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Heat Transfer Performance Test of the KN-12 Transport Cask

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ABSTRACT

Two heat transfer tests were performed as a fabrication performance test to demonstrate the heat transfer capability of the KN-12 spent nuclear fuel transport cask. The tests were conducted under normal conditions of transport with a total heat load of 12.6kW to simulate the design heat load of the cask. The heat load was best represented by twelve electrical dummy heaters, which were designed to simulate actual configurations and conditions of twelve PWR spent nuclear fuel assemblies. The test 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 design calculations. The intention of this paper is to evaluate test results which were measured during the heat transfer test for the KN-12 cask. The evaluation was done using maximum values for different cask components which were calculated for the Safety Analysis Report of the KN-12 transport cask. The test temperatures were described very well by the calculated maximum component temperatures and the calculated component temperatures were higher and therefore conservative.

INTRODUCTION

The KN-12 spent nuclear fuel transport cask, which is a Type B(U)F package designed to comply with the requirements of Korea Atomic Energy Act, IAEA Safety Standards Series No.ST-1[1] and US 10 CFR Part 71[2], has been designed for carrying up to twelve PWR fuel assemblies in a basket structure. 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, one at each end. It is mounted on the tie-down of the transport trailer and transported horizontally under a transport hood.

The heat transfer tests was performed as a fabrication performance test to demonstrate the heat transfer capability of the KN-12 cask. The tests for two fabricated casks were conducted under normal conditions of transport with a total heat load of 12.6kW to simulate the design heat load of the cask, except that the ambient is usually not the regulatory 38°C air temperature. The heat load was best represented by twelve electrical dummy heaters, which were designed to simulate actual configurations and conditions of twelve PWR fuel assemblies. For the test, the cask was in a simulated steady state transport configuration with the fuel basket and the simulated heat load, the test lid and the impact limiters installed. During the test, the cask was positioned on the tie-down structure, which was installed on the transport trailer with the transport hood, in its normal transport orientation. The test lid was constructed for the electrical, as well as for any internal thermocouple penetrations, and was capable of sealing the cask cavity to permit the use of an inert gas during the test such a gas was used in normal conditions of transport. The heat load was variable over the expected range, and the axial distribution of he heat in the cask cavity simulated that expected in service. The medium in the cask cavity during the test was helium gas. Use of helium gas in the cask cavity facilitated a direct comparison of the measured results with the results f design calculations that assumed helium gas in the cask cavity. Instrumentation consisted principally of thermocouples, although a pressure measurement of the cask cavity was appropriate. The test was conducted, initially at a low-power setting and then at progressively higher values, up to the design-basis heat load. A low-power test might be acceptable if the full heat load under steady-state conditions could potentially damage the cask. At each power increment, the cask was allowed to reach steady state. The test 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 design calculations.

The intention of this paper is to evaluate test results which were measured during the two heat transfer tests for the KN-12 cask. The evaluation was done using maximum values for different cask components which were calculated for the Safety Analysis Report(SAR) of the KN-12 transport cask[3]. The test temperatures were described very well by the corrected SAR maximum component temperatures. If one not expected large variations over the component surface, the deviations were very small. In the other case one had larger deviations which also occurred in the measured temperatures. In both cases the SAR component temperatures were higher and therefore conservative.

HEAT TRANSFER TEST

The heat transfer test was performed as a fabrication performance test to demonstrate the heat transfer capability of the KN-12 spent nuclear fuel transport cask. The tests for two fabricated casks(cask Set A and cask Set B) were conducted under normal conditions of transport with a total heat load of 12.6kW to simulate the design heat load of the cask, except that the ambient is usually not the regulatory 38°C 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.

Preparation for Testing

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 the above 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. Caution should be used in installing and removing the thermocouples, the dummy heaters and the power and the instrumentation cabling to avoid damage to the cask cavity and the fuel basket. The cask cavity was vacuum dried and filled with helium gas before the start of he 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.

Figure 1 shows the normal transport configuration of the cask; Figure 1a shows the cask horizontally mounted on the tie-down structure of the transport trailer with impact limiters and Figure 1b shows the transport hood on the transport trailer.

a. The cask mounted on the tie-down of the transport trailer with impact limiters

b. Transport hood on the transport trailer

Figure 1 Normal transport configuration of the cask

Test area and Test Equipment

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°C. The test area had access for the transport trailer loaded the cask on the cask tie-down structure with he transport hood in place.

