CRITICALITY CONTROL FOR SPENT FUEL TRANSPORTATION IN HIGH-CAPACITY TRUCK CASKS

Shiaw-Der Su
GA Technologies Inc.
San Diego, California 92138

ABSTRACT

This paper presents the criticality control approach and analysis for the high-capacity truck casks being developed by GA Technologies Inc. (GA) for transport of PWR and BWR spent fuel from commercial nuclear power plants. The casks meet the design objective of providing maximum payload with minimum fuel cavity size in full compliance with the regulatory criticality safety requirements. Boral plates are used in the cavity between and around the fuel assemblies for criticality control. The thicknesses and boron contents of the Boral plates are sufficient to maintain the package subcritical under normal transport and hypothetical accident conditions.

INTRODUCTION

GA is developing a new generation of high-capacity truck casks for PWR and BWR spent fuel shipping from commercial nuclear power plants to a federal repository or monitored retrievable storage facility. The cask capacities are four PWR assemblies and nine BWR assemblies for legal weight truck (LWT) cask designs, increasing to seven PWR assemblies and fourteen BWR assemblies for overweight truck (OWT) cask designs.

Because of the large payload capacities, criticality control is necessary to ensure full compliance with 10CFR71 performance requirements pertaining to criticality safety. This paper discusses the key design parameters considered, the design approach and features used, and pertinent analyses performed for nuclear criticality control.

DESIGN PARAMETERS

The cask design objective is to maximize payload with minimum cavity size without compromising criticality safety. The key design parameters include the following:

- cask capacity
- fuel type, enrichment and burnup
- fuel assembly pitch in cask
- poison material, thickness and density
- shielding material used for cask
- water immersion

Cask capacity has a strong influence in designing for criticality control as more fuel assemblies make the package more reactive. Reactivity also depends on the fuel type (various PWR and BWR fuel types from different manufacturers), initial U-235 enrichment and burnup. For our initial analysis, we used Westinghouse 15x15 PWR fuel and General Electric 7x7 BWR fuel with a maximum initial enrichment of 4.5%. All fuel was assumed to be fresh, without credit taken for burnup.

Fuel assembly pitch affects criticality as well as cask size. An optimum spacing was determined to satisfy both criticality safety and maximum payload requirements. The optimum pitch is 241 mm (9.5 in.) for PWR fuel assemblies and 152 mm (6.0 in.) for BWR fuel assemblies.

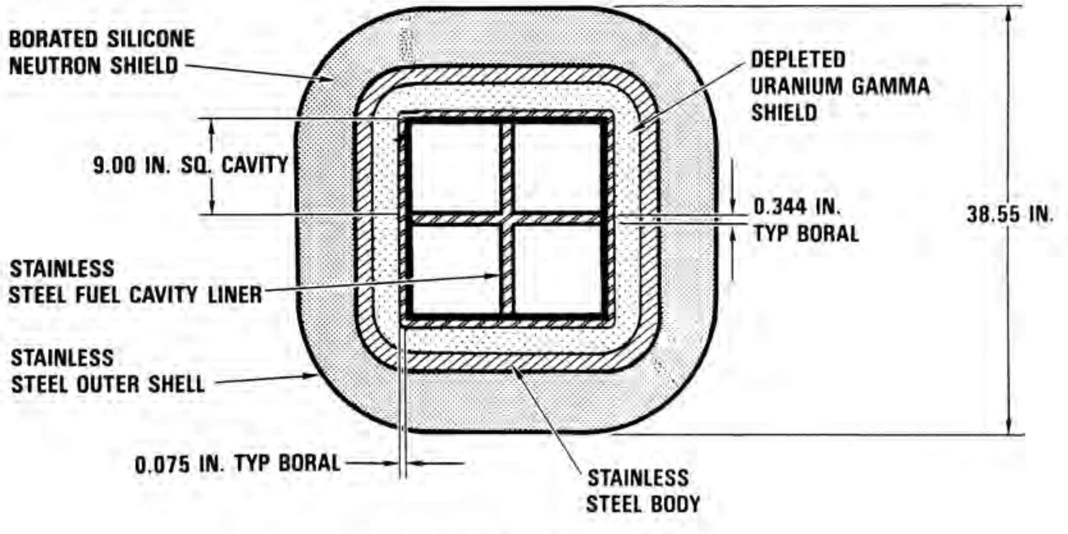
For criticality control, neutron poison needs to be provided in the cask cavity to reduce the reactivity to an allowable level. As will be discussed later, Boral poison material with appropriate thicknesses and densities was selected for use between and around fuel assemblies to achieve criticality safety for both LWT and OWT casks.

