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ASSESSMENT OF LMFBR SPENT FUEL SHIPPING CASK CONCEPTS FOR THE CRBRP AND THE U.S. CONCEPTUAL DESIGN STUDY*

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INTRODUCTION

Two major liquid metal fast breeder reactor (LMFBR) power programs are in the conceptual study design and/or initial construction phases in the United States: the Clinch River Breeder Reactor Plant (CRBRP), designed to produce 380 MWe, and the Conceptual Design Study (CDS), estimated to result in a 1000 MWe plant. Shipment of spent fuel assemblies producing 4 to 7 kW decay heat each is required for the CRBRP. The design of the CDS plant requires shipment of spent fuel assemblies producing 8 to 11 kW decay heat. This paper describes the results of continuing studies to define shipping casks for transporting spent fuel from these plants. Loading and unloading problems are assessed and cask/plant interface criteria are discussed.

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DISCUSSION

Various constraints have been defined for both plants and for the Hot Experimental Facility (HEF) which will receive and reprocess the spent fuel. For example, the handling surfaces of the cask cannot exceed 60°C (140°F) during loading and unloading operations, and the fuel clad temperature cannot exceed 650°C (1200°F) for normal operations. In addition, LMFBR spent fuel assemblies, unlike LWR assemblies, consist of an array of pins encased in a hexagonal stainless steel shell, and are further characterized by a short fuel zone from which a major portion of both decay heat and radiation are emitted. This design poses problems during loading and shipment of providing adequate shielding in the cask body near the fuel zone and efficiently distributing the heat away from the fuel zone. Previous studies (References 1-3) have shown that, to adequately distribute decay heats of 4 to 11 kW from a spent LMFBR fuel assembly through conduction, thermal radiation and natural convection, liquid coolants, such as sodium, will be required.

The basic conceptual design developed at Sandia National Laboratories (SNL) to support the CRBRP and the CDS reactors consists of a spent fuel shipping cask having a monolithic steel structure with seven basket cavities. Each cavity would contain a fuel assembly in a sealed, sodium-filled stainless steel canister. The cask cavity would be backfilled during loading, shipping and unloading with helium,

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or possibly nitrogen. As currently envisioned, triple containment of the sodium would be provided by (1) the canister, (2) an inner cask lid and (3) an outer cask lid, as illustrated in Figures 1 and 2. If the fuel pin cladding is considered to be a containment boundary, this constitutes four levels of containment for the fuel and fission products. Surrounding the steel cask body, longitudinal steel fins on the inner circumference extend through a solid neutron shield of Borosilicone rubber. This neutron shield concept is described in detail in Reference 4. External heat rejection is accomplished with spaced finlets welded to an outer steel shell encasing the neutron shield.

The specific cask designs for CRBRP and CDS are similar but of different sizes. The CRBRP fuel, shorter and smaller in cross section, requires a cask of 1.7 m in diameter and 5.1 m in length with a loaded shipping mass of approximately 55 tonne. The canisters (0.178 m OD, 4.53 m long) would fit into 0.19 m ID cavities arranged in a circle of six on a 0.44 m diameter, with one in the center. For the CDS spent fuel, the cask would be 2.1 m in diameter and 6.6 m in length with a loaded shipping mass of approximately 88 tonne. The canisters for CDS fuel (0.229 m OD, 5.284 m long) would fit into 0.24 m ID cavities, one in the center and six on a 0.54 m diameter.

Three alternate methods for designing the outer lid, the inner lid (or lids) and an alternate shield plug are illustrated in Figure 2. Crane lift capacities and other cask/plant interfacing criteria will eventually determine the concept chosen, although the cask having two lids with the shield incorporated into the inner lid is preferred. The other options add complexity to the loading/unloading procedure, the cask fabrication, or both.

