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Nuclear Criticality Safety Analysis for the Traveller PWR Fuel Shipping Package

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ABSTRACT

The Traveller PWR fresh fuel shipping package represents a radical departure from conventional PWR fuel package designs. Two immediately noticeable features of the Traveller are that it carries a single fuel assembly instead of two as do other package designs, and that it has built-in moderator, which forms part of the flux-trap system.

The criticality safety case shows that the Traveller satisfies both U.S. and IAEA licensing requirements, and demonstrates that the package remains acceptably subcritical under normal conditions and hypothetical accident conditions of transport. This paper looks at the modeling techniques that were used to analyze the several accident scenarios that were considered, including:

- Lattice pitch expansion;
- Lattice pitch expansion along the fuel assembly length;
- Preferential flooding (selective flooding of different cavities);
- Differential flooding (varying water levels inside different cavities);
- Partial flooding (varying water density);
- Axial rod displacement;
- Sensitivity studies of variable foam densities and boron content in packaging;
- Analysis for carrying loose rods in a rodbox;

The criticality safety case for the Traveller proved to be a successful cooperative effort between ENUSA and Westinghouse.

INTRODUCTION

The Traveller is a new shipping package designed to transport fresh uranium fuel that will replace the Westinghouse MCC package. The contents includes a single PWR assemblies or loose fuel rods with enrichments up to 5.0 weight percent. The criticality safety evaluation shows that the Traveller satisfies both U.S. and IAEA licensing requirements by demonstrating that the package is subcritical under normal conditions and hypothetical accident conditions of transport The Criticality Safety Index (CSI) for the Traveller is 0.7 when transporting fuel assemblies and 0.0 when transporting loose rods.

An individual fuel assembly confinement system and a permanent neutron flux trap distinguish the Traveller package design from the MCC package that is currently being used to transport PWR fuel assemblies. The Traveller packaging consists of two major structures, an outerpack and a clamshell, that function to provide confinement of the contents and limit interaction between individual packages. The outerpack structure consists of two concentric stainless steel cylindrical shells. Polyurethane foam material is sandwiched between the stainless steel shells to provide impact protection and thermal insulation for the contents. The outerpack is split along the longitudinal axis to allow for fuel handling that is similar to the MCC package. High molecular weight polyethylene blocks are affixed to the upper and lower halves of the outerpack to provide a permanent moderator for a neutron flux trap. The contents is confined in a clamshell that is a strong rectangular aluminum box mounted inside the outerpack. Neutron absorber plates are recessed into the inner surfaces of the clamshell and surround the contents with a Boron material. The polyethylene and Boron provide a permanent flux trap that effectively limits the neutron interaction between packages.

