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COOLDOWN TESTING OF NUCLEAR FUEL CASKS

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1.0 INTRODUCTION

Shipment of spent nuclear fuel from operating reactors is an important link in resolving the fuel storage and nuclear waste problems. Certain thermal problems must be considered. The nuclear spent fuel, even after a period of pool storage, has sufficient decay heat to necessitate special handling when being shipped to an off-site location. This paper presents the results of development related to the thermal interaction between dry spent fuel casks and nuclear fuel under operating situations. The tests were performed at the Barnwell Nuclear Fuel Plant (BNFP) using full-sized truck and rail casks and electrically heated dummy fuel assemblies. The safe and practical operation of the equipment developed has been shown.

The current expectation in the United States is that light water reactor (LWR) fuel will be shipped to away-from-reactor (AFR) storage pools. The fuel is packaged in large (22- to 100-ton) spent fuel shipping casks. Shipment safety is predicated upon the cask providing containment of the radioactive spent fuel material during severe accident situations. From a practical standpoint, the thick metal walls and the hermetic sealing of the fuel cavity insulate the fuel from the environment. To assure safety, regulatory licensing of the package offers no credit for the operation of forced circulation cooling systems which the shipper may include. Cooling of the cask is totally passive, i.e., conduction of heat through the cask walls and combined convection/radiation from the cask surface to the ambient environment. These casks can be rated for fuel decay heat levels in excess of 300,000 Btu/hour. As a result, both the fuel and the cask body can become hot during shipment. In a dry cask where the fuel cavity water is removed prior to shipment, fuel temperatures will be high. In these dry casks, certain operating procedures are necessary. These are:

1. COOLDOWN of the cask and fuel at the receiving site
2. DRY OUT of the cask cavity prior to shipment.

Cooldown must prevent shocking or other thermal damage to the cask body or the fuel when it is inserted in the pool. It also prevents localized boiling of the pool water upon contact with heated cask and fuel surfaces. The BNFP cooldown process consists of the introduction of hot, pressurized water into the dry cask fuel cavity. After filling, the incoming water temperature is reduced until the desired temperatures are reached. The system heat is extracted in a heat exchanger cooling loop.

Two different cooldown systems were developed and tested. The first system is permanently installed in the BNFP. This closed-loop system initially uses heated water pressurized to 235 psig and 400°F. The second system is a portable open-loop system. It uses 60 to 80 psig, ambient temperature water as a coolant. The portable system uses a bare tube bundle heat exchanger which is mounted in the fuel pool. Both systems were tested. They were successfully operated under a variety of conditions. The permanent, closed-loop system performs the cooldown 3 to 5 times faster.

Fuel cavity "dry out" is also a necessary step in a dry cask. The primary purposes of the dry cavity is to minimize the cask internal pressure buildup during an accident where the cask body is exposed to extended periods of intense heat of a hypothetical fire. Cask operations are simplified since there is no need to sample the cask coolant at receipt. The process consists of draining and then evacuating the cask cavity to a low pressure. The heat from the cask body "boils-off" the residual liquid. Examination of the cask pressure level during evacuation allows determination of the effectiveness of dry out to be made.

Development of the cooldown and dry-out procedures were necessary in the evolution of the "dry" cask. Thermal considerations imposed major operating distinctions between the wet and dry casks. The heat transfer characteristics of dry casks are inherently poor. The tests employed on actual casks have served to verify that the heat transfer problems could be surmounted. Even in thermally limiting conditions, cooldown and dry out can be performed safely and in a reasonable time period.

2.0 TEST PROGRAM

Truck and rail cask systems developed by NL Industries (NLI) were tested in this program. They are identified as the NLI 1/2 (truck cask) and the NLI 10/24 (rail cask). Table 1 compares the design parameters of the two systems. The NLI 10/24 rail cask is four times heavier and contains 10 times the number of fuel assemblies. Consequently, the design heat load is also higher. The NLI 1/2 is licensed for a heat load of 10.6 kwt; the NLI 10/24 for 70 kwt. However, in expected operating conditions, the fuel temperatures in the NLI 1/2 could be slightly higher.

Figure 1 is a cross-sectional drawing illustrating the basic cask construction. They are essentially cylindrical, stainless steel pressure vessels. Each cask has radiation shielding walls for gamma rays and neutrons. The gamma shield is either lead or a lead-uranium metal composite, 5.5 to 6 inches thick. The neutron shield consists of a water jacket which is 7 to 9 inches thick. The fuel cavity is sealed by inner and outer removable closure heads. The NLI casks employ helium gas as the cavity gas. The gas is filled through fill and vent service valve fittings which are located on the inner closure head. Helium was selected because of its good heat transfer properties (high thermal conductivity). Other dry casks employ either air or a partial vacuum in the fuel cavity. The bolted closure head to cask joint is checked for leak tightness after fuel loading. The fuel is positioned by an aluminum basket structure within the fuel cavity. The basket also serves as a conduction link for the transfer of heat from the fuel to the inner cavity wall.

