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■論 文■

Thermal Evaluation of the KN-12 Transport Cask

Sung-Hwan Chung · Kyoung-Myoung Chae · Byung-Il Choi ·
Heung-Young Lee and Myung-Jae Song
Nuclear Environment Technology Institute (NETEC), KHNP

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Abstract - The KN-12 spent nuclear fuel transport cask, which is a Type B(U) package designed to comply with the requirements of Korea Atomic Energy Act[1], IAEA Safety Standards Series No.TS-R-1[2] and US 10 CFR Part 71[3], is designed for carrying up to 12 PWR spent fuel assemblies in a basket structure. The cask has been licensed in accordance with Korea Atomic Energy Act and was fabricated in Korea in accordance with the requirements of ASME B&PV Sec.III, Div.3[4]. The cask must maintain thermal integrity in accordance with the related regulations and be evaluated to verify that the thermal performance of the cask complies with the regulatory requirements. The temperatures of the cask and components were determined by using finite elements methods with a numerical tool, safety tests using an 1/8 height slice model of the real cask were conducted to demonstrate verification of the numerical tool and methods, and heat transfer tests for normal transport conditions were performed as a fabrication acceptance test to demonstrate the heat transfer capability of the cask.

Key words : spent nuclear fuel, transport cask, thermal evaluation, thermal performance, heat transfer, heat transfer capacity, safety tests, fabrication performance test

Introduction

The KN-12 transport cask is designed for dry and wet transportation of up to 12 PWR fuel assemblies. The maximum allowable initial enrichment is 5.0wt.%. The fuel burn-up is limited to a maximum average of 50,000MWD/MTU. Prior to load in the cask, the fuel assembly must have a minimum cooling time of 7 years. W.H 14x14, 16x16 or 17x17 fuels may be loaded and subsequently transported in the cask. Each fuel assembly is assumed to have a maximum decay heat load of 1.05kW, and the cask has a total heat dissipation capability of 12.6kW. The heat rejection dissipation capability of the cask maintains the maximum fuel rod cladding temperature under normal conditions with a 12.6kW decay heat load, 38℃ ambient air and insolation. The fuels can be transported alternatively in an inert helium gas atmosphere or in a water filling inside the cask cavity. Heat is transferred between the cask and the environment by passive means only, and does not rely on any forced cooling. In transport, the cask is fitted with two impact limiters, which consist of layered wood encased within a steel cladding and act like insulators in terms of transfer of heat into and out of the cask, one at each end. The cask is transported horizontally under a transport hood. The main mode of heat transfer between fuel assemblies and the fuel basket is via conduction and radiation. Where gaps between the basket components exist, heat is transferred through the gaps between the basket and the inner surface of the cask body by conduction and radiation. And heat is transferred through the cask wall by conduction. Since the cask cavity within the basket is highly compartmentalized and the cask is transported horizontally, the effect of convection within the cask is not significant. During normal conditions the cask is covered by a transport hood, which is intended as an insolation shield. The hood is exposed to the ambient temperature. On its outer surface, heat transfer between the surface and the environment is taken place by convection and radiation while insolation heats up the outer surface of the hood. The cask exchanges heat with the surrounding by convection and radiation. Under 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. With intent to prevent from melting of the fuel pellet, the temperature of the pellet centerline must not exceed 2,593℃ for normal conditions and hypothetical accident conditions. To avoid failure of the fuel cladding from accelerated oxidation, the maximum temperature of the fuel cladding should be limited below 398℃ for normal conditions and 426℃ for accident conditions. These criteria are the same as those for the fuel assemblies in the reactor. Thermal conditions specified by the related regulations are summarized in Table 1.

The temperatures of the cask and components were determined by using finite elements methods with a numerical tool, LS-DYNA3D code[5]. From the analyses carried out, the maximum fuel pellet centerline temperature and the maximum fuel cladding temperature did not exceed their limiting temperatures for normal conditions and accident conditions. Safety tests, which include environmental tests and fire test using an 1/8 height slice model of the real cask, were conducted to demonstrate verification of the numerical tools and methods for the safety proof of the cask and compliance with the requirements of the related regulations. And heat transfer tests for normal conditions with a total heat load of 12.6kW were performed as a fabrication acceptance test to demonstrate the heat transfer capability of the cask.