The depleted uranium (DU) and lead shielding materials affect criticality, owing to additional reactivity contribution from neutron fission in DU and from neutron reflection from lead. These factors are important considerations for criticality control design.

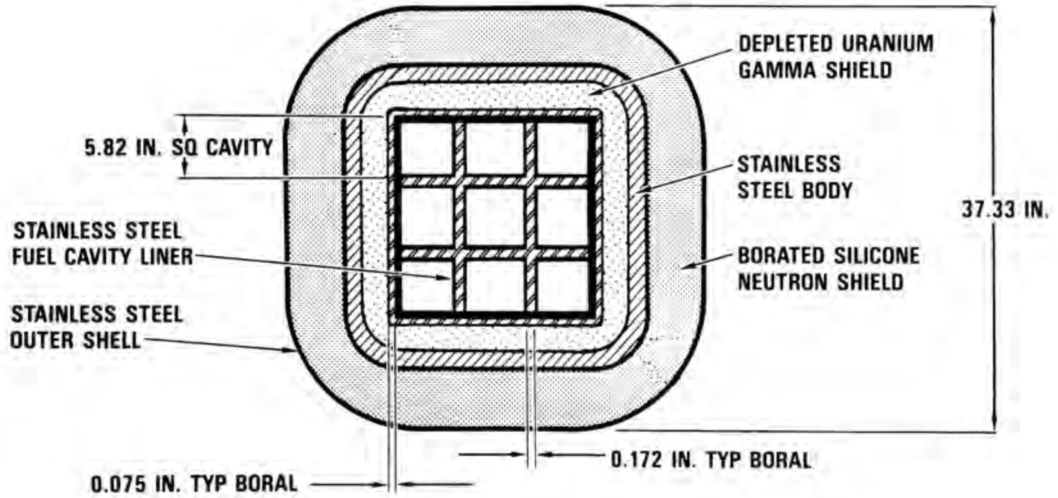
Spent fuel is generally more reactive in a flooded condition than a dry condition because of neutron moderation and reflection in water. The flooded condition must be considered for normal wet loading as well as for hypothetical accidents during transport. Therefore, the criticality analysis was focused on the flooded condition.

CRITICALITY CONTROL APPROACH

Both LWT and OWT casks employ a similar criticality control approach, as shown in Figs. 1 and 2. The cask designs meet the 10CFR71 performance requirements pertaining to crticality safety by decoupling the interactions between the fuel assemblies with Boral plates. The Boral plates are 8.73 mm (0.344 in.) thick with a natural boron content of 0.666 g/cm^2 for PWR fuel assemblies and 4.37 mm (0.172 in.) thick with a natural boron content of 0.333 g/cm^2 for BWR fuel assemblies. The determination of the Boral specification is discussed later. The Boral plates are thicker for the PWR fuel assemblies because a cask containing PWR fuel assemblies is more reactive than one containing BWR fuel assemblies. The total amount of Boral poison provided in the cavity is about equal for the PWR and BWR cask configurations.