TABLE ONE

CASK DESIGN PARAMETERS

	NLI 1/2	NLI 10/24
Type	Truck	Rail
Weight, Tons	22	100
Capacity -- PWR Assemblies	1	10
BWR Assemblies	2	24
MTU	0.45	4.50
Thermal Rating, kilowatts	10.6	70
Cavity Coolant	Helium	
Material		
Containment	Stainless Steel	
Gamma Shield	Lead, Uranium	
Neutron Shield	Water	

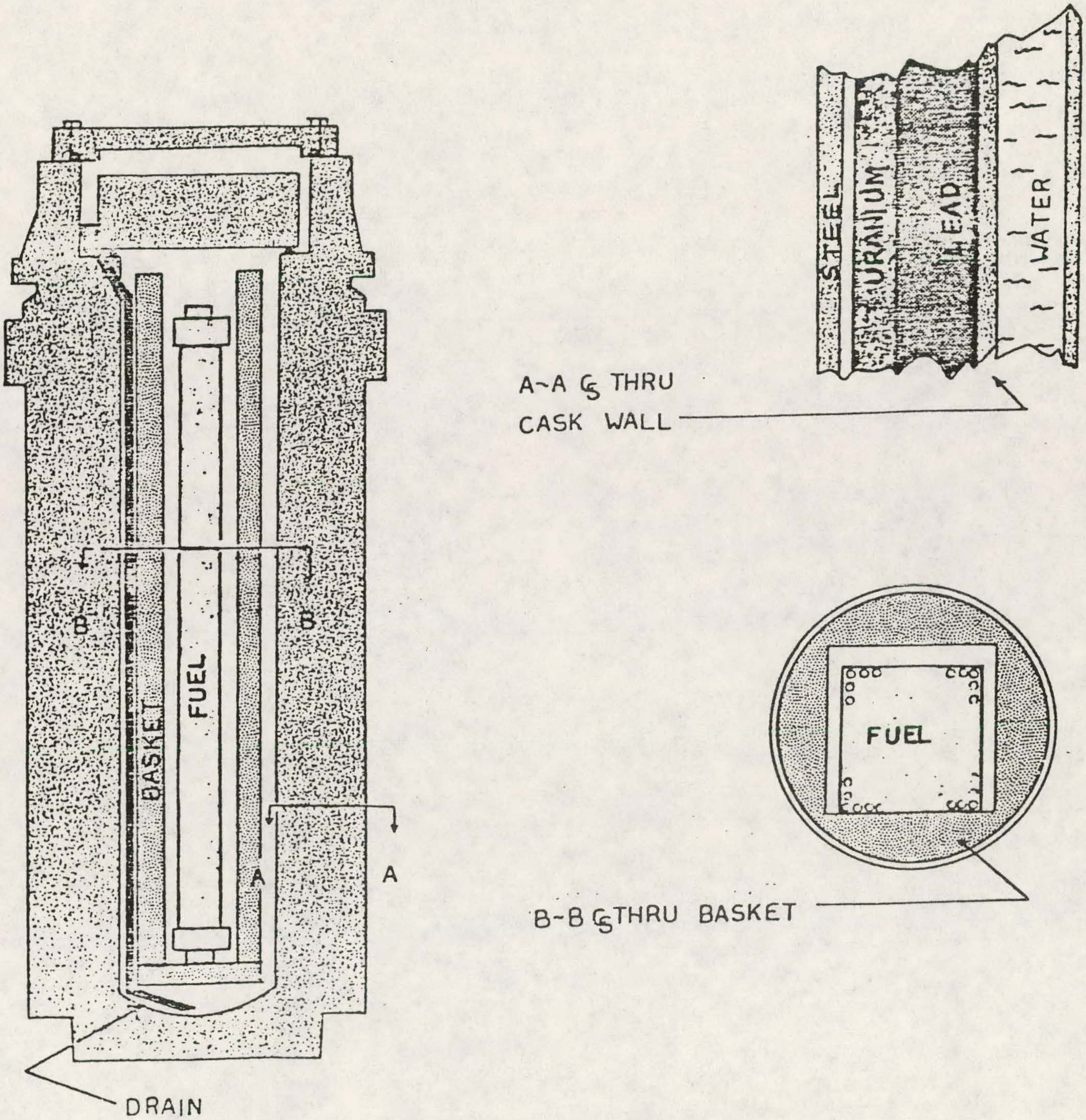


FIGURE ONE

SPENT FUEL CASK

The test program on the NLI 1/2 truck cask was conducted over a one-year period. These tests were used to develop the cooldown and dry-out system procedures. They were followed by tests of the larger NLI 10/24 rail casks. Those tests evaluated the effect of system capacity (the rail cask design heat load is 7 times higher than the truck cask). The program consisted of increasing the heat load sequentially from a minimum of 2.0 kwt with the truck cask up to 70 kwt with the rail cask. The cask body and fuel were allowed to reach thermal equilibrium prior to cooldown. Typically, this required 5 to 6 days of heating.

Electrically heated rods were used to simulate spent fuel. They were positioned in the same location the actual fuel would occupy during shipment. A sophisticated multi-rod heater replica of a pressurized water reactor (PWR) assembly was used in the truck cask tests. This assembly was fabricated by Wachter Associates of Pittsburgh, Pennsylvania (see Figure 2). Comparison tests were run to evaluate the heat transfer characteristics of a multi-rod heater (low heat flux-high mass) with a single heater (high heat flux-low mass). Single heater dummy assemblies cost much less to fabricate. Single heater assemblies were to be used in the rail cask test. The multi-rod assembly contained 205 heated and 20 non-heated rods in a 15 by 15 matrix. The rods were directly bonded to the test head. Thermocouples were positioned on the surface of 7 rods at 3 axial locations. The rail cask used single heater assemblies to simulate 10 fuel assemblies. In both the multi-rod and single-rod assemblies, electrical power levels could be raised to 11 kW per assembly. Comparison of the multi-rod and single heaters showed sufficient similarity during cooldown to permit the use of the single-rod design. Test instrumentation included thermocouples on various portions of the cask body, basket, and heater elements (see Figure 2). Temperatures were