Thermal Analyses

Thermal analyses[6] for normal transport conditions and hypothetical conditions were carried out to show that the cask does not exceed temperatures which cause melting of the fuel pellet and failure of the fuel cladding due to accelerated oxidation, to show that the cask safety components do not exceed their safe operating temperatures, and to obtain temperature distributions as input for thermal stress analyses.

The temperatures of the cask and components were determined by using finite elements methods with the numerical tools. The worst normal condition as far as temperature in the cask components and fuels are concerned is the hot condition with W.H 17x17 fuels. Hence, only the hot condition with W.H 17x17 fuels was analyzed, firstly with helium as the backfill and then with water backfill. One basic three dimensional finite element model as shown in Fig.1 was used to simulate normal conditions and accident conditions of both the dry and the wet cask, by applying different sets of boundary conditions and material properties. The half model of the cask taking

Table 1. Thermal conditions under normal conditions and hypothetical accident conditions

Thermal conditions	Ambient (℃)	Insolation (Wm^{-2})	Decay heat (kW)
Normal transport conditions(steady state)			
Hot condition	38	400	12.6
Cold condition	-40	x	12.6
Minimum temperature conditions	-40	x	x
Hypothetical accident conditions (transient)			
Initial conditions (steady state)	38	400	12.6
30 minute fire phase	800	x	12.6
Cool down phase	38	400	12.6

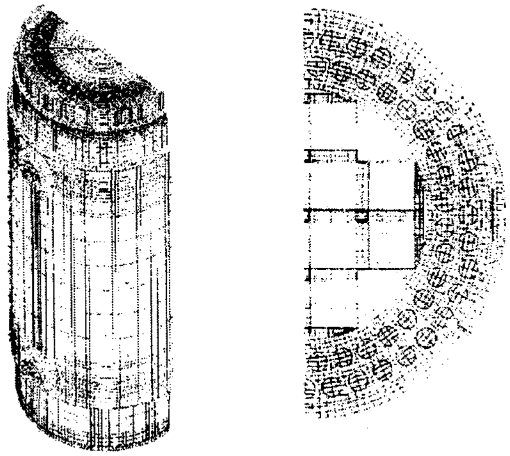

Fig. 1. Three dimensional analysis model using LS-DYNA3D code

advantage of symmetry consisted of all significant components of the whole cask. The fuel assemblies were not modeled explicitly (i.e., fuel pellet, fuel cladding, etc. are not modeled separately on their own) but instead, they were modeled as solids with homogeneous effective properties making no distinction between the different properties and heat transfer characteristics of the cladding, pellet, spaces between rods, and gaps between pellet and fuel claddings. The effective conductivities through a traverse section were calculated from a detailed two dimensional slice model of the cross section of the fuel as shown in Fig.2.

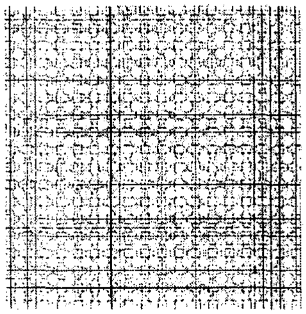

Fig. 2. Two dimensional analysis model using MSC/NASTRAN code

Two dimensional analysis to simulate the traverse heat transfer characteristic through the fuels and tocalculate the temperatures in the fuels was carried out using MSC/NASTRAN code. And steady state analyses for normal conditions and accident conditions wereperformed by using LS-DYNA3D code comparison between the temperatures of the safety related components during normal hot conditions of transport and their safe operating temperatures in Table 2 shows that the temperatures of safety related components are maintained below safe operating temperatures. The related regulations require the maximum temperature of any readily accessible surface during transport should not exceed 85℃ and the temperature of the cask exterior surface exceeds 85℃. However, the transport hood of the cask prevent access during transport and the temperature of the hood is found to be 64℃. Under normal transport conditions with no decay heat load, ambient temperature of -40℃ and no insolation, the cask experiences a uniform temperature of -40℃ throughout the