The tests used a data acquisition equipment suitable for the measurements of temperatures. The data acquisition equipment for temperature monitoring should meet the requirements:

measurement range of 0 to 250°C and accuracy of +/-3K. A total of 21 thermocouples to ensure good thermal contact was installed on the outer surface, the 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 simulated 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. Power cabling and control equipment for the dummy heaters according to the applicable electrical codes were prepared. A special test lid to accommodate the power and the instrumentation cabling required for the test was installed for use during the test. The passage of the power and the instrumentation cabling through the holes of the test lid was sealed by special leadthroughs. Figure 2 shows the test equipment of a test lid, leadthroughs, dummy heaters and thermocouples.

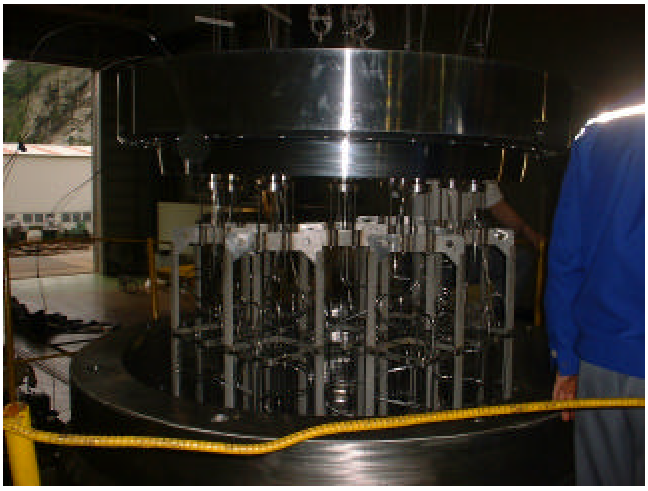


Figure 2 Test equipment(test lid, leadthroughs, dummy heaters and thermocouples)

Test Procedure

The detailed procedure for the heat transfer test is as follows:

- Complete the preliminary inspection and documentation review
- Inspect the data acquisition equipment to ensure that it is in operating order and review the certification to assure that it is current
- Install the thermocouples, the dummy heaters, the fuel basket, the test lid, the data acquisition equipment and the power and instrumentation cabling
- Make the electrical tests and inspections to assure that the dummy heaters and the thermocouples are in working order before the test lid and the impact limiters are installed
- Dry the cask cavity and backfill the cask cavity with helium gas
- The leak tightness of the test lid all the leadthroughs has to be proven
- Load the cask onto the cask tie-down structure positioned on the transport trailer
- Install the impact limiters, tie down the cask and install the transport hood
- Position the cask in the test area
- Wait until materials of the cask and the measuring equipment have reached thermal equilibrium with the surroundings

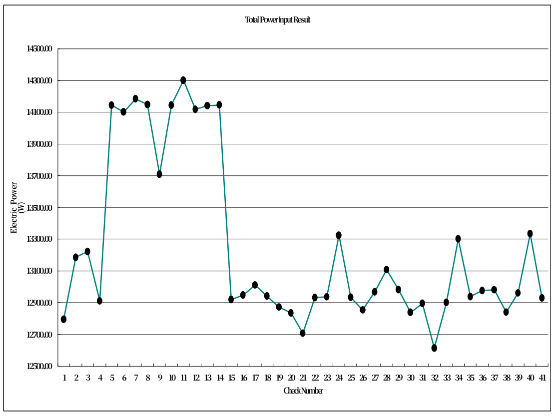
- Connect the cabling of the thermocouples to the data acquisition equipment and check the thermocouples, the cabling and the data acquisition equipment to assure that these are in working order
- Connect the power cabling to the dummy heaters and check the power cabling and the associated controls to assure that these are installed in accordance with the applicable electrical codes and that these are in working order
- Activate the data acquisition equipment used to record the ambient temperature in he test area for the duration of the test
- Energize the dummy heaters and record the date and the time that the dummy heaters are energized
- Observe the data acquisition equipment attached to the thermocouples to determine when the cask has reached steady state conditions and record when the steady state temperature conditions is reached
- After the cask has reached steady state conditions, record the steady state temperatures at all thermocouple locations
- De-energize the dummy heaters and the data acquisition equipment
- Review test report for completeness and record the certification of the test report
- Remove the impact limiters and dismantle the test lid, the power and the instrumentation cabling, the dummy heaters and the thermocouples

EVALUATION OF THE TEST RESULTS

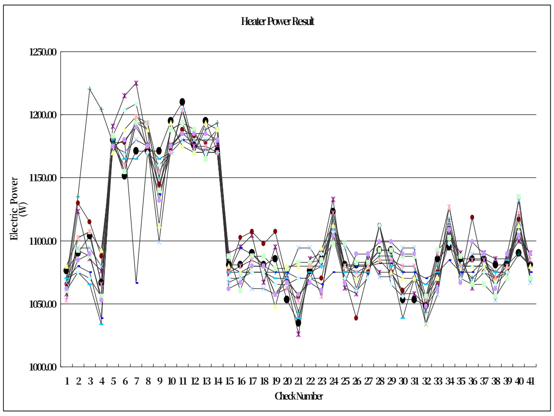
The test results which were measured during the two heat transfer tests(HTT) for the cask Set A and the cask Set B were evaluated. The evaluation was done using maximum values for different cask components which were calculated for the Safety Analysis Report of the KN-12 transport cask.