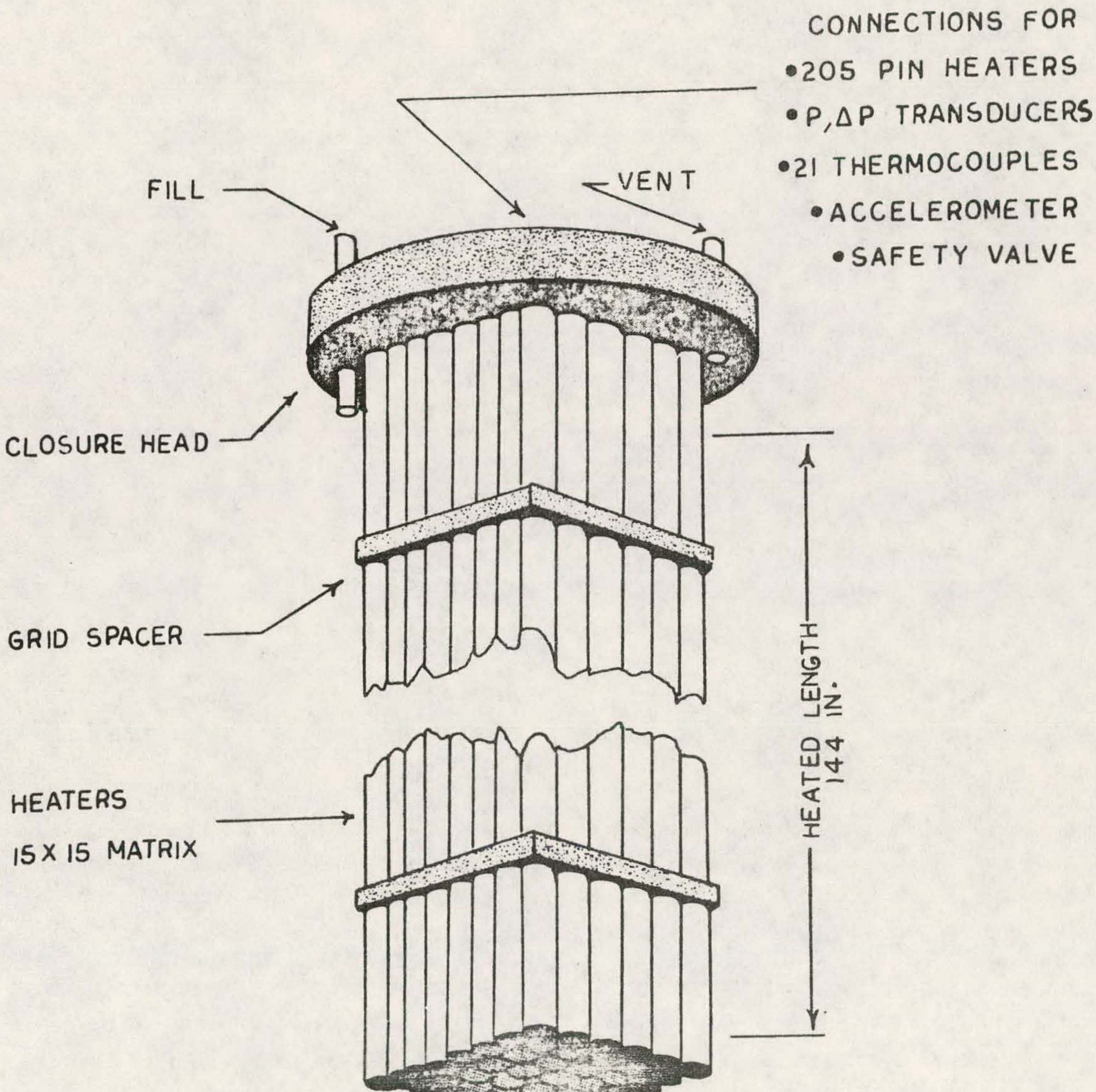


FIGURE TWO

DUMMY FUEL ASSEMBLY (WACHTER ASSOCIATES) continuously monitored and recorded during the test. Instrumentation was also provided to record coolant system pressures and temperatures.

3.0 COOLDOWN AND DRY-OUT SYSTEM DESIGN

3.1 Closed-Loop Cooldown System

Figure 3 is a simplified schematic of the permanent (closed-loop) cooldown system used in the BNFP fuel receiving station. The cooldown sequence occurs in a three-step operation as described below. At rated heat load conditions, the following temperatures are representative when thermal equilibrium is reached:

- Fuel - 600 to 800°F
- Basket - 350 to 400°F
- Cask Body - 250 to 300°F

Step One - Fuel Cooling - Hot pressurized water (from the system hot water heater) flows by gravity into the cask entering at the cavity floor. The initial hot water settling matches the average fuel basket temperature (in this case 400°F). The coolant is vaporized when it contacts the hot fuel. The resulting steam is piped to the system heat exchanger and condensed. The condensate is returned to the hot water heater. The gravity flow of water from the heater is continued until the cask is filled with water. At this point, the fuel and basket temperatures will be equal.

Step Two - Coolant Depressurized - The hot water heater is valved out of the process. The cask fuel cavity is slowly depressurized by directly pumping in cooled condensate from the system heat exchanger. The cavity water continues to boil. The steam formed in the cask is condensed in the heat exchanger. At the end of Step Two, the fuel cavity pressure has been lowered to about 5 psig. The coolant, fuel, and basket temperatures have been lowered to about 220°F.