Table 2. Maximum temperatures for normal hot conditions of transport

Cask component	Safe temperatures, ℃	Temperature, ℃	
		Helium	Water
Cask outer/inner/bottom surface	-	101 / 113 / 92	100 / 109 / 91
Lid	O-ring seals: -40 to 250	103	107
Moderator rod inner/outer row	Max. 120	109 / 109	108/107
Inner/outer basket wall	-	198 / 192	170/168
Boronated aluminium plates	Max. 400	197	170
Fuel cladding	Max. 398	227	201
Backfill medium	-	168	146

cask. The temperatures of all safety related components and contents of the cask do not go below minimum safe operating temperature.

The transient thermal analysis was carried out for the 30 minute fire phase and another transient thermal analysis was carried out for post-fire cool down phase. The cool down phase of these analyses were allowed to run for 30 hours or more to ensure that all the components reach their maximum temperature. The maximum component temperatures during the fire and cool down phases are found in Table 3. Table 3 shows that all the safety related cask components do not exceed their maximum safe operating temperatures under hypothetical accident conditions except for the moderator rods and the moderator plate below the cask. As hypothetical accident conditions assume the absence of the neutron moderator, the temperatures of the moderator rods and plates may exceed the safe operating temperature.

From the analyses carried out, the maximum fuel pellet centerline temperature and the maximum fuel cladding temperature did not exceed their limiting temperatures for normal conditions and accident conditions.

Safety Tests

Safety tests[7] were conducted to demonstrate verification of the numerical tools and methods for the safety proof of the KN-12 cask and compliance with the regulatory requirements. The safety tests were performed for two environmental tests and a thermal test. The environmental test splits up into a cold (-40℃ air) and a hot (38℃ air) environmental test. And the thermal test was a fire condition with the outer surface temperature of 800℃. During the environmental and thermal tests an 1/8 height slice model of the real cask, which is only possible to test the radial temperature distribution and heat flux, was used.

The objective of the environmental test as shown in Fig.3 is to verify the numerical tool and methods used in demonstrating thermal performance of the cask and also to verify some temperature limits using test data. The temperatures were measured in three cross sections and 61 positions of the slice model using calibrated thermocouples. To demonstrate

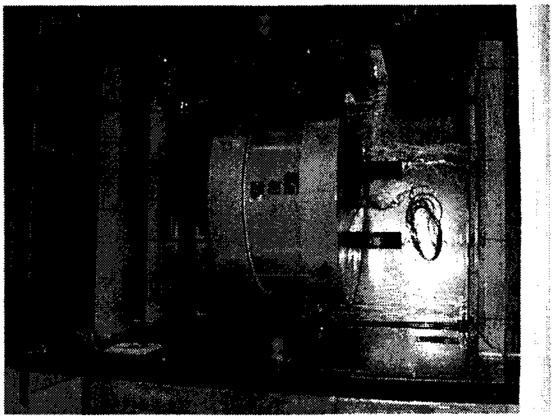

Fig. 3. Environmental test

Table 3. Maximum temperatures for hypothetical accidental conditions

Cask component	Safe temperatures, ℃	Temperature, ℃	
		Helium	Water
Cask outer/inner/bottom surface	-	390 / 202 / 130	387 / 196 / 125
Lid	O-ring seals: -40 to 250	130	124
Moderator rod inner/outer row	Max. 120	230 / 311	198 / 308
Inner/outer basket wall	-	245 / 243	221 / 219
Boronated aluminium plates	Max. 400	244	221
Fuel cladding	Max. 426	272	225
Backfill medium	-	192	178