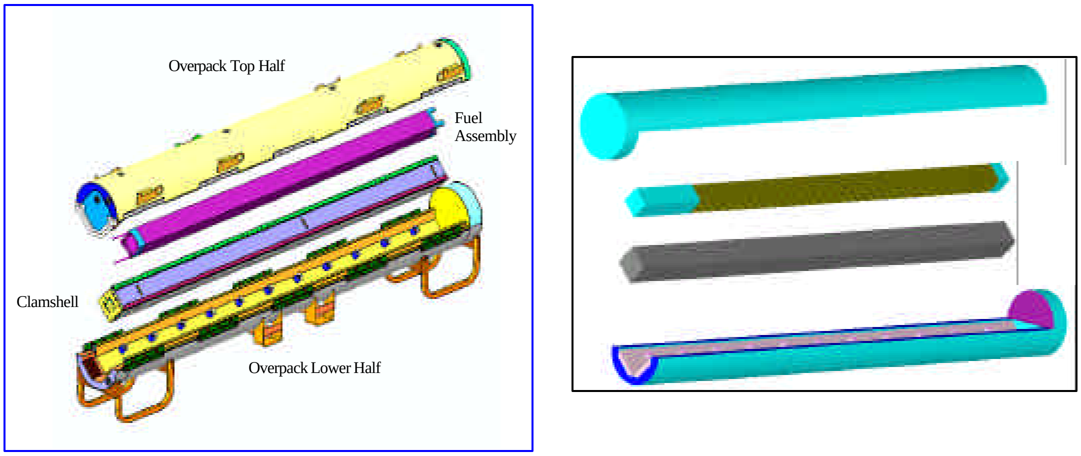

Figure 1 Engineering Model and Keno3D Rendering of Traveller

The Traveller was tested in accordance with U.S. [1] and IAEA [2] requirements for Type A packages. Mechanical design calculations, finite element analysis calculations, actual drop test data, reasoned engineering analysis, and sound engineering judgment were used to determine worst-case orientations for the mechanical and thermal tests. The criticality safety evaluation assumes a package configuration consistent with the mechanical and thermal test results combined with assumed worst-case flooding configurations, conservative material assumptions, and conservative fuel assembly assumptions.

METHODOLOGY

Calculation Method

SCALE Control Module for Enhanced Criticality Safety Analysis with KENO VI (CSAS6) is used to evaluate the Traveller package [3]. KENO-VI features such as geometry intersections, body rotation, hexagonal arrays, and array boundaries allow accurate and efficient representation of complex geometric shapes in the packaging. In addition, the hexagonal arrays allows triangular pitch for package arrays and loose fuel rod contents. Body rotation and geometry intersections allows efficient representation of differential and partial flooding scenarios. The analyses used in this evaluation were performed using the broad-structure, 44-group neutron cross-section library.

A validation of the calculation method was done by selecting 55 critical experiments to benchmark the effect of contents and packaging materials. Fuel rod lattice experiments were selected to represent the simple lattice, separator plates, flux trap, and water holes in the Traveller package model. No single group of critical benchmark experiments (simple lattice, separator plate, flux trap, or water hole) contains all the characteristics of the Traveller shipping package. However, the four groups each represent different aspects of the package model that are important to understanding the bias associated with the package modeling. The simple lattice and water hole experiments represent the fuel region modeling (i.e. fuel enrichment, lattice pitch, water-to-fuel ratio), and the separator plate and flux trap experiments represent additional characteristics of the package modeling (i.e. moderator, neutron absorbers).

A qualitative comparison is also made for the critical experiment and package model properties. The range of properties for the critical experiment includes range of values for the Traveller package. In addition, a qualitative evaluation of the neutron event probabilities is also done to compare the importance of the contents and packaging materials relative to neutron absorption. Comparing the absorption probabilities for the critical experiments and package indicates that the importance of neutron absorption is similar between the critical experiments and package model.

Results indicate that an upper safety limit (USL) of 0.94 is acceptable based an administrative margin , $\Delta k_m = 0.05$, and a bias of negative 0.01. The administrative margin is acceptable because for all grouping of experiments the minimum statistically based subcritical margin is less than that provided by the administrative margin. The application of the statistically based subcritical margin indicates the administrative margin is adequate by a margin of at least

0.015 even for groups were there is a limited number of data points (i.e. flux trap, water hole). Therefore, the bias determination is made by including all 55 experiments in the USL calculation.

Package Model

Contents

The fuel assembly types to be transported in the Traveller are 14x14, 15X15, 16X16, 17X17, and 18x18 PWR fuel assembly types. Fuel assembly characteristics considered in evaluating the most reactive contents are the fuel pellet diameter, fuel rod lattice pitch, and fuel rod and thimble tube positions. Calculations were performed to determine which fuel assembly would be the most reactive for the normal condition and rearrangement of the fuel lattice in the first 100 cm at the bottom or top end of the fuel assembly. Limiting the expansion to 100 cm is consistent with the impact test results and is supported by testing of light water reactor PWR fuel rods [4]. Rearrangement of the fuel assembly considered lattice expansion to the maximum lateral dimension of the clamshell confinement and axial rod displacement. Fuel rod rearrangement considers expansion of fuel within the confinement of a cylinder or square shaped confinement.

Loose rod evaluation includes two separate product containers, a cylindrical pipe and a square box. No attempt is made to determine a maximum dimension for the product containers because existing designs in use in other shipping packages will also be used in the Traveller. Each product container was modeled in the Traveller packaging using the hypothetical accident conditions for individual package and package array cases. The evaluation demonstrates that the package is subcritical for optimum pellet pitch-to-diameter ratio. Therefore, no restriction is imposed on the number or arrangement of loose rods within the confinement of the product container.

