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THERMAL TESTING OF A DRY SPENT FUEL CASK

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I. INTRODUCTION

A nuclear spent fuel cask that employs air or an inert gas such as helium as the cooling medium in the fuel cavity is commonly known as a "dry" cask. The gas serves as a passive coolant. There is no forced circulation of the gas by mechanical means. The heat from the nuclear fuel is removed solely by natural convection and thermal radiation from the outer surface of the cask to the atmosphere. In recent years, several casks have been designed for dry shipment as opposed to being water filled. The dry cask has an important safety advantage. The fuel cavity pressure remains less than a few atmospheres under accident conditions, when the cask surface is exposed to intense heat from a fire. This low pressure feature permits the cask to be designed for "zero-release" of radioactive material during an accident. An operational advantage is the eliminating of the need to sample the coolant for radioactivity at any time.

The thermal characteristics of a dry cask differ considerably from a wet cask. A gas is a poorer heat transfer medium than water. As a result, the fuel and cask basket temperatures will be higher for a given fuel heat level. The response characteristics during operating transients will also differ. Detailed thermal tests on a dry cask were performed to verify design parameters and to obtain operational data for shipping and unloading. This paper presents the results of a number of thermal tests performed at the Barnwell Nuclear Fuel Plant (BNFP). The uniqueness of these tests are that they were performed using a full-scale geometric and thermal mockup of a nuclear fuel assembly. This results in more realistic fuel and basket temperatures being measured than those obtained using a simpler, single heater assembly.

II. TEST EQUIPMENT

The cask tested was the NLI 1/2 legal weight truck cask. This cask is shown in Figure 1. It uses water as a neutron shield and a lead-depleted uranium gamma shield sandwiched radially between layers of stainless steel. The cavity coolant is helium filled at atmospheric pressure. Helium was selected because it has better heat transfer properties than air. The cask is capable of carrying either one pressurized water (PWR) fuel assembly or two boiling water (BWR) assemblies at a maximum heat load of 10.6 kwt (36,100 Btu/hr). Two different basket types can be used depending on the integrity of the fuel prior to shipping. So called "leaker" assemblies would be placed within a separate cylindrical "leaker-can" basket consisting of a leak-tight pressure vessel within the fuel cavity. Nonleaker fuel would be placed in an extruded aluminum basket which also fits within the cask cavity (see Figure 1). The latter is denoted as the normal shipping basket.

The mockup fuel assembly was designed and fabricated by Wachter Associates of Pittsburgh, Pennsylvania (see Figure 2). It consisted of 205 electrically heated rods and 20 dummy rods in a 15 x 15 matrix. The intent was to simulate a typical PWR fuel assembly. A PWR assembly was selected since it represents the thermally limiting situation. The heater rods were directly bonded to a cylindrical test head which was bolted in the place of the cask's normal inner closure head. The 12-foot heated length of the assembly corresponded to the axial location of nuclear fuel when being shipped. A total of 21 thermocouples were positioned in three axial locations on each of seven different heated rods. These temperatures were automatically recorded during the course of the test. Means for measuring a number of local basket and cask surface temperatures were also provided. The cask test head provided for normal fill and vent valves which permit evacuation of the cask cavity, and subsequent filling with helium gas. The electrical current and voltage to the mockup assembly was routinely monitored to assure constant thermal output from the heaters.