the validity of the numerical tool and analysis methodology used in the thermal analyses the same numerical tool, LS-DYNA3D code and the same modeling methodology was applied in the analyses of the safety tests as in the analyses of the full size cask. Conditions of the hot environmental test like a fairly constant ambient temperature of 38℃, with still air, no insolation and the total heat flux of 2,287±2W from the 12 electrical dummy heaters were maintained for a period of 7 days. Thermal equilibrium was reached after about 96 hours. Temperatures at locations corresponding to the location of thermocouples in the environmental test were extracted from the finite element model. The temperatures obtained from the middle section of the test model during the hot environmental test and the simulation are summarized in Table 4. Agreement between test and simulation in the cask wall is generally very good. Typically, in the cask wall test temperatures are 5 to 10℃ below simulation temperatures. This represents quite a small difference given the temperature range spanned in the cask. And the simulation is conservative as far as the surface and cask wall temperatures are concerned. Within the basket, temperatures appear to be over-predicted by the simulation. The simulation conservatively assumes uniform 0.3 mm gaps around all the basket receptacles, whereas in reality in the test model, there is generally of the order of 0.3mm, 10 of the 12 considerable variation in gap size through the basket. Although the gaps in the test model are basket receptacles surveyed are in contact (no gap) with the surrounding boronated plates on at least one face, resulting in a much better thermal contact than is prescribed in the simulation. The path of the lowest thermal resistance for heat leaving the basket radially is where it rests on the cask at the base. The basket receptacles most remote from these regions are those at the center of the basket and at the top of the basket. Around these receptacles, discrepancies between experiment and simulation temperatures are most prominent, due to differences in isolation (air gaps) around these receptacles. The assumption of uniform 0.3mm gaps causes out a conservative prediction of temperatures in the basket. And, to demonstrate the compliance of the cask with the requirements, it is possible to check some features using test results. A comparison of the measured PE rods temperatures with the safe operating temperatures for the moderator components and for the compression springs of the moderator rods shows that the maximum measured temperatures are far below the safe operating temperature of 120℃.

The cold environmental test was not be evaluated sine the low ambient temperature does not be reached with the available test facility.

A fire test as shown in Fig.4 was carried

Table 4. Measured and calculated temperatures of the middle section during hot environmental test

Location		Temperature (℃)		
		Test	Simulation	Difference
I	Basket	163	198	+35
	Surface	73	75	+2
II	Basket	133	138	+5
	Surface	74	76	+2
III	Basket	148	174	+26
	Surface	72	76	+4
Ambient		38±1	38	±1

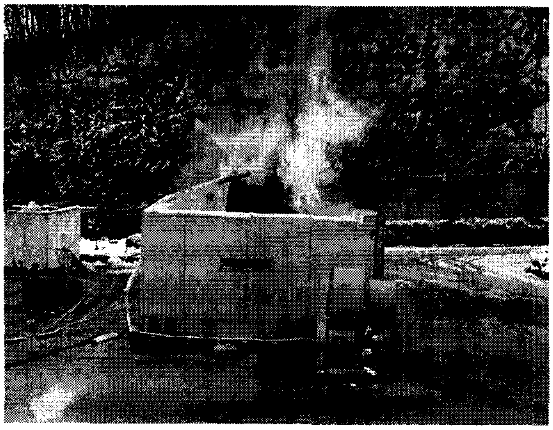

Fig. 4. Fire test

out on the 1/8 height slice test model, which was used for the environmental tests, in a test chamber with 3.5m x 4m. Prior to ignition of the fire, the test chamber was maintained at approximately 8℃. No insolation was applied and the equal heat flux used for the environmental test was maintained for sufficient time to allow a steady state temperature distribution to be reached in the model. The average flame emissivity was assumed to be 0.75, the model surface absorptivity was 1.0 and the convective coefficient was estimated to be 25Wm^{-2}K. The constant heat flux from the dummy heaters was maintained all through the fire test. The fire was continued for approximately 38 minutes. Thermocouples were used to monitor the air temperature outside the perimeter of the cask. Temperature transients at locations corresponding to the location of thermocouples in the fire test were extracted from the analysis model and tabulated in Table 5. The analysis result is more conservative than the test result. The analysis temperatures are consistently and significantly higher than those measured in the test. The only location at which this does not hold true is at the outer surface of the cask. The only explanation is that the surface temperatures from the test are too high. This is in line with observations from the hot environmental test. One possible explanation is that the measuring point of the thermocouples are not well contacted to the model and get heat from their outer part which is influenced by the fire.In conclusion the fire loading used in the analysis and represented by the compensated constant flame temperature is higher than the values in reality in the fire test.

