Consideration on Packaging and Transportation of Spent Fuels for Japanized Horizontal Modular Storage System

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1. INTRODUCTION

The objectives of this study are to present the features of the Japanese horizontal modular storage system for dry storage of PWR and BWR spent fuel assemblies and to establish the means to accomplish the design activities.

This report focuses on the packaging and transportation system for the Japanized horizontal modular storage system for the case where it will be installed away from reactor (AFR), and confirm its feasibility in accordance with the Japanese regulations.

2. CONCEPT OF HORIZONTAL MODULAR STORAGE SYSTEM

The horizontal modular storage system, which is called NUHOMS® in the United States (Pacific Nuclear 1991), is a dry storage system for PWR and BWR spent fuel assemblies with passive natural circulation air cooling. It has been used at ISFSIs at a number of reactor sites in the United States. It consists of the canisters, the concrete modules, the transfer cask and the transportation system for the canister. The arrangement of the system is shown in Figure 1.

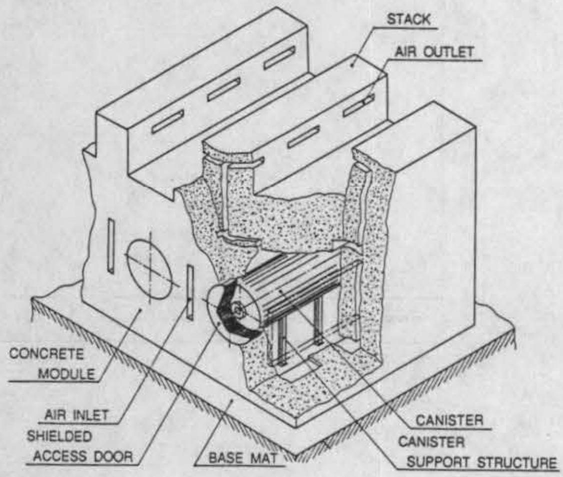


Figure 1 Japanized Horizontal Modular Storage System Arrangement

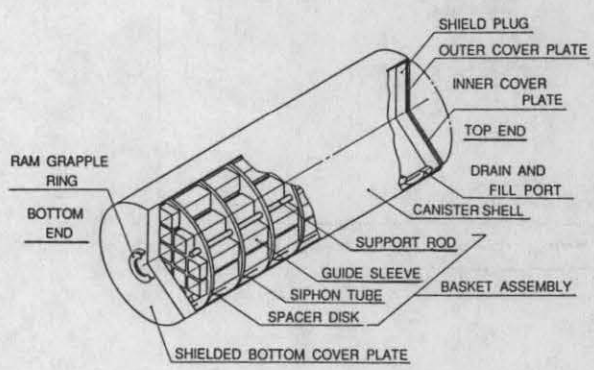


Figure 2 Illustration of PWR Canister

Figure 2 shows the illustration of the canister. It is a cylindrical stainless steel vessel which confines the fuel assemblies in a helium atmosphere. The diameter is about 1.7 m and the length is about 5 m. The cylindrical shell, and the top and bottom cover plate assemblies, form the pressure-retaining containment boundary for the spent fuel. Both ends are shielded with shield plugs. The internal basket assembly, which consists of spacer disks, guide sleeves and support rods, provides a storage position for each fuel assembly. The helium atmosphere improves heat transfer performance and prevents the long-term corrosion of the cladding.
24 PWR fuel assemblies or 52 BWR fuel assemblies can be stored in a canister.

The concrete module provides a structure for storage of spent fuel confined in a canister as illustrated in Figure 1. It is constructed from reinforced concrete and structural steel. The thick concrete roof and walls of the module provide substantial neutron and gamma shielding. The module provides a means of removing spent fuel decay heat by a natural circulation air flow. Ambient air enters the module through ventilation inlet openings in the front wall and circulates around the canister. Air exits the module through outlet openings in the stack assembly.

The canister transfer cask is a cylindrical shielded container which is used to transfer a loaded canister. The outside diameter is about 2.4 m and the length is about 6 m. The cask is designed not only to meet the requirement to transfer the canister at reactor (AR) but also to meet the requirement to ship away from reactor (AFR). For the case where it will be shipped away from the reactor, impact limiters are attached to both ends. The illustration of the canister transfer/transportation cask is shown in Figure 3.