Two canisters for CRBRP fuel are currently under consideration. Both are of stainless steel pipe construction with a welded bottom of tapered stainless steel. The two designs differ in the sealing mechanisms at the head of the canisters. In one (Reference 5) a mechanical seal is used, while the other canister is seal-welded. The mechanically sealed canister would be indefinitely reusable, but the sealing mechanism reliability may be in question. The welded lid design is configured to allow the welded area to be mechanically removed and rewelded approximately ten different times. This design should provide an extremely reliable sealing mechanism.

Drop testing of the mechanically sealed canisters with surrogate fuel and coolant has been initiated. In the first test, which was a 9 m, end-on drop onto an unyielding target, the canister was filled with an 80-percent glycerine/20-percent alcohol mixture serving as the sodium surrogate. This mixture provides the same acoustic impedance as liquid sodium at 450°C. The test was conducted with the canister and contents at an ambient condition of approximately 24°C. Following impact, the canister appeared to be structurally sound with no buckling or cracking. Drop tests from 9 m have also been performed with the canister impacting side-on, and in a "slap-down" orientation with the bottom end of the canister impacting first. In these tests significant canister deformation was observed, but no cracks were found nor was there any leakage of the liquid from the canister body. However, the mechanical seals did fail, causing leakage of the surrogate coolant. Further tests at lower drop heights will be performed to define the failure threshold of the seals, and the thresholds can then be analytically related to the performance of the canister in the cask during impact. Based upon the drop tests to date, it is postulated that the seal-welded canister should survive a 9 m drop independent of the cask and of impact orientation.

Heat transfer analyses of the CRBRP and CDS conceptual designs were used to examine operating temperatures under normal solar input at 55°C ambient. The assembly heat output is assumed to be 7 kW for CRBRP with a backfill gas of helium between the canisters and the cavities after the cask is sealed. The CDS cask temperatures were examined with helium and nitrogen as backfill gases. The heat load used for CDS is a ring of six 11 kW assemblies with one 4 kW core component in the center cavity to prevent overheating at that location. Resulting cask temperature profiles are shown in Table I. No analysis has been attempted to accurately estimate pin temperatures inside the assembly. However, it is felt that, based on data from References 1 and 2, the additional rise from the canister temperature to the maximum pin temperature is on the order of 30 to 50°C for the decay heat outputs considered.

An emissivity of 0.3 was generally assumed for the canister and cavity surfaces. Higher canister temperatures were calculated for the nitrogen-backfilled cask than for the helium-backfilled cask. This can be offset by increasing the emissivity of both canister and cavity as shown in Table I, which could be accomplished with various surface treatments.

One of the problems addressed has been the method of canister loading. Because of sodium expansion and cover gas pressure buildup in the canister, the simple method of loading a hot assembly into liquid sodium at or just above sodium melt temperature was rejected. Instead, heating the canisters and sodium to the approximate normal operating temperature before loading is proposed. The operating temperature in this case is defined by the maximum cask load of 49 kW for CRBRP and 70 kW for CDS (see Table I). The amount of sodium contained in each canister is governed by accident (off-normal) conditions. The cask analysis in a fire environment has not been completed. However, calculations using a bounding, i.e. worst case, condition of 676°C (1250°F) for the fuel cladding (and therefore the sodium) and a 10 atm pressure in the canister cover gas, indicate a sodium level at loading should be 0.254 m below the top of the CRBRP assembly. Further analysis of the cask response to an 800°C thermal source, which is discussed later, suggests that the actual temperature response may be less severe and that the sodium level might only need to be 0.038 m below the top of the assembly. Data from Reference 1 show that the heat rejection in the vertical position is not significantly affected if the sodium is below the top of the assembly. An alternate loading method would be to heat the sodium to a temperature greater than that expected during normal operation. This would result in a gas pressure lower than 10 atm in the canister at off-normal (i.e., accident) temperatures and subatmospheric pressure during normal shipping.