The correlation between the test results and the analysis results demonstrates 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 in the hot environmental test and the fire test, also demonstrates that the numerical tool and modeling methodology used in the thermal analysis of the real full scale cask are also robust and sufficient. It is also shown, by the environmental test and the fire test, that the temperatures of the PE rods are well below the

Table 5. Measured and calculated temperatures of the middle section during fire test

Location		Test		Simulation	
		Max. temperature (℃)	Time (h)	Max. temperature (℃)	Time (h)
I	Basket	169	9.50	229	8.50
	Surface	285	0.00	288	0.00
II	Basket	163	9.83	188	5.50
	Surface	371	0.00	306	0.00
III	Basket	179	8.17	220	6.90
	Surface	382	0.00	324	0.00

safe operating temperature for the moderator components.

Fabrication Acceptance Tests

Two heat transfer tests[8] were performed as a fabrication acceptance test to demonstrate the heat transfer capability of the KN-12 cask. The tests for two fabricated casks were conducted under normal transport conditions with a total heat load of 12.6kW to simulate the design heat load of the KN-12 cask, except that the ambient was usually not the regulatory 38℃ air temperature. The heat load was best represented by 12 electrical dummy heaters, which were designed to simulate actual configurations and conditions of 12 PWR spent nuclear fuel assemblies. The tests determined steady state temperatures on the outer surfaces of the cask and impact limiters and within the fuel basket. The steady state temperatures were compared to the calculated temperatures to determine the accuracy of the analysis results

The inspections and tests of the cask, which consisted of trial assembly without fuel basket, load test, hydrostatic test, trial assembly with fuel basket and impact limiters, shielding integrity test, and inspection of the transport trailer with transport hood, were to be completed with acceptable results before the commencement of the heat transfer test. The certification of all the inspections and tests for the cask was reviewed, and the results were certified as acceptable before the test commences. The cask was mechanically complete and ready for operation before the initiation of the test. The test equipment and temporary equipment were installed. The cask cavity was vacuum dried and filled with helium before the start of the test. The cask with the test equipment was mounted on the cask tie-down structure on the transport trailer with the impact limiters and the transport hood in place for the duration of the test. The normal transport configuration of the cask is shown in Fig.4; the cask horizontally mounted on the tie-down structure of the transport trailer with impact limiters and the transport hood on the transport trailer. The tests were carried out in an area that was not subject to the heating effects of direct sunlight. The test area had free-flowing natural convective ventilation and did not have supplementary heating or cooling for the duration of the test except that the ambient temperature of the test area was in the normal comfort range of about 20℃. The test area had access for the transport trailer loaded the cask on the cask tie-down structure with the transport hood in place. The tests used a data acquisition equipment suitable for the measurements of temperatures. A total of 21 thermocouples to ensure good thermal contact was installed on the outer surface, the