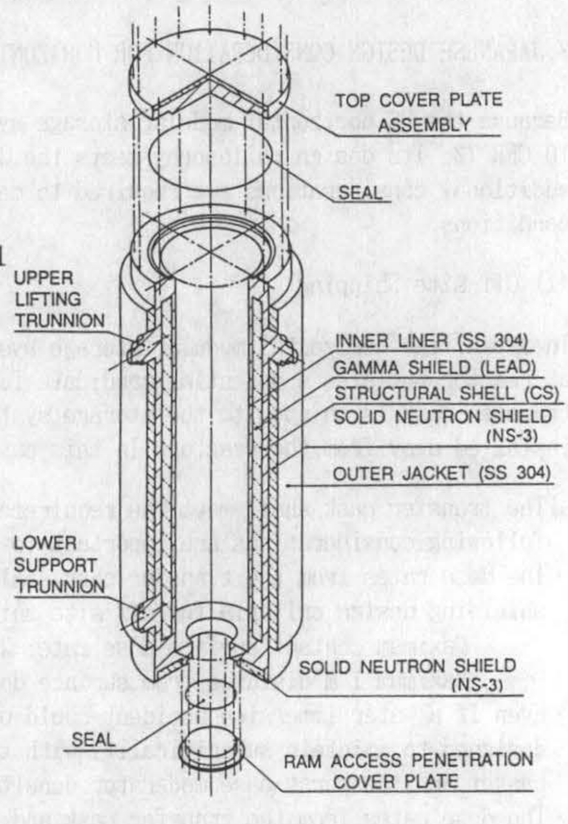


Figure 3 Illustration of Canister Transfer cask

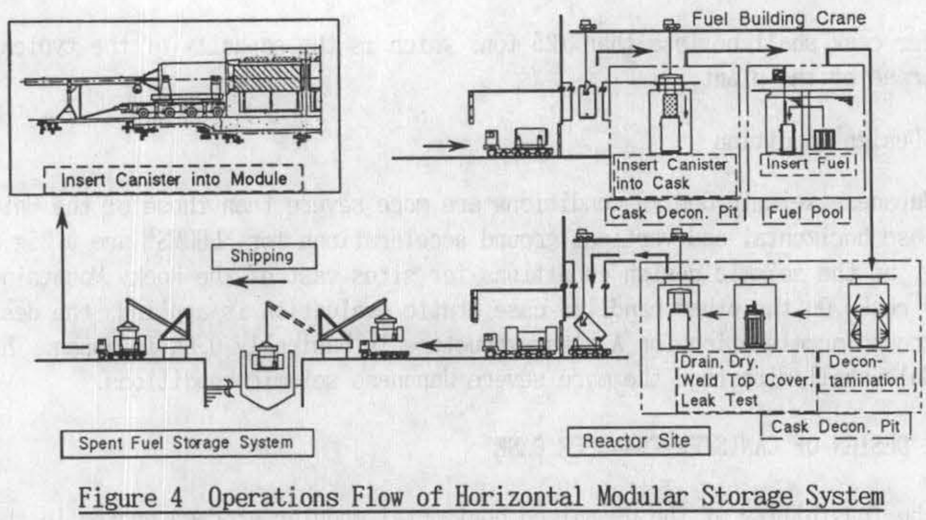


Figure 4 Operations Flow of Horizontal Modular Storage System

Figure 4 shows the operational sequence for the horizontal modular storage system. At the fuel storage pool, the spent fuel assemblies are inserted into the canister, which is placed in the canister transfer cask. Then, the cask is transferred to the decontamination pit. At the pit, the canister is drained, dried and filled with helium, and then the top cover plate is welded, forming the containment boundary. The cask which contains a canister is then transferred by a trailer to the storage system. For the case where the horizontal modular storage system is installed away from reactor (AFR), it is expected that a cargo vessel will be used to transfer the cask to the AFR storage system.

3. JAPANESE DESIGN CONSIDERATION FOR HORIZONTAL MODULAR STORAGE SYSTEM

Because the US horizontal modular storage system, NUHOMS®, is designed in accordance with 10 CFR 72, its design philosophy meets the Japanese rules and regulations basically. But additional considerations are required to meet Japanese regulatory and site-specific conditions.