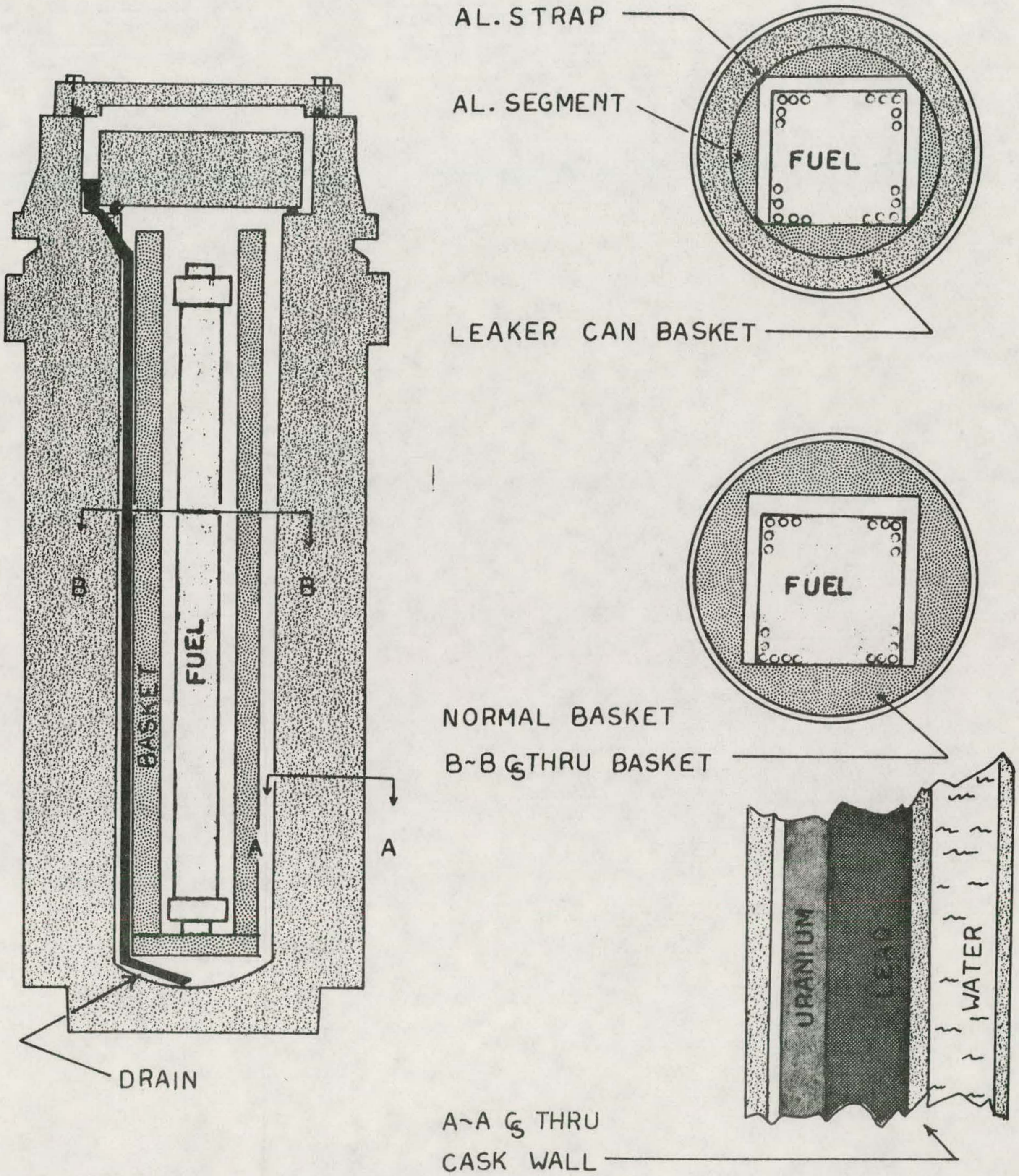

FIG. 1 - NL1/2 SPENT FUEL CASK

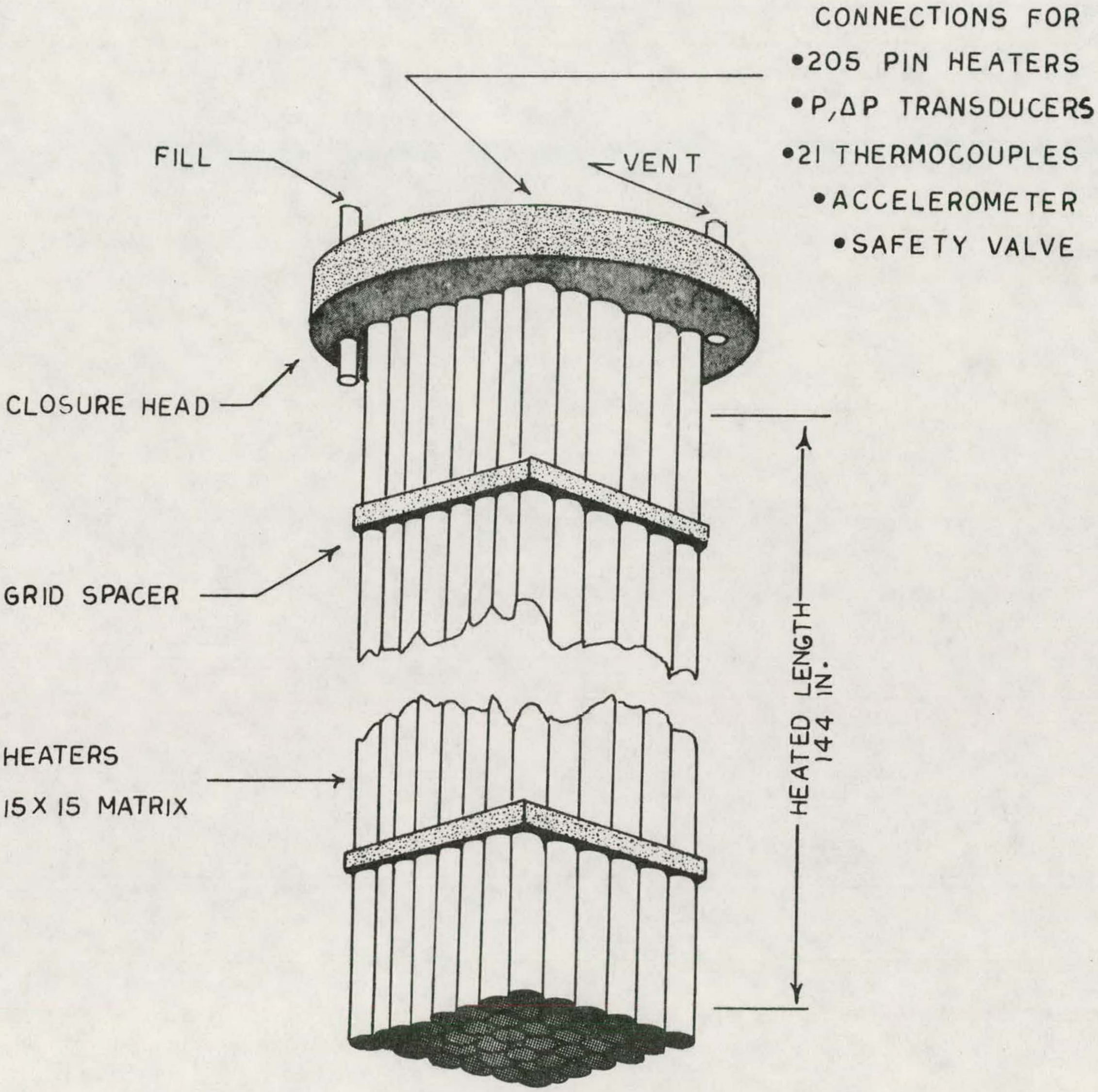

FIG. 2 - DUMMY FUEL ASSEMBLY (Wachter Associates)

III. TEST RESULTS - NORMAL CONDITIONS

The primary purpose of the testing was to obtain the temperatures of the cask and fuel under a variety of arrival conditions at the BNFP. This information was to be used in the development testing of the BNFP cask cooldown system.[1] Data on cask surface temperatures had been obtained previously using a single heater assembly. Computer analyses of the fuel and basket temperatures had also been developed for the package Safety Analysis Report (SAR). However, these analyses did not consider the wide range of arrival conditions which can be expected. For example, they do not consider fuel heat-up rate, and operating conditions at less than the design heat level. An additional objective was to obtain comparative data on the fuel and basket temperatures for the two different basket types.