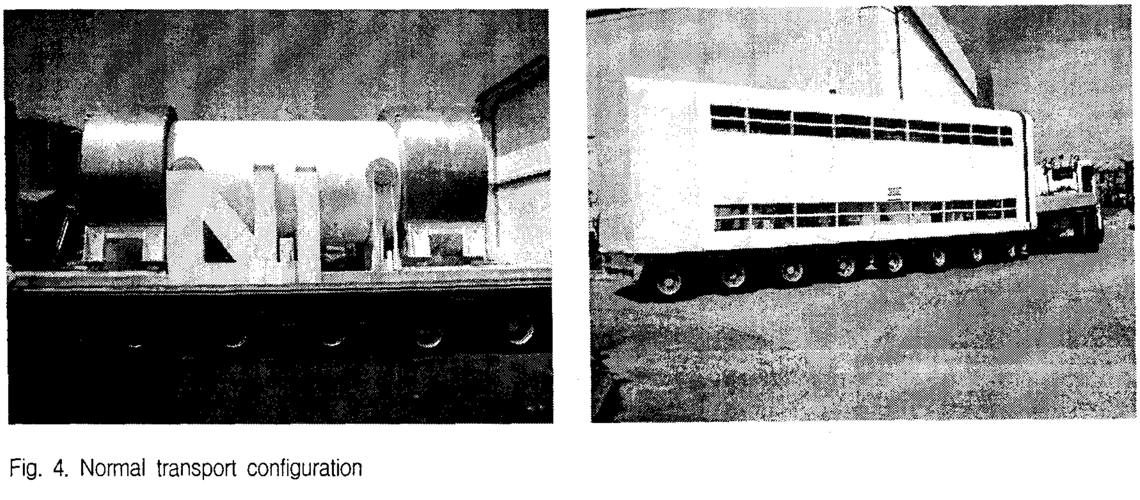

Fig. 4. Normal transport configuration

impact limiters and in the cask cavity of the cask. The thermocouples installed on the inner and the outer surfaces of the cask were connected to the data acquisition equipment which was used record the temperature profile of the cask as it was heated by the dummy heaters. The recorded temperature profile was used to determine when the cask had reached steady state thermal conditions. The 12 electric powered dummy heaters, which simulate the size and the shape of the fuel assemblies to be inserted into the cask, were provided for use within the cask during the test. Each dummy heater had a heating capacity of 1.05kW, and a total of 12 dummy heaters were provided giving a total heating capacity with the cask cavity of 12.6kW for the test.

The test results which were measured during the two heat transfer tests for two casks were evaluated. The evaluation was done using maximum values for different cask components which were calculated for the analysis results. Figure 5 shows the temperature data for measurements at cask components of one cask of the two casks. The cask component temperatures tend to a constant temperature - the thermal equilibrium - which was adjusted after a sufficient long time. In order to achieve the thermal state it was measured for one cask about 6 days and for another cask about 8 days. As thermal equilibrium temperature it was taken the last temperature measurement. All measured values as well as the calculated maximum component temperatures in the analysis are shown in Table 6. In order to provide a correct comparison, the analysis temperatures are corrected for the casks test environmental conditions. The differences between the measured and the calculated and corrected analysis temperatures are also given by Table 6. Comparing the measured component temperatures and the maximum calculation values one gets a good agreement. Especially the outer surface temperatures are close together. The analysis values are just slightly higher since these are maximum component temperatures. This demonstrates that the measurements can be good described by the analysis. The differences are higher for basket