(1) Off-site Shipping

In Japan, the horizontal modular storage system is not only a candidate for the storage system at reactor but also a potential candidate for the storage system away from the reactor. The transfer cask is shipped to the storage system by a cargo vessel in case the storage system is installed away from the reactor. In this case the following requirements must be considered:

a) The transfer cask shall meet the requirement of type B shipping cask. Especially the following considerations are important to maintain the feasibility of the system.

- The dose rates from the transfer cask shall not exceed the following doses which are the shielding design criteria for off-site shipping container given by Japanese regulation.
  Maximum contact surface dose rate: 2.0 mSv/h
  Maximum 1 m distance from surface dose rate: 0.1 mSv/h
- Even if a water immersion accident could occur during cask shipment, the canister shall be designed to maintain subcriticality with the worst-case geometrical arrangement of the basket and the worst-case moderator density.
- The dose rates from the transfer cask and the radioactive material generated after the 200 m deep water immersion test shall not exceed the quantity which is prescribed by Japanese regulation.

b) The transfer cask shall be less than 125 ton, which is the capacity of the typical fuel building crane of the plant.

(2) Seismic Design Condition

Generally, Japanese seismic design conditions are more severe than those of the United States. The design base horizontal and vertical ground accelerations for NUHOMS® are 0.25g and 0.17g, respectively, as the seismic design conditions for sites east of the Rocky Mountain front underlaid by rock. On the other hand, in case static evaluation is applied, the design basis horizontal ground acceleration for A class structure is basically 0.6g in Japan. Therefore the concrete module shall withstand the more severe Japanese seismic conditions.

4. CONCEPTUAL DESIGN OF CANISTER TRANSFER CASK

To confirm the feasibility of the Japanized horizontal modular storage system in the case where it will be installed away from reactor, the conceptual design of the off-site transfer cask is performed and the following three key parameters are evaluated.

(1) Soundness after 200 m Deep Water Immersion Test

To meet the requirement after 200 m deep water immersion test, the cask is designed to withstand 200 m deep water immersion. It is evaluated that the thickness of the cask body shall be more than 50 mm to withstand an outer pressure of 2 MPa, equivalent to 200 m water head. Based on this result, the 76 mm is selected as the cask body thickness.

(2) Radiation Shielding Performance of Canister Transfer Cask

To meet with the shielding design criteria of an off-site shipping container, the transfer cask design that has been used at ISFSIs in the United States is modified. The shielding design conditions are shown in Table 1. The cask shield thickness is increased to keep the dose rate from the cask less than the allowable level.

Shield composition of this off-site transfer cask is also quite the same as the NUHOMS® on-site one, except for the shield thickness. Radial shields are composed of canister shell, cask structural shell, lead gamma shield slab and solid neutron shield slab. Axial shields are composed of the canister end plugs and axial shielding, and cask lid and fixed neutron shielding.

Shielding analysis has been preformed, using 1-D transport code ANISN to evaluate the radiation dose rate around the cask. Table 2 shows shielding analysis conditions.

Table-1 Shielding Design Conditions

Category	Criteria or Parameter
Fuel Acceptance Criteria*	
·Assembly Type (No. of SFAs)	PWR : 8x 8 (24P) BWR : 17x17 (52B)
·Cooling Time	> 5 years
·Burn-up	PWR : 40,000 MWD/MTU BWR : 35,000 MWD/MTU
·Initial Enrichment	4.0 w/o
Cask Shielding Criteria	
·Maximum Contact Surface Dose Rate	2.0 mSv/h
·Maximum 1 m Distance From Surface Dose Rate	0.1 mSv/h

*: It is temporarily assumed the same as NUHOMS® shielding design conditions in the USA

Table 2 Shielding Analysis Conditions

Calculation Parameter	Value
Computer Code	ANISN
·P_l order	P_3
·S_n order	S_{12}
Discrete Ordinate Method	Mixed Linear
Convergence Criteria	< 0.0001
Cross Section Library	DLC-23E n :22 groups γ:18 groups
Boundary Conditions	Vacuum at Cask Surface Reflection at Canister Center
Radiation Source Strength*	
·Neutron (n/cm³/sec)	6.69×10^2
·Gamma Ray (γ/cm³/sec)	2.22×10^{10}
Calculation Model	
·Geometry	Infinite Cylinder
·Axial Leakage	Fuel Length Buckling

*: 5-years cooling PWR spent fuel radiation sources, which are larger than the same BWR ones

Figure 5 shows the radiation dose rate distributions over cask radial direction, based on the calculation results. It shows that both the cask surface contact dose rate and the 1 m distance from cask surface dose rate are lower than the maximum permissible dose rates specified in Table 1, 2.0 mSv/h and 0.1 mSv/h, respectively. Lead and solid neutron shieldings are 12.2 cm and 12.9 cm thick, respectively. The total cask weight including spent fuel assemblies is about 120 ton, which 125-ton capacity crane can handle.