Table I. Axial Center Cask Temperatures During Steady State Operation

CASK CONFIGURATION	CRBRP	CDS	CDS	
Spent Fuel Assemblies	Seven, 7kW	Six, 11kW One, 4kW	Six, 11kW One, 4kW	
Cask Cavity Cover Gas	Helium	Helium	Nitrogen	
Canister/Cavity Emittance	0.3	0.3	0.3	0.8
Cask Surface Temp (°C)	170	190	190	190
N-Shield/Steel Body Interface Temp (°C)	290	330	330	330
Outer Cavities Temp (°C)	330	385	385	385
Outer Canisters Temp (°C)*	405	465	535	459
Inner Cavity Temp (°C)	375	440	450	439
Inner Canister Temp (°C)*	430	460	495	453

*Maximum fuel pin temperature would be 30 to 50°C above the canister temperatures shown (see References 1 and 2). Maximum allowed pin temperature is 650°C.

The requirement of maintaining cask-handling surface temperatures below 60°C (140°F) presents difficulties in both loading and unloading modes. The loading sequence assumed was that one canister would be loaded per hour. The large thermal mass of the cask significantly delays surface temperature rise during loading. However, external natural convection alone is insufficient to prevent overheating while the cask is in plant. Surface temperatures were calculated to exceed 60°C (140°F) in 9 to 12 h after loading is initiated. This time is insufficient to allow for cask loading and sealing operations and removal from plant.

To provide a feasible method of cooling during loading and unloading, internal channels can be provided in the cask body. The assumed coolant flow pattern is one pass up and down, then out. Twelve pairs of channels, each with a cross-sectional area of 7.39×10^{-4} m^2 for the CRBRP cask and 1.098×10^{-3} m^2 for the CDS cask are spaced between the steel structure and neutron shield. Thus the coolant channels lie outside of the containment boundary and are near the cask surface, allowing the surface temperatures to be reduced rapidly by the pumping of coolant. The coolant inlet and outlet are at the bottom of the cask, with the channels extending upward to just below the lid.

For the CRBRP cask, calculations showed that a flow rate of 288 litre/min (76 gal/min) of 20°C (67°F) water in the channels maintains the surface temperatures of the cask below the 60°C requirement during loading. For the CDS cask, calculations showed that a flow rate of 490 litre/min (130 gal/min) of 20°C water maintained the surface temperatures below 60°C for approximately 42 h; and a flow rate of 980 litre/min (260 gal/min) maintains the surface temperatures below 60°C indefinitely. Further effort is required here to assess methods for enhancing the heat transfer to the water channels and reducing the required flow rates. The results of these calculations are summarized in Table II. Because it was assumed that the cooling channels did not extend into the lid, this portion of the cask could heat up during bolting and sealing operations. This problem is discussed later.

As indicated by the temperature profiles in Table I, the cask on arrival at the HEF will have a surface temperature far above the allowable 60°C. External air cooling at reasonable flow rates is ineffective in reducing surface temperatures following shipment. External water cooling improves this somewhat, although access to the cask surface is then limited. Furthermore, because large quantities of heat are stored in the cask body, external water cooling cannot be suspended during the unloading operation without rapid surface temperature rise to unacceptable levels.

Table II. CRBRP and CDS Cask Heat-Up During Loading

CASK TYPE	COOLING METHOD	CAVITY BACKFILL GAS	TIME TO REACH 60°C AT SURFACE
CRBRP	Natural Convection	He or Ar	9 h
CRBRP	288 litre/min of 20°C water	He or Ar	Steady state surface temperature less than 60°C
CDS	Natural Convection	He or N_2	12 h
CDS	490 litre/min of 20°C water	He or N_2	42 h
CDS	980 litre/min of 20°C water	He or N_2	Steady state surface temperature less than 60°C

Several modes of cask cooldown using internal water flow have been examined. Only the most promising method is reported here. The water flow would initially enter at 10 atm, 179°C (354°F), and would utilize the heat of vaporization in extracting heat from the cask. When the coolant exit temperature falls below 180°C (355°F), the inlet water temperature would be lowered to 95°C (202°F), while still maintaining the pressure. Once the exit temperature falls below 100°C (212°F) the pressure may be reduced and water at 20°C (67°F) introduced. In addition to the internal water cooling, external 20°C forced air cooling over the lid only was required for reasonable cooldown times.