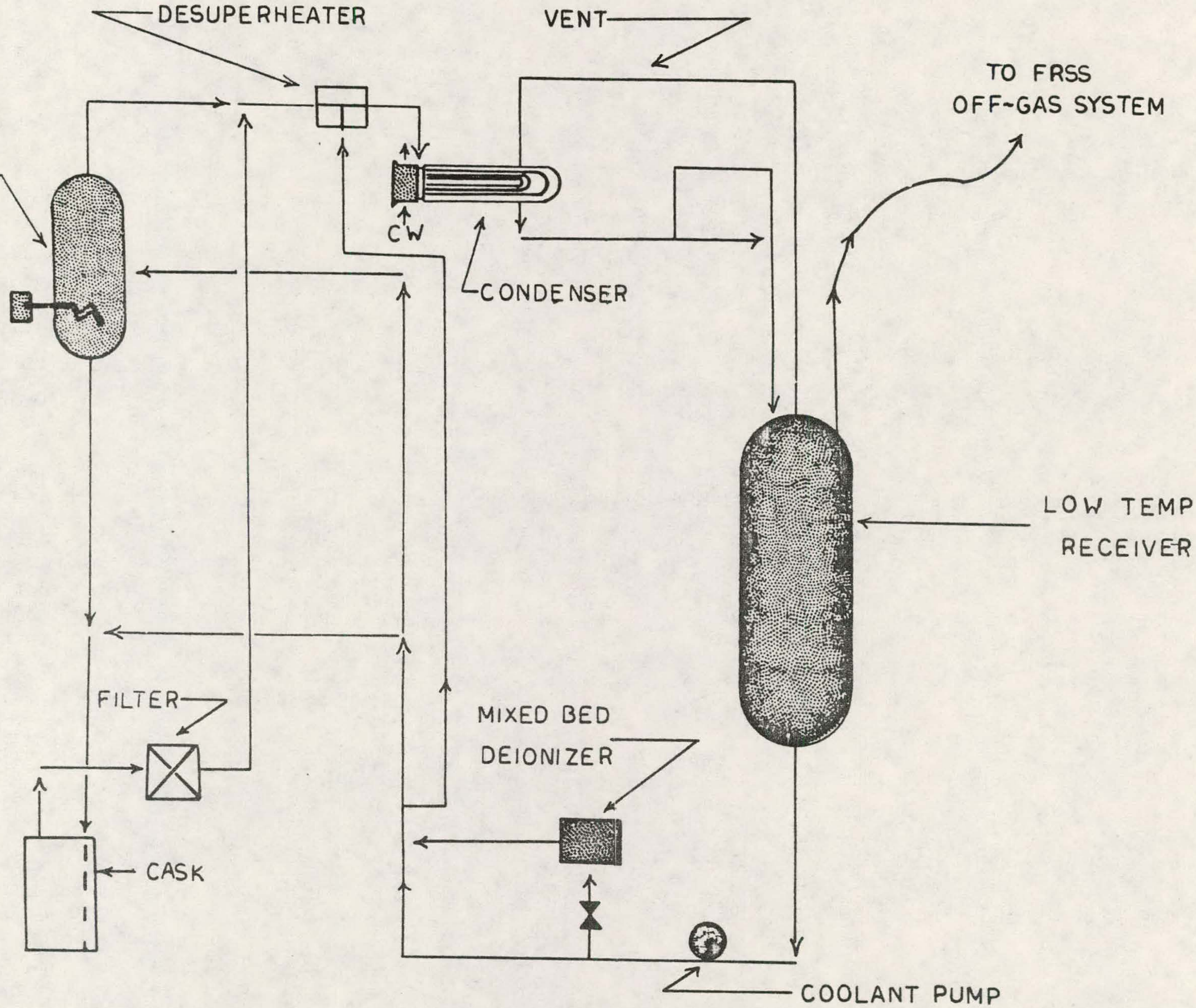


FIGURE THREE

BNFP COOLDOWN SYSTEM PROCESS FLOW DIAGRAM

Step Three - Rapid Flush - Water at ambient temperature is rapidly pumped through the cask until the fuel and cask internal temperatures are less than about 140°F.

3.2 Portable (Open Loop) Cooldown System

A need was seen for a portable cooldown system which could be used in emergency or backup situations. A portable system is useful when rapid cooldown is not required. Figure 4 is a schematic of this skid-mounted system. The design differences between the portable system and the BNFP permanent system are:

1. OPEN LOOP - The coolant is not recycled, but pumped directly into the fuel pool.

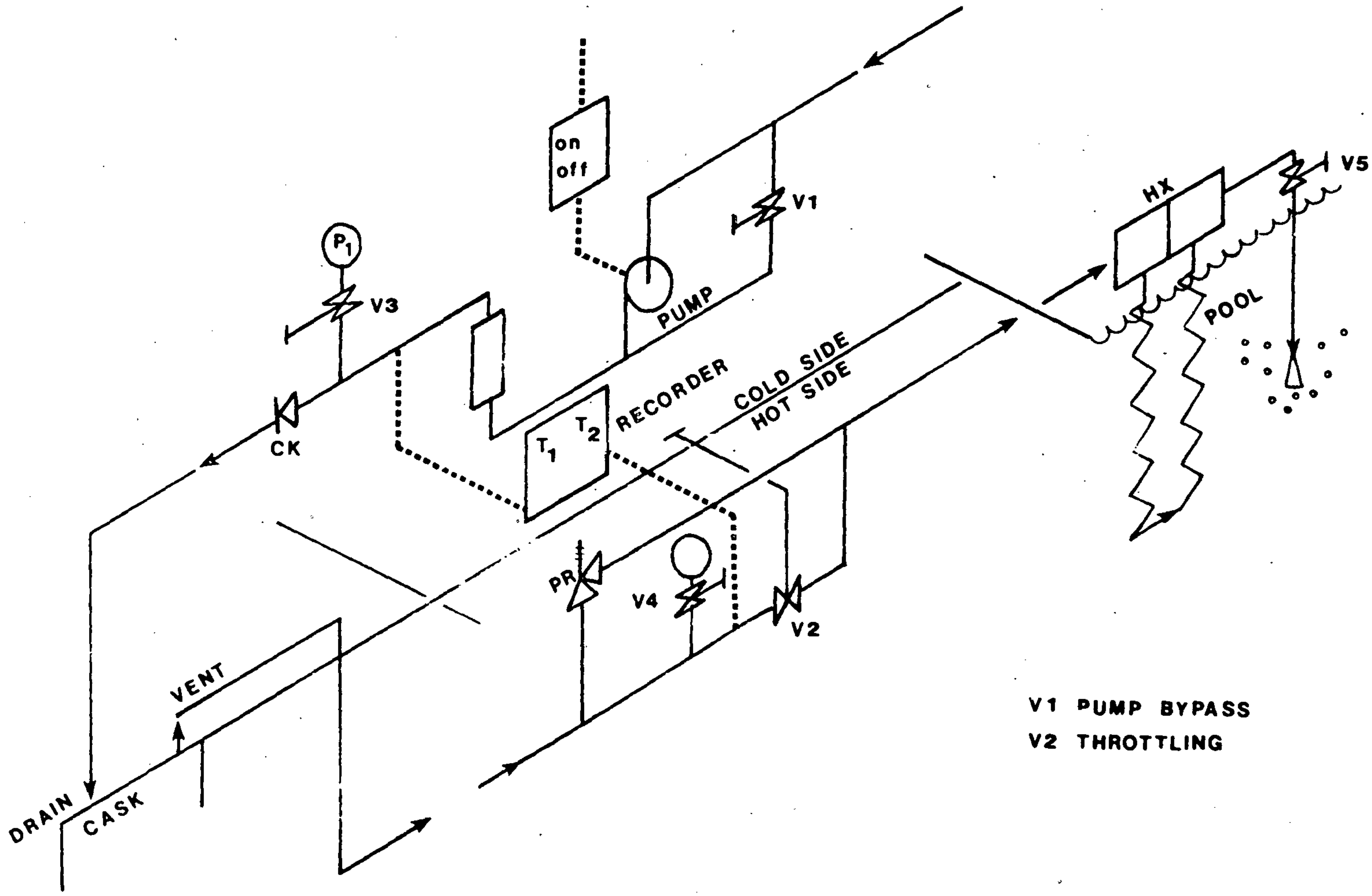
2. NO HOT WATER HEATER - The stored heat in the cask body is used to preheat the water.

3. SLOW FLOW RATE - Coolant flow rates 1 to 2 gpm versus 15 to 40 gpm for the BNFP permanent system.

4. NATURAL CONVECTION HEAT EXCHANGER - The bare tube bundle is suspended in the fuel pool. The pool water serves as the heat sink.

5. MANUAL OPERATION - System pressure and coolant flow rate is manually controlled.

Operation of the BNFP permanent system was rapid and the thermal gradients smaller. However, the resulting thermal gradients in the portable system were not appreciably large. The operational steps in this system were in two phases (rather than three), namely:



V1 PUMP BYPASS
V2 THROTTLING

FIGURE FOUR

PORTABLE COOLDOWN SYSTEM

Step One - Filling - The cask is filled with water and the fuel/basket is cooled to about 230°F.

Step Two - Slow Flushing - The cask and internals are flushed with ambient water until the fuel basket and cavity water are below 140°F.

3.3 "Dry-Out" System

Figure 5 is a schematic of the vacuum drying system. The system employs a Stokes, Model 148-H 50 cfm vacuum pump. The vacuum system contains a low-pressure "Piranni" vacuum gauge. This gauge permits system pressures of from 0.1 to 50 Torr to be read accurately.

The following procedure was developed for the vacuum "dry out".

Step One - Draining - The water in the cask cavity is forced out by air pressure (drained). Only a small residual of moisture on the cavity floor remains.

Step Two - Vacuum Pump "Heat Up" - The vacuum pump is operated for about one half hour under no-load conditions. This permits the pump seal oil temperature to rise to 150 to 160°F.

Step Three - Cavity "Pump Down" and Dry Out - The cask cavity is evacuated using the vacuum pump. The pump ballast valve is opened to expell steam vapor and to prevent the vapors from condensing in the seal oil. Evacuation continues until the cavity pressure drops to 1 to 2 Torr.

The vacuum dry-out technique was tested on both the truck cask and the rail cask. The rail cask with a considerably larger cavity void (about 75 cubic feet) took longer to dry out. Dry-out time could be reduced using a larger vacuum pump.

4.0 DEVELOPMENT RESULTS

4.1 Cooldown Testing (BNFP Permanent System)

The BNFP system was tested on both casks over heat level extending to 70 kwt. The cooldown process was continuous and predictable. The cask and fuel transient temperatures were analyzed to assure that an overstressing condition did not exist. Table 2 presents the experimental cooldown times as a function of cask heat level. Also included are the initial cooldown temperatures. Determination of an initial temperature which corresponded to the approximate basket temperature resulted in more efficient cooldown. It also minimized the possibility of excess thermal stress.

Figure 6 characterizes the fuel and coolant temperatures during the cooldown process. It must be noted that the coolant flow is upward from the cask cavity floor through the fuel bundle. The cooling regimes were distinct and corresponded closely to the three distinct cooling steps (see Figure 6). There was a concern evidenced prior to testing. There was a presumed possibility of a severe over-pressure surge occurring in the cask when the coolant initially contacted the hot fuel. Safety valves were located on the test closure head to relieve excess pressure. Slight overpressures of 15 to 25 psi (rail) were observed only during the maximum heat test. However, the pressure ramp was slow and lasted for a few minutes. Cask design pressures were not exceeded and the safety relief valves did not lift.

Examination of the cooldown test results indicated that the fuel and basket were adequately cooled. However, there was comparatively little cooling of the cask body. Cask exterior surface temperatures were not lowered at all. Cask inner body temperatures were reduced slightly. The heat transfer rate through the cask body was the limiting factor. This was measured by permitting the cavity water to remain stagnant in the cask after shutting down the cooldown system. The flow of heat was reversed from the cask body into the coolant water. The coolant temperature rise in the fuel cavity was measured for a number of hours. The resultant heat balance data was used to estimate the temperature profile in the cask wall. The following effects were noted:

1. At decay heat levels in excess of 70% of design rating, the cavity coolant would only need 2 to 4 hours to begin boiling. The cask body temperatures prior to cooldown, in these cases, were in excess of 220°F.