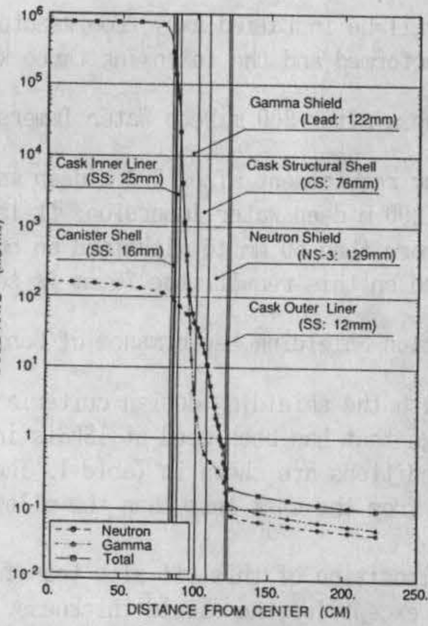


Figure 5 Radiation Dose Rate Distribution Over Cask Radial Direction

(3) Criticality Performance

The US canister design for BWR fuels is designed to maintain subcriticality in water pool by installing neutron absorber sheets in the canister basket. Therefore, the canister for BWR fuels will be able to apply to the off-site transportation by a cargo vessel without any design change, even if a water immersion accident should occur during cask shipment.

However, the US canister design for PWR fuels is designed to load spent fuel in borated water pool, whose boron content is sufficient to provide subcriticality. Then the canister design for PWR fuels has to either be modified to meet the subcriticality requirement ($k_{eff} + 2\sigma \leq 0.95$) for pure water immersion in the canister or be licensed to avoid moderator intrusion. For Japan, a fixed neutron absorber design is selected to meet the criticality criteria. Three design options with fixed neutron absorbers:

Option-1 : Borated Stainless Steel Guide Sleeves (Figure 6a)

Option-2 : Borated Aluminum Guide Sleeves (Figure 6a)

Option-3 : Sintered B_4C-Al Composite Panels with Stainless Steel Guide Tubes (Figure 6b)

were considered for evaluation. The original configuration of the basket is assumed to be preserved as closely as possible.

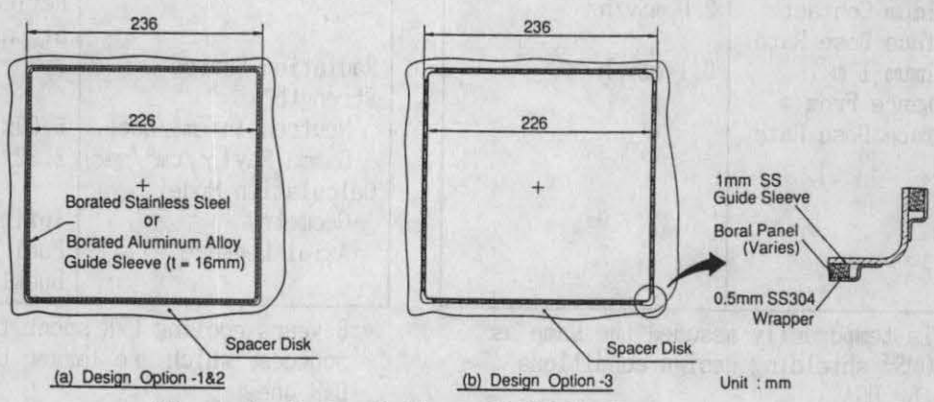
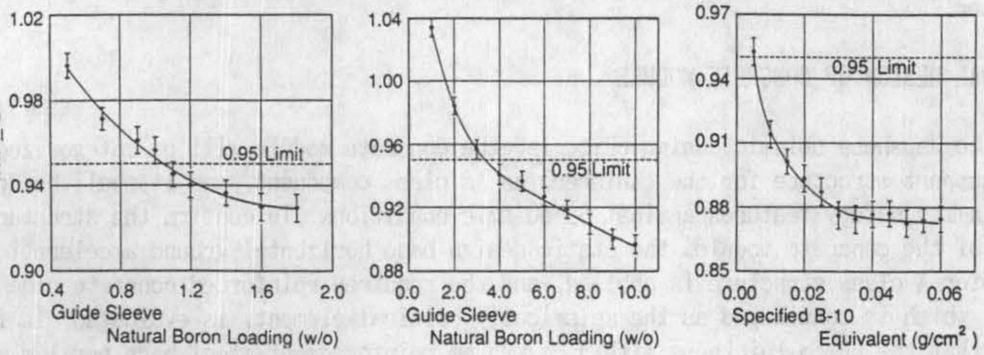