Discussion of the Test Results

In Figures 3a and 3b the total and single electric power histories of the 12 dummy heaters are presented. It is clearly visible that the total power and the single dummy heater power is nearly always above the limit of 12.6 kW and 1.05 kW, respectively, which is specified in the heat transfer test procedure[4]. Therefore, a basic assumption which is essential for comparing the test data with the SAR analyses is validated.



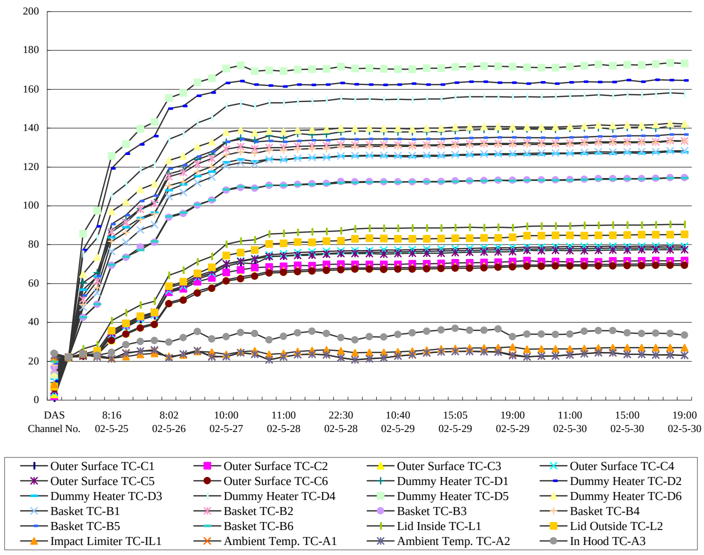
a. Total



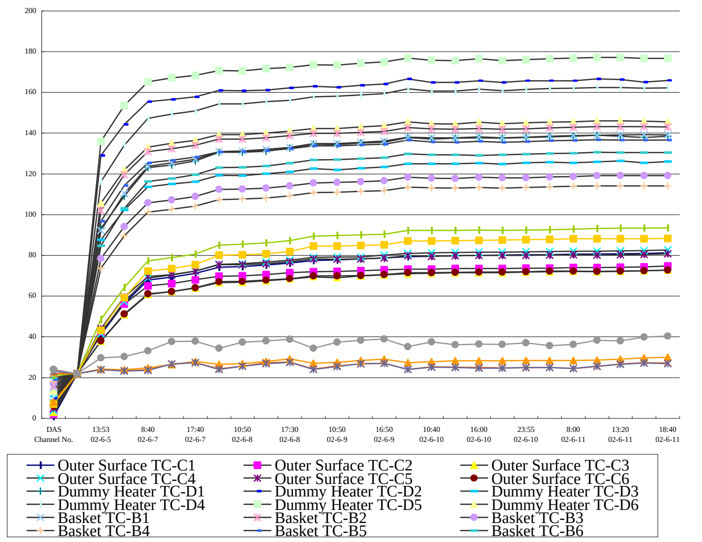
b. Single

Figure 3 Electrical power of the dummy heaters

Figures 4a and 4b show the thermocouples(TC) temperature data for measurements at the cask Set A and the cask Set B, respectively.