2. When the cask body temperature, prior to cooldown, was less than 200°F, the time required for boiling to occur was in excess of 10 hours. In this case, the prime source of heat to the water was the fuel assembly decay heat -- not reverse heat transfer through the cask walls.

3. Extending the rapid flushing period (Phase Three of cooldown) for several additional hours had different effects on the truck and the rail cask. In the rail cask, the water temperature rise was reduced after shutdown of the cooldown system. There was no effect in the truck cask. The difference is attributed to the difference in the design of the cask structure. In the rail cask, the shielding lead is bonded directly to the stainless steel walls. A continuous conduction path is formed. The truck cask has a layered depleted uranium-lead wall. This is separated from the stainless steel inner wall of the cask by a thin air gap. The air gap

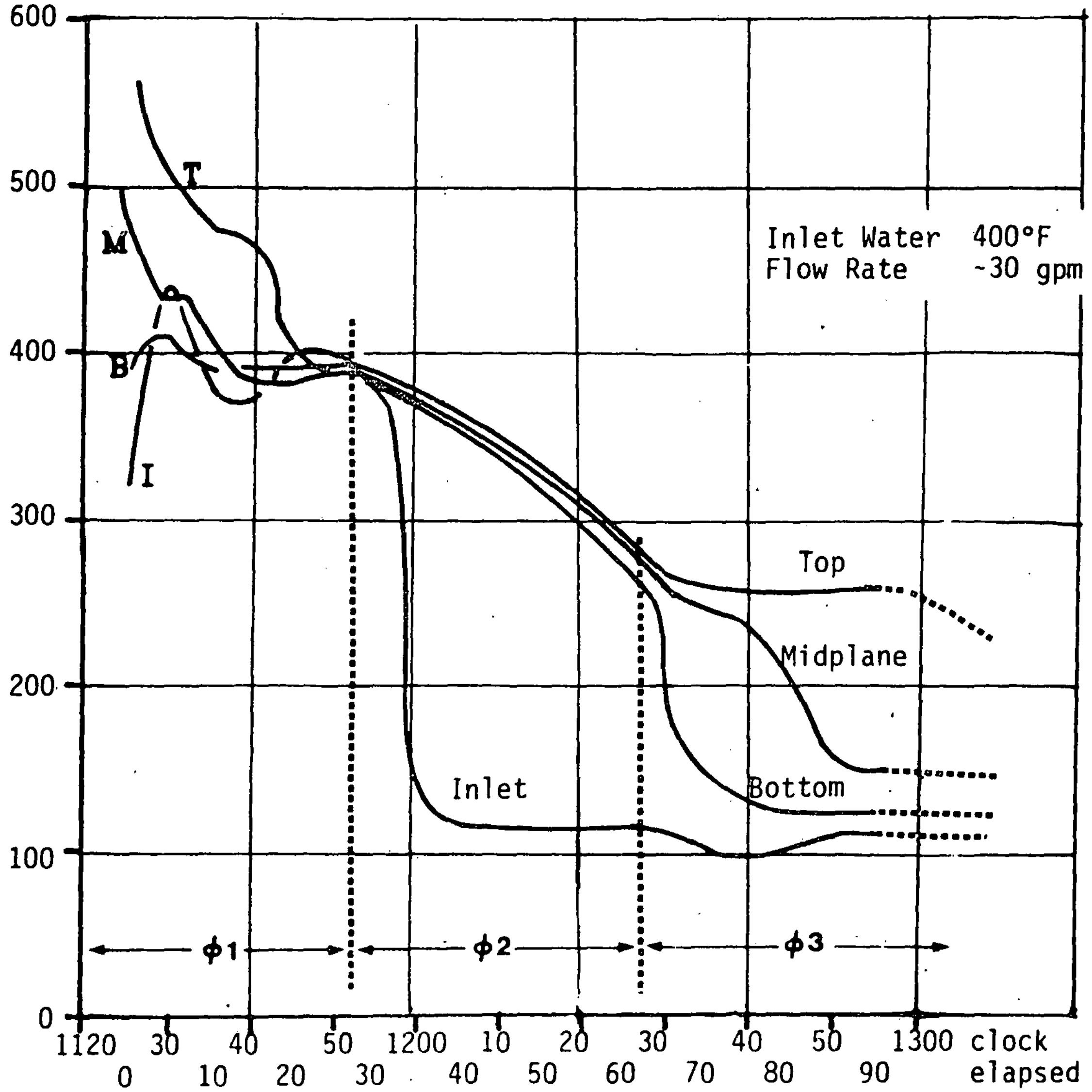


FIGURE SIX

CHARACTERISTIC COOLDOWN CURVE (BNFP PERMANENT SYSTEM) presents a thermal discontinuity which limits the heat transfer rate between the coolant in the cask cavity and the cask body. It is possible to cool down the rail cask body by continued flushing. The thermal discontinuity formed by the air gap in the truck cask wall negates the effect of continued flushing.

4. Cooldown system operating procedures were modified to accommodate reheating of the cask water. Water temperature is monitored. The cooldown system can be restarted if necessary. In most cases, this should not be a problem. Cask heat levels are expected to be low. Also, the time required to place the cask in the pool after cooldown is completed is less than two hours.