Figure 6 Design Options of PWR Basket

Three sets of parametric studies were run using KENO-Va and the Hansen-Roach cross section library. Design parameters are natural boron concentration for Case-1 and Case-2, and specified B-10 content equivalent for Case-3. The results of these calculations are shown in Figure 7. The fuel acceptance criteria are the same for the shielding analysis except fuel initial enrichment. 3.5 weight percent is fixed for the parametric calculations.



(a) Option -1: Borated Stainless Steel Guide Sleeve (b) Option -2: Borated Aluminum Alloy Guide Sleeve (c) Option -3: Sintered B4C-Al Composite Panel

Figure 7 KENO Results - 3.5% Enriched Fuel

A 4.0 weight percent enrichment subcriticality analysis was performed subsequent to 3.5% scoping analyses for the selected canister design. In order to calculate a specific result, 2σ uncertainties plus about 0.02 for other mechanical uncertainty such as fuel position, absorber thickness etc. must be added to the calculated k_{eff}. The following evaluations were performed for each case.

Option-1 : Borated Stainless Steel Guide Sleeves

In order to maintain the current guide sleeve geometry, the required boron loading for stainless steel sheets would be about 1.6 weight percent natural boron for 3.5% enrichment fuel. This limits the apparent usefulness of borated steel since the material loses much of its ductility and is difficult to manufacture at higher boron levels. It has a necessity of using isotopically enriched boron instead of natural boron to control boron loading in stainless steel less than 1 percent.

Option-2 : Borated Aluminum Guide Sleeves

Due to the difference in density between aluminum and steel, a proportionately higher boron density is required. It appears that about 6.0 weight percent boron would provide sufficient neutron absorption to maintain subcriticality for 3.5% enrichment fuel. The upper limit of boron loading in aluminum is presently 3 weight percent due to the same reasons for stainless steel sheets. Therefore, isotopically enriched material is necessary for aluminum sheet to be fabricated.

Option-3 : Sintered B_4C-Al Composite Panels with Stainless Steel Guide Tubes

Sintered B_4C-Al composite panels with a specified B-10 content of 0.010 g/cm² appear to offer sufficient neutron attenuation for 3.5% fuel. The total thickness of the panel is about 1.9 mm, which is within an allowable dimension of 3.1 mm. This ensures no geometry change of the current guide sleeve. Sintered B_4C-Al composite panels are also applicable for 4.0 weight percent initial enrichment, because of 0.025 g/cm² B-10 content and 2.1 mm panel total thickness.

Option-1 and Option-2 are less attractive because of high cost, restrictive mechanical properties and low availability of isotopically enriched boron loaded material. Option-3 is selected for neutron poison basket design because of natural boron availability and no basket design change. The PWR canister with the newly selected neutron poison basket Option-3 can provide sufficient subcriticality for all design conditions, including water intrusion into the canister.

5. CONCEPTUAL DESIGN OF CONCRETE MODULE

According to Japanese seismic design criteria, the concrete module will be categorized as an indirect support structure for the canister, an As class component, and it shall be designed to maintain its safety features against S_2 seismic conditions. To confirm the structural integrity of the concrete module, the static design base horizontal ground acceleration, $3C_1=0.6g$, for A class structure is applied, and the required reinforced concrete side wall thickness, which is considered as the seismically critical element, is evaluated. It is confirmed that the 60 cm thickness with 5 - ϕ25 mm reinforcement steel bars per 1 m wall length is enough to withstand up to 0.6g of static force. The concrete module sliding and overturning due to seismic conditions are also evaluated, and it has been confirmed that the sliding and overturning will not occur. Based on the evaluations it is concluded that the concrete module will be able to withstand the Japanese seismic conditions.