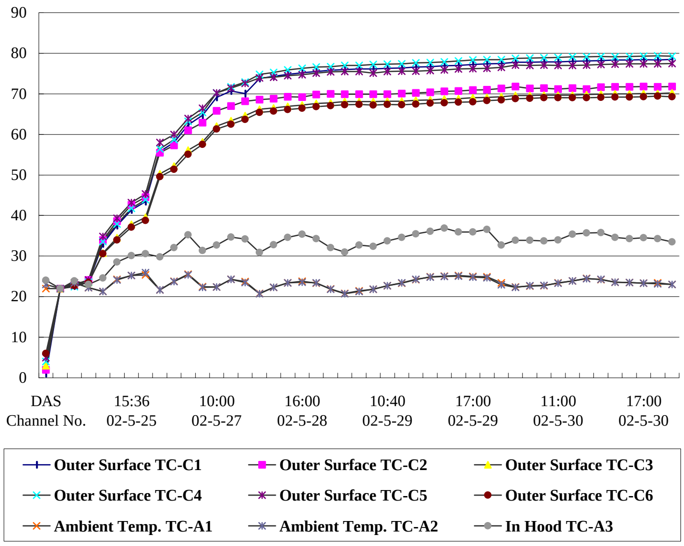
a. Cask Set A



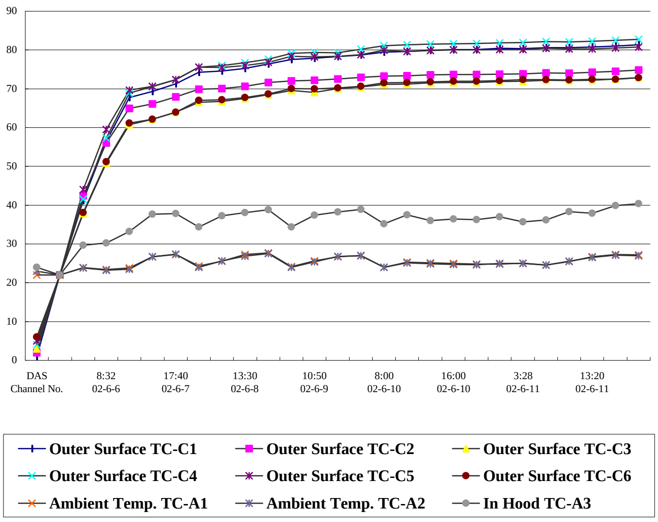
b. Cask Set B

Figure 4 Thermocouples temperature histories for measurements

Figures 5a and 5B show the temperature data at the outer cask, the ambient and under the hood (In Hood) for measurements at the cask Set A and the cask Set B, respectively. The temperature histories of the outer cask are examples for data taken at cask components. The cask component temperatures tend to a constant temperature - the thermal equilibrium - which will be adjusted after a sufficient long time. In order to achieve the thermal state it was measured for the cask Set A about 6 days and for the cask Set B about 8 days. As thermal equilibrium temperature it was taken the last temperature measurement. Since there remained a slight temperature drift, one got slightly higher component temperatures for the cask Set B. Another source for the higher component temperatures is the higher ambient temperature during the Set B HTT compared to the Set A HTT. The ambient and the In Hood temperature histories show a total different behavior. Since it was not possible to adjust a constant ambient or environmental temperature, the histories show the day night variation with an amplitude of about 3K. Additional to this variation the In Hood history has a significant increase which was induced by heating the hood volume by the cask. In order to derive an ambient temperature value which could be compared with the computed SAR temperature, it should not be taken the last measured value of this history curve as done. A better estimate for the long term behavior is the overall mean of the ambient temperature history. Therefore, the mean of the ambient temperature is used for comparisons with calculations. In order to get an In Hood comparison value - which has a slight increase as mentioned above - it is used the mean taken from the last day of the measurement.



a. Cask Set A



b. Cask Set B

Figure 5 Temperatures at the outer surface, the ambient and under the hood of the cask

Adjustment of Calculated Temperatures

Comparing the measurements with the computed SAR temperatures, the environmental or ambient temperature of the HTT could not be adjusted to $T_{ambient}$ = 38°C, which was used for the analysis in order to match the conditions in the related regulations. There was also no insolation applied, so that the environmental conditions differ from the calculations. For the environmental condition used in the SAR (38°C and insolation) the hood and air temperatures were calculated in the reference [5]. In order to compare the HTT measurements with the analysis the same calculation was repeated for 23°C and no inslation. Table 1 shows the results of the two analyses. The difference of the In Hood temperatures for these two environmental conditions is;

$\Delta T = T_{In\ Hood}$ (23°C, no insolation) – $T_{In\ Hood}$ (38°C, no insolation) = -16K.

Table 1 Results of hood temperature analyses

	$T_{ambient}$=23°C and no insolation	$T_{ambient}$=38°C and insolation	Difference ÄT, K
In Hood temperature, °C	29.0	45.0	16.0

As can be seen in Table 2, the ambient temperature of the cask Set A HTT is closed to $T_{In\ Hood}$ = 23°C. Therefore, the calculated SAR component temperatures have to be corrected by ΔT = -16K. The ambient temperature of the cask Set B HTT is approximately 2K higher. Here a correction of ΔT = -14K is applied to the SAR component temperatures in order to compare them correctly with the measured cask Set B values.