Moderation

Moderation of the package is considered as follows: (1) moderation from *packaging* materials of construction (e.g. thermal insulation and neutron flux traps); (2) moderation inside the *primary containment* system defined as the individual fuel rods; (3) moderation due to *partial and progressive flooding* of different void regions in the packages (4) moderation *interspersed* in the region between the packages in an array. The density of water in all void regions within and between packages to determine is varied from zero to full density to determine the optimum moderating density.

Packaging materials of construction - Foam is used as both a thermal insulator and impact absorbing material in the overpack. The hydrogen content in the polyurethane foam moderates neutrons outside the confinement boundary of the individual package. Change to the foam composition can significantly affect the interaction between packages in an array.

There is a significant quantity of moderator provided by the rubber material used in the shock mounts that attach the clamshell to the overpack. The shock mounts are partially imbedded in the holes in polyethylene moderator blocks. The shock mount material is not included in the normal and accident models.

Moderator blocks are a packaging component that maintain a fixed amount of moderation between the contents in the individual packages. The polyethylene moderator blocks provide moderation that in combination with a neutron poison effectively reduces the interaction between packages. The polyethylene material is included in the normal and accident models.

Moderation inside primary containment - The fuel rods contain the fuel pellets and are normally dry. Damage to the fuel rods may allow water to fill the gap between the pellets and fuel tube. Moderating the pellet-clad gap in all fuel rods results in an increase in k_{eff} and is included in the accident model.

Moderation due to partial and progressive flooding - The package has multiple void regions, including regions within the confinement system. Moderating only the fuel assembly envelope with full density water results in the maximum neutron interaction between packages and bounds any variations on the flooding sequence.

Interspersed Moderation - Spacing provided by the outer shell maintains void regions between the packages where environmental factors (snow, rain, ice, and immersion) may provide moderation and materials of construction may scatter or moderate neutrons. The spacing is assumed to be no less than 25 inches provided by the nominal diameter of the overpack outer shell. Interspersed moderation is considered to be moderation in the space which separates one package form another in the and does not include any moderation provided by the polyethylene or foam within the Traveller package.

Neutron absorbing materials

Neutron poison is intentionally added in the form of Boron specifically for the purpose of absorbing neutrons to limit neutron reactivity increases during accident conditions. However, the effectiveness of the Boron does not require flooding resulting from an accident condition, but relies on moderation provided by the fixed polyethylene. The system is designed to ensure an acceptable subcritical margin for the most reactive flooding scenario, that is, the contents are moderated inside the Clamshell and there is no moderator in void spaces outside the Clamshell or between the packages. The stainless steel material used in the packaging is also an effective neutron absorber.

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Accident Transport Condition

The Accident Condition model is consistent with the actual condition of the package after the impact and thermal tests and an assumed most reactive flooding configuration. The Outerpack diameter was unchanged, the moderator blocks were in place and not damaged, all shock mounts were in place and holding the Clamshell, and the cork liner was in place. The polyurethane foam starts to burn when the temperature exceeds 600 °F (315 °C) leaving a low density char residual material. The polyurethane foam is not included in the normal and hypothetical accident models, because of any variance in the hydrogen content during the normal service life of the package and uncertainty in the foam content due to thermal degradation during an accident condition.

The bottom nozzle impact produces the most severe localized damage to the fuel assembly. Further, it is the orientation most likely to produce lattice expansion. In the several prototype and qualification tests conducted prior to the certification test unit testing, it was found that all drop angles other than the end drop compress the fuel assembly lattice. Only the end drop resulted in any lattice expansion, but the lattice pitch did not expand uniformly to the inside dimension of the Clamshell. Close examination of the rod arrangement showed that throughout the assembly there was a combination of compressed, nominal, and slightly expanded rod pitches. Several rows of rods were actually touching, some were at nominal pitch, and one or two rods had larger pitch. The limiting accident case models the fuel assembly so that it bounds the actual condition. Therefore, the model assumes uniform lattice pitch expansion to 23.114 cm (9.1 in) for the Traveller and 23.384 cm (9.6 in) for the Traveller XL. Lattice extends along 100 cm of fuel length near the bottom of the fuel assembly.