6. CONFINEMENT FEATURE OF CANISTER

The horizontal modular storage system has redundant confinement barriers. The fuel cladding is the first barrier for confinement of radioactive materials and the canister is the second barrier. Moreover, the canister is a stainless steel cylindrical vessel with welded cover plates. It is fabricated in accordance with a highly reliable quality assurance program and from quality materials. Thus the system has sufficient confinement barriers to prevent the generation of radioactive materials. This configuration of the confinement barriers also meets the Japanese requirements, but if higher reliability is requested, an additional barrier can be installed. Figure 8 shows the over-pack concept. The over-pack is fixed in the concrete module and it can contain a canister. After the canister is placed in the over-pack, the cover plate is seal welded and the additional confinement barrier is formed. This concept can offer redundant confinement barriers without fuel cladding. This concept also offers a monitoring system for canister helium gas leakage by monitoring the pressure between the canister and the over-pack.

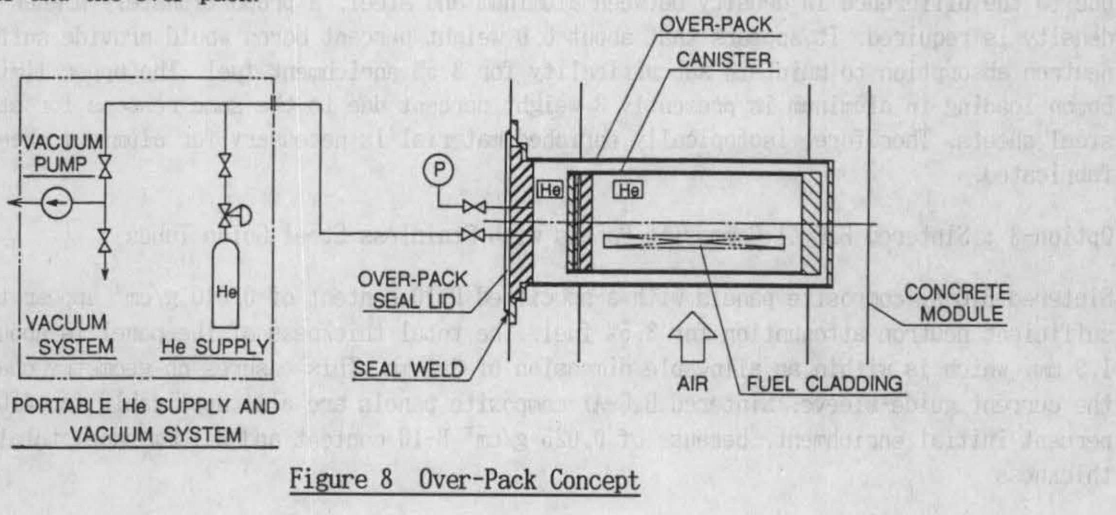


Figure 8 Over-Pack Concept

7. CONCLUSIONS

The feasibility of the packaging and transportation system for the Japanized horizontal modular storage system for the case where it will be installed away from reactor (AFR), has been evaluated in accordance with the Japanese regulations.

It has been confirmed that;

- The canister transfer cask is able to withstand the design condition of 200 m deep water immersion,
- Both the cask surface contact dose rate and the 1 m distance from cask surface dose rate are lower than the maximum permissible dose rates, 2.0 mSv/h and 0.1 mSv/h, respectively,
- The total cask weight including spent fuel assemblies is about 120 ton, which a 125-ton capacity crane, the typical fuel building crane, can handle,
- The PWR canister with the newly selected neutron poison basket can provide sufficient subcriticality for all design conditions, including water intrusion into the canister.
- The concrete module is designed to withstand Japanese seismic conditions.

It is concluded that the Japanized horizontal modular storage system is a feasible concept for Japanese PWR and BWR spent fuel dry storage system which is installed either at reactor (AR) and/or away from reactor (AFR).

During the detailed design phase, the system will be optimized for cost while preserving conservative design margins.

8. REFERENCE

Pacific Nuclear Fuel Services, Sep.1991, "Safety Analysis Report for the Standardized NUHOMS® Horizontal Storage System for Irradiated Nuclear Fuel"