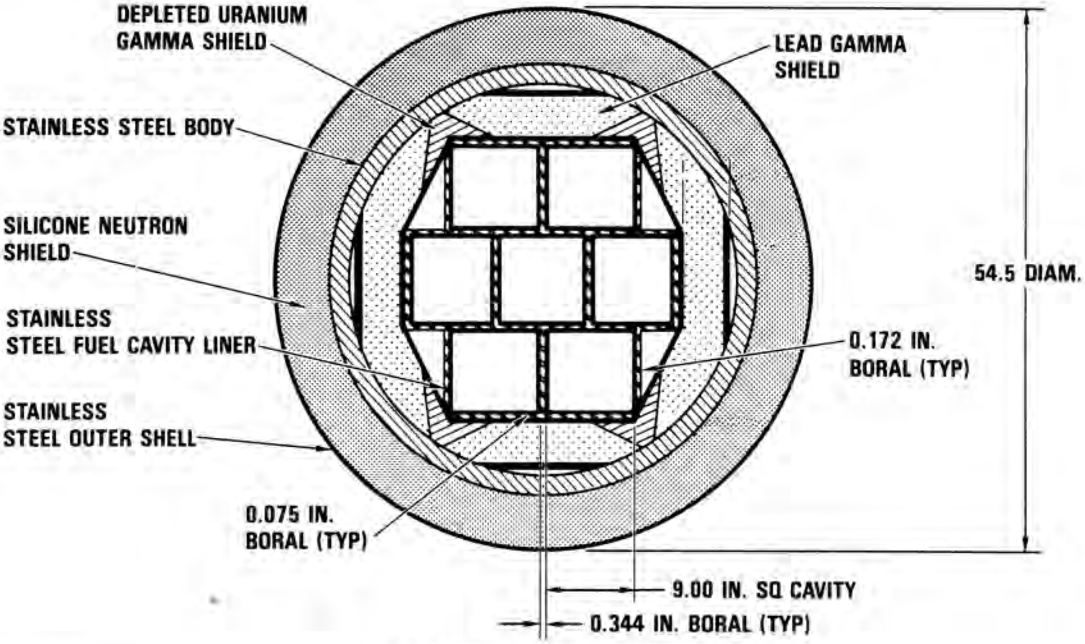


CAPACITY: 4 PWR ELEMENTS



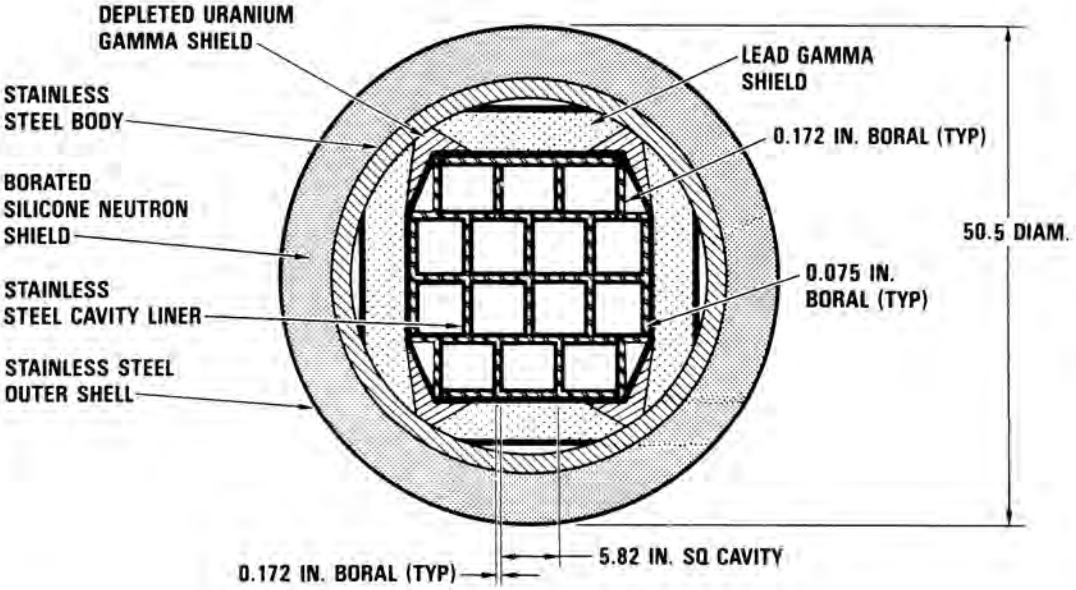
CAPACITY: 9 BWR ELEMENTS

Fig. 1. Legal Weight Truck (LWT) Cask Configurations.



I-073(1)

CAPACITY: 7 PWR ELEMENTS



CAPACITY: 14 BWR ELEMENTS

I-073(2)

Fig. 2. Overweight Truck (OWT) Cask Configuration.

In addition to the Boral plates between the fuel assemblies described above, Boral plates, each 1.91 mm (0.075 in.) thick with a natural boron content of 0.111 g/cm^2, also enclose the outside of the fuel assemblies. The same thickness is used for both PWR and BWR fuel assemblies. These outer Boral plates absorb neutrons scattering back from the cask side wall, as well as prevent thermal neutrons from entering the depleted uranium shield.