4.2 Portable Cooldown System Tests

Portable cooldown system tests were performed on the NLI 1/2 truck cask. Testing with the rail cask was not possible due to time constraints. However, examination of truck cask results indicated that the portable system could be used. However, cooldown times would be considerable (see Table 2). Figure 7 presents the characteristic cooldown curves for the portable system. The test results illustrated the distinct two-step cooling process. The cooling regimes are not sharply demarcated due to the reduced coolant flow.

The capability of the stored heat in the cask body to preheat the inlet water (during Step One) was verified. This eliminates the need for a separate hot water heater on the cooling skid. Manual control of the process flow rate and flow rate system pressure was readily accomplished. The coolant pump is not needed if system pressure is at least 60 psig. These simplifications lead to an economical and

TABLE TWO

COOLDOWN SYSTEM TEST RESULTS

			PERMANENT SYSTEM		PORTABLE SYSTEM	
CASK	THERMAL LEVEL (kilowatts)	FUELAGE (years)	COOLDOWN TIME (minutes)	INITIAL TEMP./PRESS. (°F/psig)	COOLDOWN TIME (minutes)	INITIAL TEMP./PRESS. (°F/psig)
Truck	4	1.5	20	200/15	60	80/60
Truck	7.5	1	35	310/65	90	80/60
Truck	10.6	0.4	50	400/235	120	80/60
Rail	25	2	90	270/30	---	---
Rail	70	1	180	400/235	---	---

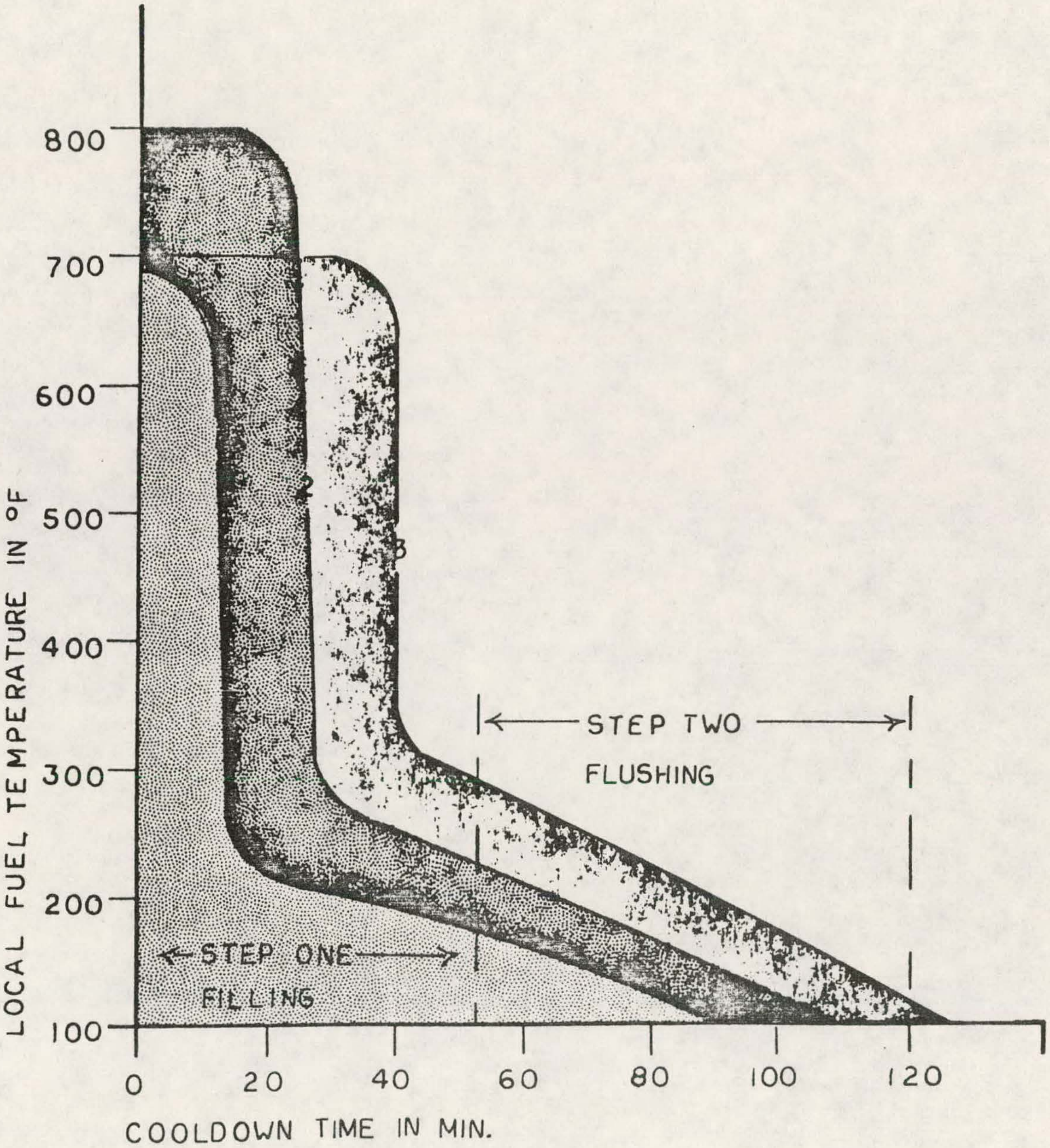


FIGURE SEVEN

CHARACTERISTIC COOLDOWN CURVE -- PORTABLE COOLDOWN SYSTEM easily operated process system. The skid is transportable. The portable cooldown system can be employed at any nuclear site where a fuel pool is present.

4.3 Vacuum Dry-Out System Tests

Vacuum dry out of the cask was successfully demonstrated. Dry-out times were in the range of 20 minutes to 1 hour. Dry out was even verified in a cold cask (wall temperature <70°F) with the fuel removed. The sole thermal driving force was the temperature gradient between the cask body and the vaporizing fluid. Visual confirmation of the drying process was obtained by using a Plexiglas closure. The vapor pressure of the water was so low that at times frost was observed in the vicinity of the drain tube entrance. A "shaped" drain tube was developed. This assured that only a small residual of water remained in the cask after the draining operation. The drain tube entrance configuration minimized the formation of fluid swirls or vortices.