The tests were performed by placing the heater assembly into the cask and horizontally mounting the cask on a truck trailer (the normal shipping condition). The power input in successive tests ranged from 2 kw to 10.6 kw. The cask was located in shaded conditions with an ambient temperature range between 68° and 72°F.

Table 1 presents the average equilibrium temperatures for the fuel and the basket. The average fuel temperature was calculated by analytically weighing the measured rod temperature with the expected temperature derived from computer analyses. This technique was estimated to have a maximum inaccuracy of about ±30°F. The average fuel and basket temperatures were in reasonably close agreement with previous analyses. Other observations were:

(1) The fuel temperatures, in the leaker can basket, were a maximum of 60°F higher than the normal basket. This was expected since the can represents an additional thermal barrier. (Note: The leaker can basket will be used infrequently and only with "well-aged" fuel.)

TABLE I

AVERAGE EQUILBRIUM TEMPERATURES*

Basket	Fuel Temp.	Basket Temp.
Leaker Can	850°F	515°F
Normal	780°F	390°F

*NL1/2 Cask - 10.6 kwt - 70°F Ambient.

(2) The maximum hot-spot temperature was at the axial centerline of an interior rod. It is about 175°F hotter than the average fuel temperature.

(3) A typical "chopped cosine" temperature profile was observed axially along each fuel rod. The temperatures at the fuel rod ends were about 100 to 150°F cooler than at the centerline.

Figure 3 is a plot of average fuel, basket, and cask surface equilibrium temperatures, as a function of spent fuel decay heat. The decay heat level is related to an approximate fuel age. In the current "millieu," fuel will be allowed to "age" in the reactor fuel pools for at least three to five years.

Temperature transients differ between dry and wet casks. Gaseous layers separate the fuel from the basket and the basket from the cask body and serve to thermally "decouple" the response. As shown in Table 2, the fuel temperature rises far more rapidly than the cask body. As a practical consequence, at design rating, the fuel temperature will rise 500-600°F in a few hours. In the same time period, the cask surface temperature will not have changed. As a result, the cask surface (the only observable temperature) presents no indication of internal temperatures until three to four days have elapsed. In an operating situation, the actual duration of many truck cask shipments is expected to be less than a day. Fuel and cask internal temperatures can be estimated from test data by means of Figure 3 and Table 2.

There are two situations where test data does not agree with computer analyses. The reason for these variances are (1) natural circulation patterns of the fuel cavity gas and neutron shield water and (2) the horizontal orientation of the cask during shipment.