Discussion of the Comparison

All measured values as well as the calculated maximum component temperatures in the SAR are shown in Table 2. In order to provide a correct comparison, the SAR component temperatures were corrected for the cask Set A and the cask Set B HTT environmental conditions. The differences between the measured and the computed and corrected SAR component temperatures are also given by Table 2. Comparing the measured component temperatures and the maximum calculation values one gets a good agreement. Especially the outer surface temperatures are close together. The SAR values are just slightly higher(5 to 15K) since these are maximum component temperatures. This demonstrates that the measurements can be good described by the SAR calculations.

The differences are higher for basket components. This could be expected, since variations in the component temperatures should be larger, when regarding temperatures near the dummy heaters. Variations of about 23K are visible in the range of the measured temperatures of B1 to B6. Since the SAR values consider just the hottest point on the basket, deviations of about 60K are natural.

In order to compare the temperatures of the dummy heaters, which were not foreseen in the SAR calculations, it is more correct to use the temperatures of the basket's receptacle than the fuel cladding temperature. This becomes also clear when studying the construction of the dummy heaters. The comparison itself delivers differences in the order of 50K which are little bit smaller than the basket differences. The sources for the deviations are the same as for the basket. High variations of about 46K are also visible in the temperature range of D1 to D6.

The lid temperatures have a very good agreement with the calculations as was also stated for other outer surface elements. The differences in the impact limiters temperatures is quite large(56K). 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. A better analysis value can be taken from the SAR. There one gets for the outer part of the impact limiters a component temperature of about 60°C. Applying the corrections to this value one gets a difference of about 15°C, which is close to other outer surface temperature deviations.

The remaining thermocouples A1 to A3 are partly used to calculate the temperature correction for the SAR component values. Only A3, the In Hood temperature, could be compared. Due to the location of the thermocouple above the cask, A3 gives approximately the maximum value of the In Hood temperature profile and has therefore a larger value than the calculated mean In Hood temperature. The negative deviation of about 5K was therefore expected.

Table 2 Comparison of measured and calculated temperatures

Component	Temerature, °C					
	HTT			SAR[1)]	Deviation	
	TC ID	$T_{Set\ A}$	$T_{Set\ B}$	T_{SAR}	$T_{SAR\ coorescted}$[2)] $-T_{Set\ A}$	$T_{SAR\ corrected}$[3)] $-T_{Set\ B}$
Cask outer surface	C1	78.43	81.37	101.00	6.57	5.63
	C2	71.84	74.69		13.16	12.31
	C3	70.16	72.87		14.84	14.13
	C4	79.33	83.03		5.67	3.97
	C5	77.47	80.88		7.53	6.12
	C6	69.35	72.93		15.65	14.07
Basket	B1	128.35	130.57	192.00	47.65	47.43
	B2	133.56	139.16		42.44	38.84
	B3	114.46	114.14		61.54	63.86
	B4	133.20	136.39		42.80	41.61
	B5	136.64	142.86		39.36	35.14
	B6	114.31	119.13		61.69	58.87
Dummy heater	D1	140.66	138.36	198.00	41.34	45.64
	D2	164.85	166.70		17.15	18.30
	D3	127.67	125.92		54.33	58.08
	D4	157.94	162.19		24.06	21.81
	D5	173.41	176.54		8.59	7.46
	D6	142.29	145.61		39.71	38.39
Lid inside	L1	90.32	93.73	103.00	-3.32	-4.73
Lid outside	L2	85.28	88.68		1.72	0.32
Impact limiter	IL1	27.00	30.00	99.00	56.00	55.00
Ambient	A1	22.64	24.81	38.00	-0.64	-0.81
	A2	22.53	24.70		-0.53	-0.70
In hood	A3	33.91	38.97	45.00	-4.91	-7.97

1) Maximum temperature in SAR

2) $T_{SAR\ corrected}$(cask SET A) = T_{SAR} – 16K

3) $T_{SAR\ corrected}$(cask SET B) = T_{SAR} – 14K

CONCLUSION

Two heat transfer tests were conducted to demonstrate the heat transfer capability of the KN-12 cask under normal conditions of transport with a total heat load of 12.6kW to simulate the design heat load of the cask. The test results were compared to the calculated temperatures to determine the accuracy of the design calculations and were evaluated using maximum values for different cask components which were calculated for the SAR of the KN-12 transport cask.

In summary, the Heat Transfer Test temperatures are described very well by the corrected SAR 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 SAR component temperatures are higher and therefore conservative.

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