembly cross section	Figure 3. 1/8th Slice Model

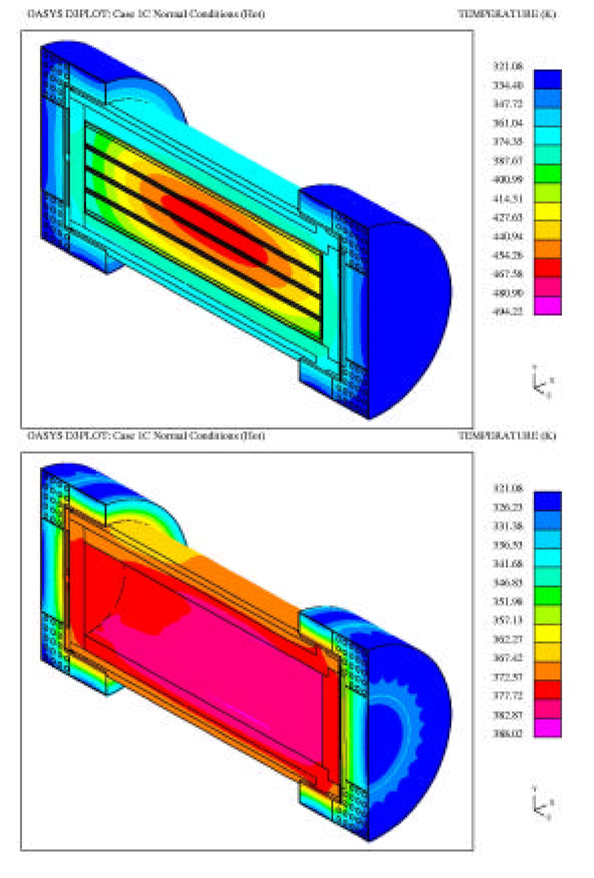


Figure 4a. Helium Backfill - Normal (Hot) Conditions (shown with and without contents)

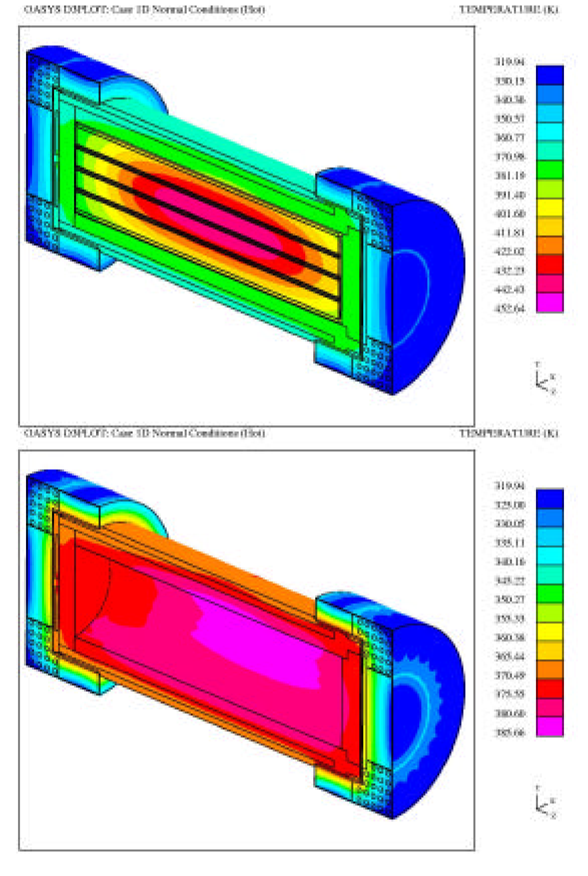


Figure 4b. Water Backfill - Normal (Hot) Conditions (shown with and without contents)

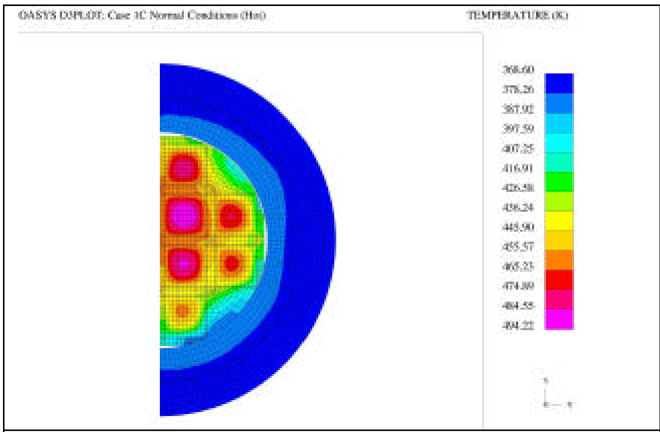


Figure 5a. Helium Backfill - Normal (Hot) Conditions – cross section through hottest area