The Boral plates cover the full length of the active fuel portion to ensure complete decoupling of the fuel assemblies. Boral plates consist of a core component clad in aluminum. The core component is made of a mixture of B_4C and aluminum, each 50% by volume. The Boral plates specified are commercially available in the thicknesses and densities required. The boron content provides sufficient poison for criticality control.

CRITICALITY ANALYSIS

The cask design meets the criticality safety requirements by limiting the effective reactivity multiplication factor (k_{eff}) for the worst case to less than 0.93. This limit allows a minimum margin of 2% in k_{eff} for uncertainties before reaching the limit of 0.95 accepted by the Nuclear Regulatory Commission (NRC).

LWT Cask Design

To determine the Boral poison requirements for the LWR casks, a series of criticality calculations were made for the PWR cask configuration containing four fresh fuel assemblies with 4% enrichment and a 9.5 in. fuel assembly pitch. The analysis used a one-quarter geometrical model (because of symmetry) with appropriate reflective boundary conditions. The cask geometry was explicitly modelled. However, each fuel assembly was smeared as a single region. Cell-averaged neutron cross sections were obtained with the MICROX-2 code for the smeared fuel region (1)

Treatment of the fuel assembly in a smeared manner was found to be satisfactory, as compared with the result for an explicit fuel-rod model. Consequently, all subsequent criticality analyses used the smeared fuel model for simplicity. Criticality calculations were made with the 3-D KENO Monte Carlo code (2) to obtain k_{eff} as a function of natural boron poison content (g/cm^2) for the inner Boral. The boron content for the outer Boral was fixed at 0.11 g/cm^2, which provides sufficient poison for absorbing thermal neutrons originating from the fuel region or reflecting from the cask wall. The results of the KENO calculations are shown in Fig. 3 with a $\pm$ i σ statistical uncertainty at each calculated point.

To meet the design limit of 0.93 for k_{eff}, Fig. 3 shows that a natural boron content of 0.666 g/cm^2 is required for the inner Boral in the PWR LWT cask cavity. The boron content for the BWR LWT cask can be reduced to 0.333 g/cm^2, maintaining an approximately equal amount of total Boral poison in the cavity as for the PWR cask. Table I summarizes the Boral specification for both PWR and BWR casks.

The KENO code was also used to verify criticality safety for the LWT cask configurations containing both PWR and BWR fuel assemblies. The results are presented in the following section.

OWT Cask Design

The design features for the OWT casks are virtually identical to those for the LWT casks. In other words, the Boral specification is the same for both OWT and LWT casks.

Criticality safety for the OWT casks was verified with the 2-D TWODANT transport code (3) for the r-z (radial-axial) geometry. The required neutron cross sections were generated with the MICROX-2 code. The TWODANT code is a state-of-the-art transport program obtained from Los Alamos National Laboratory and installed on CRAY at the San Diego Supercomputer Center.

CRITICALITY RESULTS

The criticality results of the 2-D and 3-D calculations for the worst case configuration with flooding within the fuel assemblies are given in Table II. The maximum effective multiplication factor (k_{eff}) is 0.95 for the PWR cask and 0.85 for the BWR cask. For dry conditions, k_{eff} is less than 0.5 for all cask configurations. The reactivity includes the contribution from fission reactions in the fuel and the depleted uranium shield.

These results demonstrate that the package would remain in a safe subcritical condition with the k_{eff} being less than the NRC accepted limit of 0.95 under normal transport and hypothetical accident conditions. The results also confirm that the BWR cask configuration is less reactive than the PWR cask configuration.

The cask capacity is affected by initial enrichment as well as burnup credit. As listed in Table III, with burnup credit (required for PWR fuel only), the LWT and OWT casks can accommodate the design capacity for 4.5% fuel enrichment. Without burnup credit, the PWR cask capacity is reduced by one fuel assembly for 4.5% enrichment. The design capacities for the PWR casks can be maintained for 4.0% enrichment without burnup. Burnup credit is not required on BWR fuel.