The CRBRP cask cooldown results show that 25 to 53 h are needed to attain surface temperatures under 60°C. The calculated base case was 326 litre/min (86 gal/min) with no external air cooling on the lid, which corresponds to 53 h cooldown. For the base case, the lid was the slowest cooling portion. Both the air flow rate over the lid and the water flow rate in the cask were varied to assess those flow rates which lead to shorter cooldown times. The greatest assumed velocity of air over the lid for CRBRP was 12.2 m/s, and the greatest flow rate of water was 974 litre/min (257 gal/min), which gave a 25 h cooldown. The results are shown in Table III.

The CDS cask cooldown analysis indicates times of 27 h to greater than 72 h. Once again, the longest time to cool resulted from the calculated base case of 480 litre/min (128 gal/min) internal water cooling with no forced external cooling. To obtain 27 h cooldown, internal water cooling of 960 litre/min with air velocity on the lid of 15.4 m/s was required. These results are also presented in Table III.

With the internal cooling of the cask body only, the lid is the slowest portion of the cask to cool. The method considered here to improve cooling times was external air cooling of the lid. Another option, separate cooling channels in the lid, could improve the cooling times even further. From examination of the cooldown of the base sections, which, like the lid, have no heat source nearby, it may be safely assumed that lid cooldown could be eliminated as the controlling factor in cooldown time if such internal cooling channels are used.

TABLE III. Cask Cooldown at HEF

CASK CONFIGURATION	AIR VELOCITY OVER LID (m/s)	WATER FLOW RATE IN CASK CHANNELS (litre/min)	TIME TO COOL HANDLING SURFACES TO 60°C (h)
CRBRP	0	326	53
	6.1	326	42
	12.2	326	35
	6.1	652	33
	12.2	652	27
	6.1	974	31
	12.2	974	25
CDS	0	480	>72
	7.6	480	69
	12.2	480	40
	15.4	480	35
	7.6	960	68
	12.2	960	33
	15.4	960	27

Initial calculations of the response of the cask to the regulatory thermal test exposures have been completed. Maximum canister temperatures were found to occur 9 to 10 h following initial exposure to the 800°C (1475°F) thermal source. Table IV compares the maximum canister temperatures during normal operation and following exposure to the thermal test environment. From these data it can be concluded that the thermal test does not control the design.

TABLE IV. Comparison of Maximum Canister Temperatures for CRBRP and CDS Casks

	NORMAL OPERATION (°C)	THERMAL TEST (°C)
CRBRP Cask	430	455
CDS Cask, Helium Backfill	465	480
CDS Cask, Nitrogen Backfill	535	545

Beginning in October 1980, a detailed conceptual design study was initiated for a CRBRP spent fuel shipping cask. The study is based upon the results of the efforts described above. The detailed concept for the cask should be completed in late 1981.

CONCLUSION

In conclusion, the study of conceptual shipping systems for CRBRP and CDS spent fuel has shown that systems significantly different from those used for LWR spent fuel will be required. In the conceptual design, liquid sodium was assumed to be the coolant in canisters containing the spent fuel assemblies, and multiple levels of containment were provided by canisters, an inner cask lid and an outer cask lid. Cask cooling at the reactor site during loading, and cooldown at the receiving site prior to unloading are signficant but tractable problems.