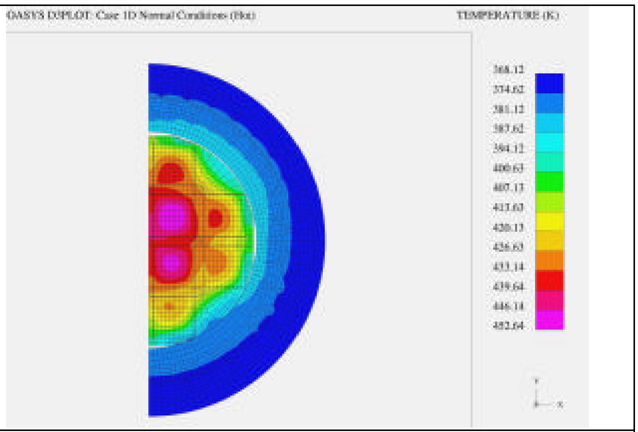


Figure 5b. Water Backfill - Normal (Hot) Conditions - cross section through hottest area

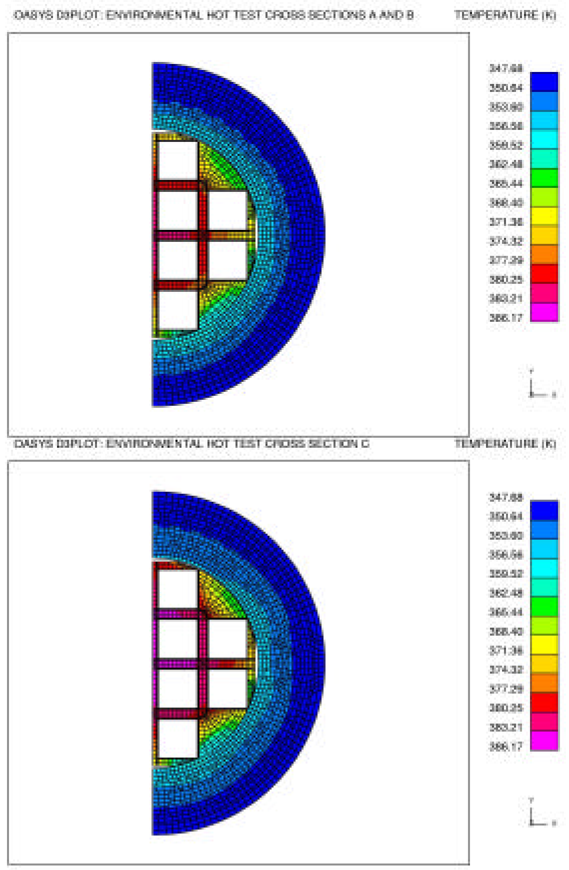


Figure 6a. Environmental Test - Hot Conditions

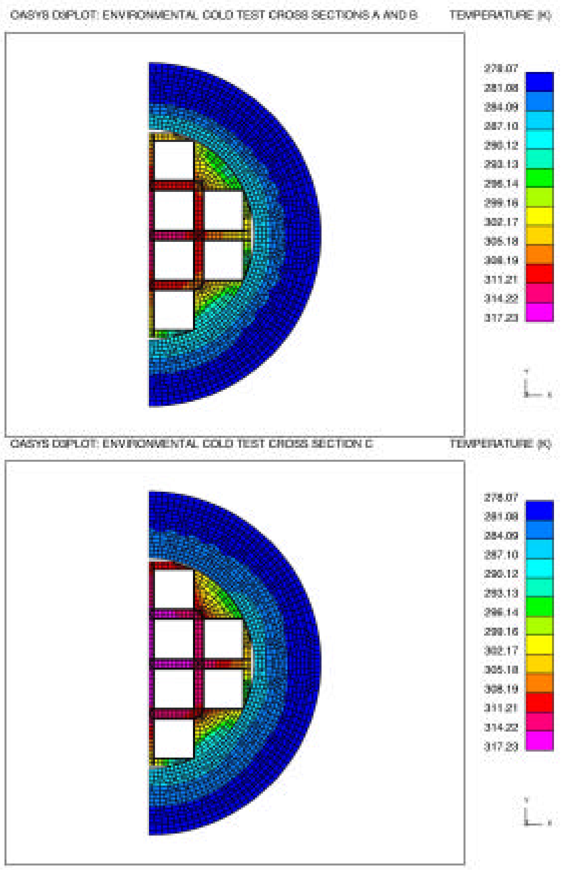


Figure 6b. Environmental Test - Cold Conditions