FIG.3-NL 1/2 CASK TEMPERATURE PROFILE

- 70° F AMBIENT
- NORMAL BASKET
- HORIZONTAL

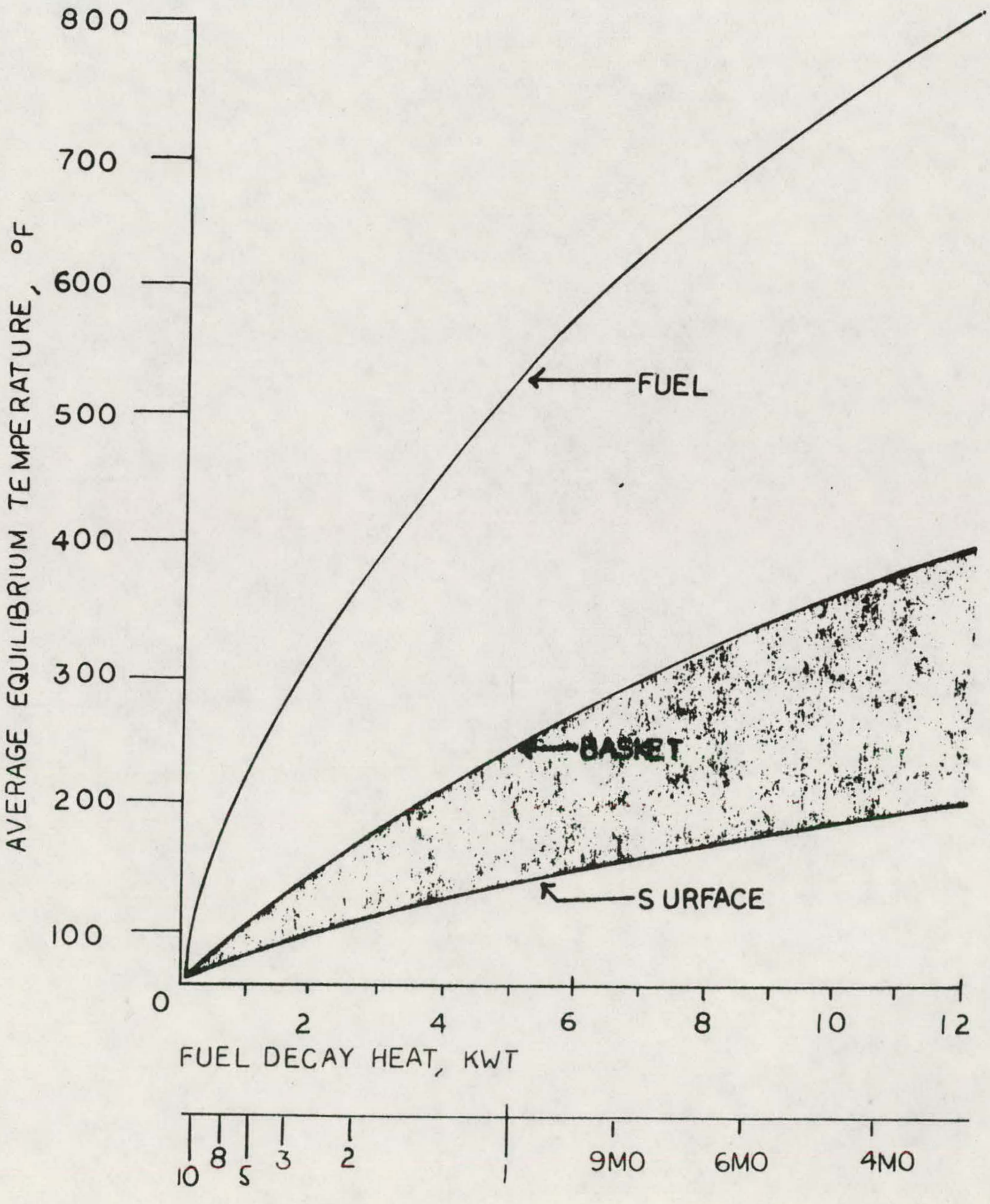

TABLE II

TRANSIENT THERMAL RESPONSE

	Time to Reach		
Component	60%	90%	of equilibrium
Fuel	5 hours	23 hours	
Basket	13 hours	52 hours	
Outer Surface	32 hours	66 hours	

(1) Cask Surface Temperatures (Figure 4A) - Natural circulation of the fluid in the neutron shield tank and the ambient air in proximity to the cask results in the upper surface of the cask being hotter than the lower. This general effect has also been observed with the TN-9 cask where a solid hydrogeneous neutron shield is used, and in the NAC-1 cask where a four-chambered, water-filled neutron shield tank is employed.

(2) Fuel/Basket Temperatures (Figure 4B) - The fuel rods directly contact the lower surface of the basket when the cask is horizontal. In turn, the gap width of the gas layer between the fuel and the upper region of the basket is doubled. The lower region of the basket, is hotter than the upper region due to direct conduction between the fuel rod and the basket segments. The double width of gas in the upper region accentuates this effect by acting as an insulator.