Figure 8 illustrates the characteristic vacuum dry-out curve. Observation of the cask pressure when the vacuum pump is running presents evidence of proper or faulty system operation. This is an important verification of dryness since the operator cannot visually ascertain that the cavity is dry. Total dry out of the cask is assured when the cavity vacuum rapidly drops below about 1 to 2 Torr (saturated vapor temperature less than 35°F). Curve A of Figure 8 illustrates proper operation. Curve B occurs when the vacuum pump is slightly undersized or a thin layer of water remains in the cask. Curve C (no dry out) occurs either when the cask closure is leaking; the pump oil is badly contaminated with water; or a deep layer of water still remains in the cask. In this event, the operator would have evidence that the cask was not drying. Additional steps would be required to evaluate the fault.

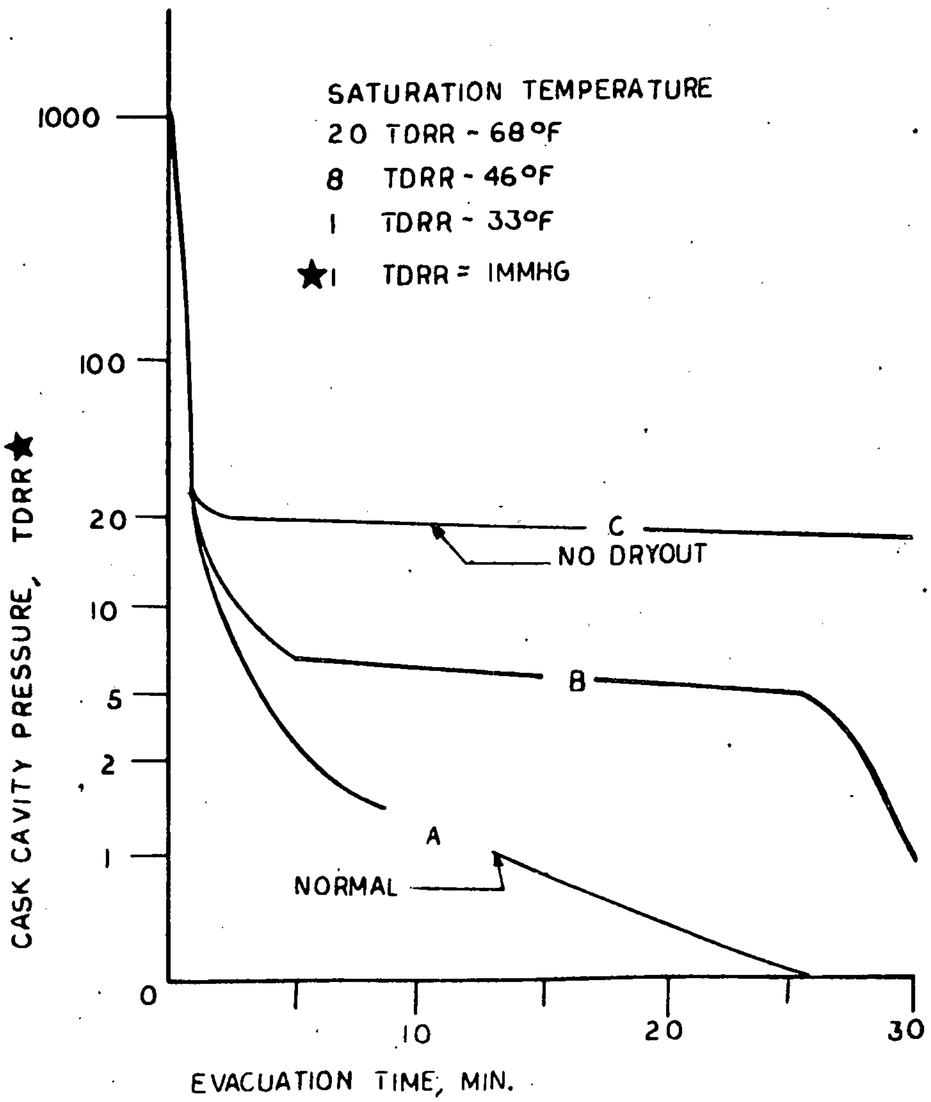


FIGURE EIGHT

CHARACTERISTIC CASK DRYOUT CURVE

5.0 SUMMARY AND CONCLUSIONS

The cooldown and dry-out processes were successfully conducted on a repeatable basis under a variety of operating conditions. The processes can be performed in a safe and predictable manner on a production basis. The operational time required does not cause abnormal inconvenience. In general, these thermal considerations are peculiar to a dry cask. The results of this development program show that these dry cask operations should not cause problems during loading or unloading in excess of that experienced with a wet cask.

In recent years, the emphasis on spent fuel shipping data has changed from short-term cooling to long-term cooling. The "aging" of the spent fuel in reactor pools permits the decay heat level to drop markedly, as noted below:

Cooling Period, Years	Decay Heat, kwt*
0.5	10.6
1.0	6.2
2.0	3.2
5.0	1.1

*PWR assembly.

Current projections are that most fuel will be "aged" at the reactor prior to shipment. In these situations, thermal considerations, whether for a wet or a dry shipment, are very small. After five years, even local "hot spot" fuel temperatures will not exceed 275 to 300°F. The basket and cask body temperatures will be well below 200°F. The cooldown and dry-out steps will rarely be required in these situations. The point of demarcation during which thermal effects must be considered is during the first two to three years of cooling.