CONCLUSIONS

The GA LWT and OWT casks provide maximum payload capacities while meeting criticality safety requirements. The maximum effective multiplication factor,

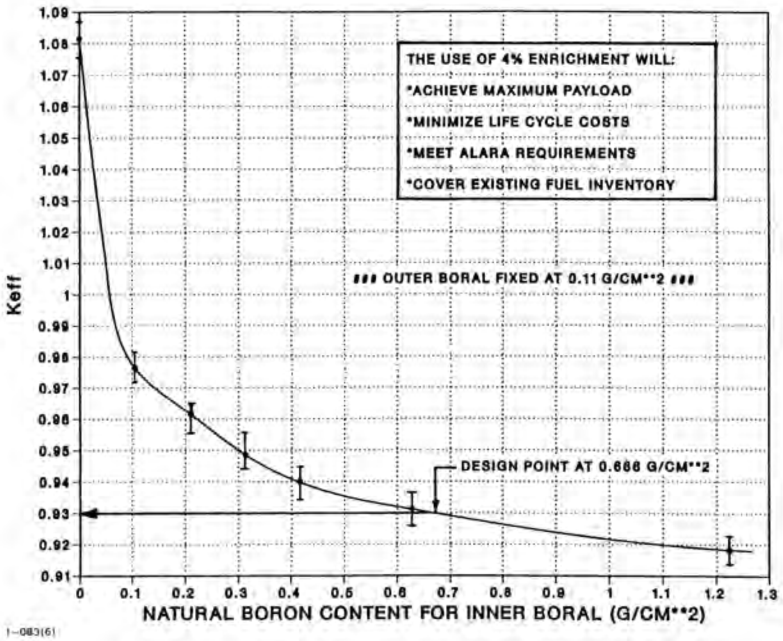


Figure 3. Selection Basis for Boron content in Boral For PWR LWT cask
(Fresh Fuel, 4% Enrichment, 9.5 IN. Fuel Assembly Pitch)

Fig. 3. Selection Basis for Boron Content in Boral for PWR LWT Cask (Fresh Fuel, 4% Enrichment, 9.5 in. Fuel Assembly Pitch).

TABLE I

Boral Specification for Criticality Control

BORAL REQUIREMENT	PWR CASK	BWR CASK
INNER BORAL THICKNESS, IN.	0.344	0.172
OUTER BORAL THICKNESS, IN.	0.075	0.075
INNER BORAL B CONTENT, G/CM^2	0.666	0.333
OUTER BORAL B CONTENT, G/CM^2	0.111	0.111

- **TOTAL BORAL AMOUNT IN CAVITY ABOUT EQUAL FOR PWR AND BWR CASKS**
- **APPLICABLE TO LWT AND OWT CASKS**
- **ALL BORAL PLATES ARE COMMERCIALLY AVAILABLE IN THICKNESSES AND DENSITIÈS REQUIRED**

I-076(36)

TABLE II

Criticality Results (no Burnup Credit)

CASK	TYPE	CAPACITY	ENRICHMENT	K_{EFF}
PWR	LWT	4	4%	0.93
BWR	LWT	9	4.5%	0.85
PWR	OWT	7	4%	0.93
BWR	OWT	14	4.5%	0.82

- **MAXIMUM K_{EFF} ALLOWS 0.02 UNCERTAINTY TO MEET THE NRC LIMIT OF 0.95**

TABLE III

Cask Capacity With and Without Burnup Credit

CONDITION	CASK CAPACITY			
	LWT		OWT	
	PWR	BWR	PWR	BWR
WITHOUT BURNUP CREDIT				
MAXIMUM 4% ENRICHMENT	4	9	7	14
MAXIMUM 4.5% ENRICHMENT	3	9	6	14
WITH BURNUP CREDIT				
4.5% ENRICHMENT	4	9	7	14

I–076(38)

including margin for calculational uncertainties, is less than the regulatory limit of 0.95.

REFERENCES

1. D. Mathews and P. Koch, "MICROX-2, An Improved Two-Region Flux Spectrum Code For The Efficient Calculation Of Group Cross Sections," GA-A15009, General Atomic Company (1979)
2. L. M. Petrie and N. F. Cross, "KENO IV An Improved Monte Carlo Criticality Program," ORNL-4938, Oak Ridge National Laboratory (1975)
3. R. E. Alcouffe, et al., "Users Guide For TWODANT: A Code Package For Two-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport," LA-10049-M, Los Alamos National Laboratory (1986)