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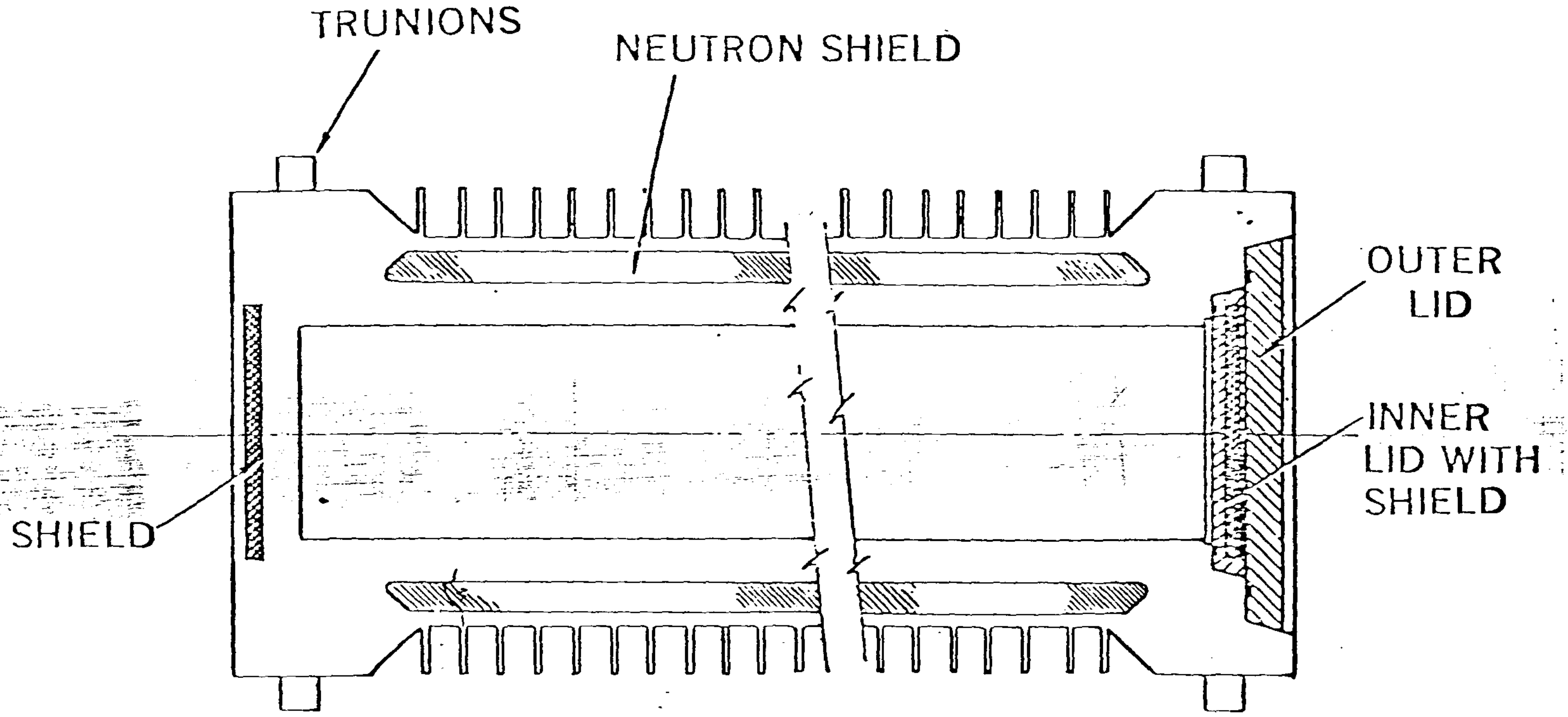