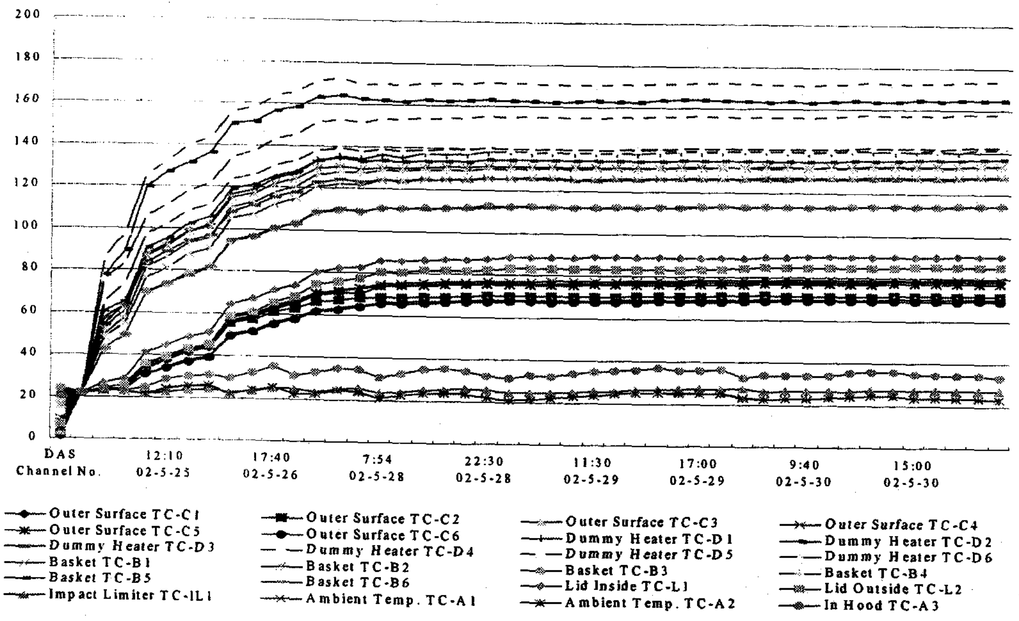

Fig. 5. Temperature time histories for measurements at cask components

Table 6. Comparison of measured and calculated temperatures

Component	Temperature (℃)				
	Acceptance test		Analysis	Deviation	
	T_1	T_2	T_A	$T_{A\ \mathrm{coorected}}^{1)} - T_1$	$T_{A\ \mathrm{coorected}}^{2)} - T_2$
Outer surface	78.43	81.37	101.0	6.57	5.63
Basket	136.64	142.86	192.0	39.36	35.14
Dummy heater	173.41	176.54	198.0	8.59	7.46
Lid inside	90.32	93.73	103.0	-3.32	-4.73
Lid outside	85.28	88.68		1.72	0.32
Impact limiter	27.00	30.00	99.0	56.00	55.00
Ambient	22.64	24.81	38.0	-0.64	-0.81
In hood	33.91	38.97	45.0	-4.91	-7.97

[1] $T_{A\ \mathrm{corrected}}$ (cask 1) = T_A -16K ; [2] $T_{A\ \mathrm{corrected}}$ (cask 2) = T_A -14K

components. This is expected, since variations in the component temperatures should be larger, when regarding temperatures near the dummy heaters. The lid temperatures have a very good agreement with the analysis as was also states for other outer surface elements. The differences in the impact limiters temperatures is quite large. The source of this deviation is the location of the maximum component temperature, which is near the lid. Therefore, the maximum impact limiters temperature is approximately the lid temperature and can not be compared very well with the measured impact limiters temperature. Comparing the measurements with the calculated temperatures, the environmental or ambient temperature of the heat transfer tests cannot be adjusted to 38℃, which is used for the analysis in order to match the conditions in the related regulations. There is also no insolation applied, so that the environmental conditions differ from the analysis. In order to compare the heat transfer test measurements with the analysis the same calculation is repeated for 23℃ and no inslation. The difference of the hood temperatures for these two environmental conditions is; $T = T_{\mathrm{In\ Hood}}$ (23℃, no insolation) - $T_{\mathrm{In\ Hood}}$ (38℃, insolation) = -16K. The ambient temperature of one cask is closed to 23℃, and the analysis temperatures have to be corrected by -16K. The ambient temperature of another cask is approximately 2K higher. A correction of -14K is applied to the analysis temperatures in order to compare them correctly with the measured another cask values.

The acceptance results are described very well by the corrected analysis maximum component temperatures. If one not expects large variations over the component surface, the deviations are very small. In the other case one has larger deviations which also occur in the measured temperatures. In both cases the analysis component temperatures are higher and therefore conservative.

Conclusion

The KN-12 cask was evaluated to verify that the thermal performance of the cask complies with the regulatory requirements through thermal analyses, safety tests and fabrication acceptance tests. The temperatures of the cask and components were determined by using LS-DYNA3D code to show that the cask does not exceed temperatures which cause melting of the fuel pellet and failure of the fuel cladding due to accelerated oxidation, to show that the cask safety components do not exceed their safe operating temperatures, and to obtain temperature distributions as input for thermal stress analyses. From the analyses carried out, the maximum fuel pellet centerline temperature and the maximum fuel cladding temperature do not exceed their limiting temperatures for normal conditions and accident conditions.

Safety tests, which include environmental tests and fire test were conducted to demonstrate verification of the numerical tools and methods for the safety proof of the cask and compliance with the requirements of the related regulations. The safety tests were performed for two environmental tests and a thermal test. The correlation between the test results and the analysis results demonstrates that the numerical tool and the analysis methodology are robust and sufficient.

And, two heat transfer tests for two fabricated casks were performed as a fabrication acceptance test to demonstrate the heat transfer capability of the cask under normal transport conditions. The steady state temperatures were compared to the calculated temperatures to determine the accuracy of the analysis results. Comparing the measured component temperatures and the maximum calculation values one gets a good agreement. The analysis values are just slightly higher since these are maximum component temperatures. This demonstrates that the measurements can be good described by the analysis.

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