The surface temperature effect is well known and presents no structural problem. However, the skewing of the temperatures in the fuel basket was unexpected. The initial tests performed with the "leaker can" basket indicated as much as a 350°F difference between the upper and lower regions. The four segments of the basket were connected with thin aluminum straps at each corner (Figure 4B). In effect, there was no conduction path to redistribute heat. Slight cracking of the welds was observed at the juncture of the basket segment and the aluminum strap. Testing of the normal basket showed that heat redistribution was considerably improved. The normal basket is fabricated as a continuous aluminum extrusion with a minimum ligament thickness of 5/8-inch in the corners. This adequately redistributes the heat from the bottom of the basket to the upper regions by conduction. The maximum differential between any of 18 measured locations on the normal basket was less than 70°F. In addition, the method of mounting the basket within the cask permits 0.5-inches of axial growth. This basket design, when tested, presented no thermal or structural problems.

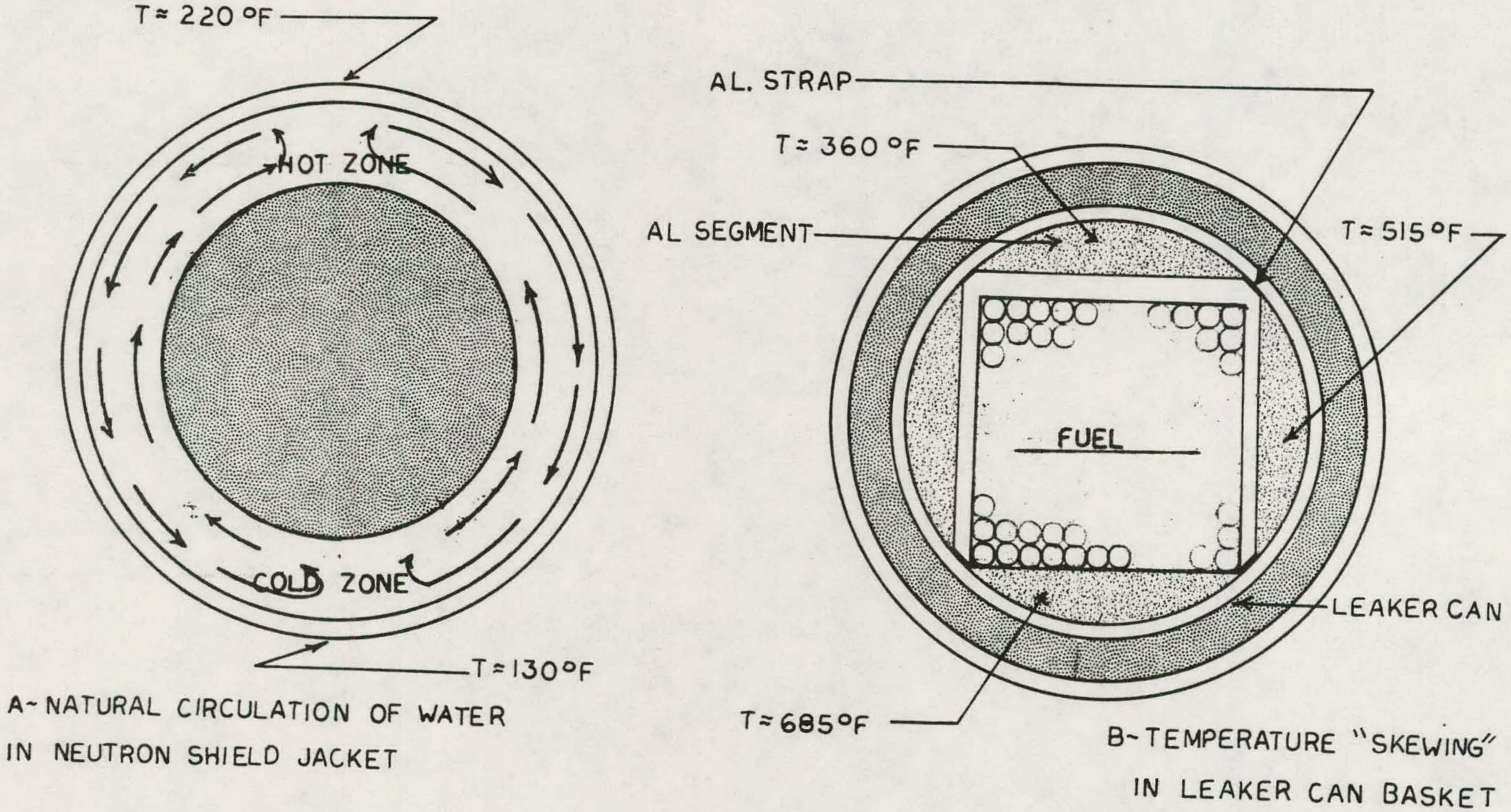

FIG. 4 - TEMPERATURE PATTERNS IN A HORIZONAL CASK

IV. ABNORMAL OPERATING CONDITION - TEST RESULTS

Additional tests were conducted to obtain general insight on other thermal aspects of dry casks. These included (1) vertically orienting the cask, (2) using air as the cavity gas, and (3) using a single calrod heater.

A. Vertical Casks

The thermal characteristics of a vertical cask are better and more predictable than when horizontal. The natural circulation of fluids (both helium and water) within cask chambers are greatly increased, thereby, improving heat transfer. This results in both lower and more uniform temperatures. Fuel temperatures are as much as 110°F lower. Additionally, since a uniform gap exists between the fuel and the basket, no "skewing" of basket temperatures, as previously described occurs. The driving force for natural circulation of a fluid is proportional to chamber height. This is the so-called "chimney" effect. Hence the improvements in heat transfer in the long, narrow, vertical fuel cavity of the cask is expected.

B. Air Coolant