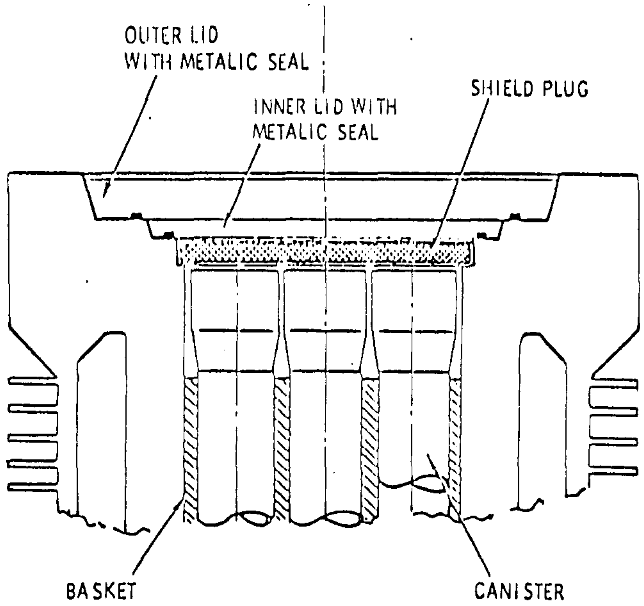
CASK CONFIGURATION

	CRBRP	CDS
SIZE	1.7mDX 5.1mL	2.1mDX 6.6mL
WT.	88 TONNES	55 TONNES

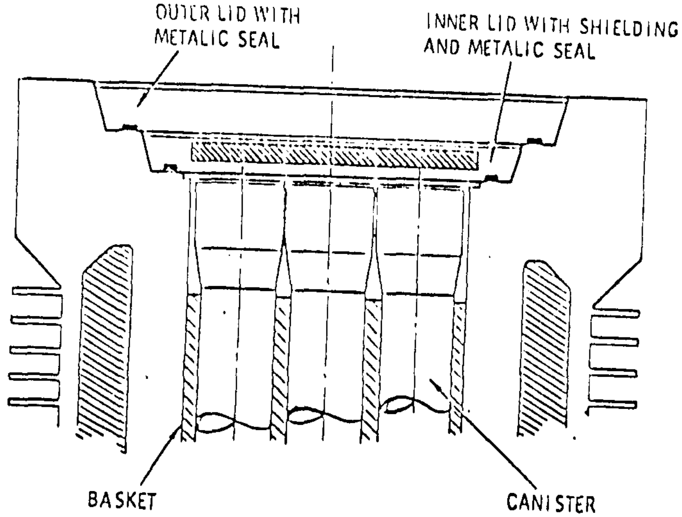
55 88

Figure is in Tech Art

Figure 1



SEVEN ELEMENT CASK
WITH SEPARATE SHIELD PLUG



SEVEN ~~FUEL~~ ELEMENT CASK
~~CASK DESIGN~~ WITH TWO LIDS

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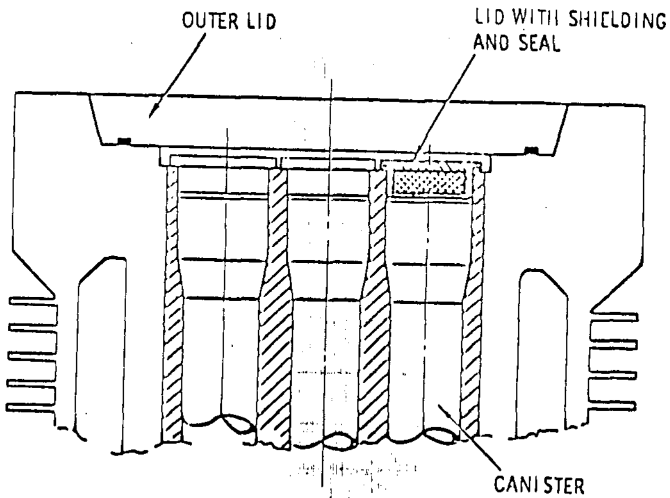

~~CASK DESIGN:~~
SEVEN ELEMENT CASK
WITH INDIVIDUAL ~~SEALED~~ INNER LIDS
AND SHIELDED ~~CANISTERS~~ PLUGS

Figure 2