Helium was experimentally shown to be superior to air. The thermal conductivity of air is about one-forth that of helium (0.03 versus 0.13 Btu/hr-ft-°F). In a horizontal cask, there is little natural convection within the fuel cavity. The modes of heat transfer from the fuel to the basket are only radiation and conduction through the gas. At the design heat level, the average temperature of the fuel was about 90°F hotter in air. Of greater cause for concern was the increased "skewed" temperature variations in the leaker-can basket. The difference in temperature between the upper and lower regions of the basket increased from 350°F to 510°F in air. Evidently, the doubled thickness of air above the fuel assembly was at fault. The insulating effect of the air accentuates this situation.

C. Single Calrod Heater

Many thermal tests have been performed using single calrod heaters, typically 0.75 to 1.0 inch in diameter, because of lower cost. The cask outer surface temperatures will be the same no matter what type of heater is used. However, cask cavity temperatures will vary significantly. This was shown by measuring temperature distributions during both heat-up and cooldown tests.(1) The primary reasons are:

(1) Fuel heat fluxes are lower and stored heat level higher in the 15 x 15 fuel assembly than in a single heater. There is about a factor of ten difference.

(2) The difference in cross-sectional area between the two types of heaters causes significant differences in the natural circulation patterns exhibited by the gas coolant.

(3) The actual fuel assembly contacts the basket directly when the cask is horizontal.

V. CONCLUSIONS

1. Shipment of nuclear fuel in a dry cask should present no operating or safety problems even when shipping "six-month" cooled fuel. Operations with "aged" fuel can be simpler for a dry cask than a wet cask.

2. Thermal concerns for fuel aged 3 to 5 years or more are negligible. The temperatures of the fuel and the cask will be relatively low irrespective of cavity coolant or orientation of the cask.

3. Natural circulation of the gas in the fuel cavity is only of importance when the cask is vertically oriented.

4. Fuel baskets should be designed with sufficient metal thickness to permit proper heat distribution. This will prevent warping or other thermally induced damage.

5. Helium gas results in both lower and more uniform fuel cavity temperatures than air when shipping fuel with a high heat level.

REFERENCES

1. Anderson, R.T. - Operational Facets of a Dry Spent Fuel Cask - Presented at the Fifth International Symposium for Packaging and Transportation of Radioactive Materials - May, 1978.