CALCULATIONS AND RESULTS

Contents

The analysis to determine the most reactive contents compares k_{eff} for a single fuel assembly closely reflected by 20 cm of water where a 100 cm length of the assembly is expanded from nominal fuel envelope up to 14 inches (35.56 cm) square envelope. The maximum expansion dimension far exceeds the confinement system maximum lateral dimension, but the results are intended show the relationship of the confinement system dimension relative to an optimum water to fuel ratio. This demonstrates both the importance and sensitivity of the confinement system lateral dimension in maintaining the package subcritical.

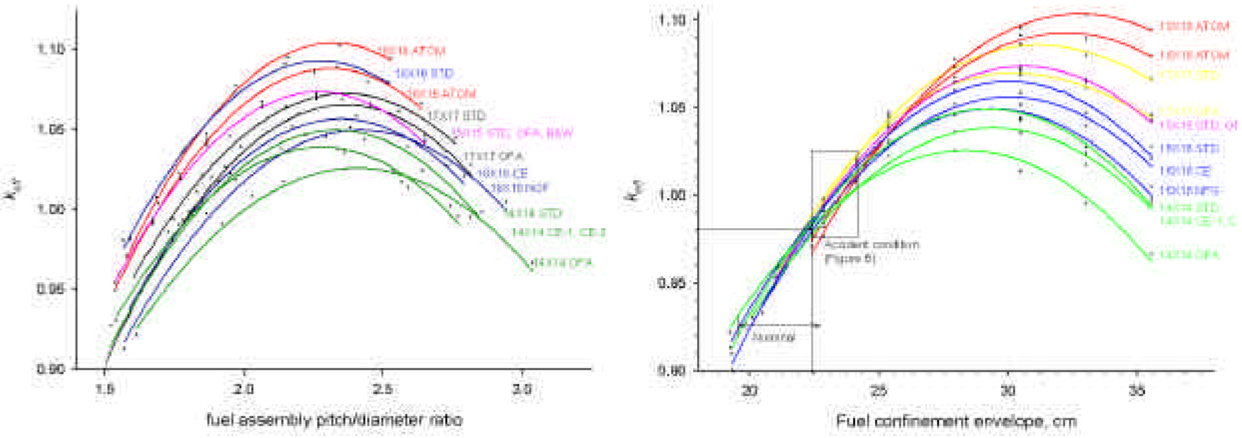

Figure 2 -Comparison to determine most reactive fuel assembly type

Comparison of the fuel assembly reactivity using the pitch to diameter ratio shows that the maximum reactivity for occurs in range of 2.0 to 2.5. However, the most reactive contents must be defined by the confinement dimension, and the comparison on this basis indicates that the 17x17OFA is the most reactive fuel assembly in the range of interest up to 24.384 cm (9.6 inches) fuel envelope. The 17x17OFA is used in all evaluations for individual package and package array.

The maximum reactivity for the loose rod contents also occurs at approximately a pitch to pellet diameter ratio of 2.0 regardless of the pellet diameter. However, maximum reactivity for the product container is much lower than a fuel assembly because the geometry of the rod pipe or rod box restricts the number of fuel rods at the optimum moderation conditions.

Individual Package and Package Array Evaluations

Table 1 shows the maximum k_{eff} calculated for conditions consistent with the normal and accident transport conditions. In case of the loose rods contents, the individual package is more reactive than the package for the accident condition because the effect of close full reflection on k_{eff} is greater than the interaction between product containers.

Table 1 Summary of normal and accident condition maximum reactivity for Traveller

	Fuel assembly	Loose rods
Individual Package in Isolation		
Normal	0.194	
Accident condition	0.905	0.749
Package Array		
Normal (5N=infinite)	0.263	
Accident condition (2N=150)	0.932	0.681

Sensitivity Analysis

Evaluations included calculating the effect of fuel rearrangement including lattice expansion and fuel rod axial displacement, variance in neutron poison Boron content, and moderation within void spaces and between packages. These evaluations were used to understand the margin of safety in terms of the material properties and transport condition of the package. These results were compared to the actual test results and used in the package design to ensure the design is robust.

Lattice expansion

The effect of the length of lattice expansion is evaluated for an individual package and finite package arrays. The finite package array is evaluated with a fuel assembly lattice expansion confined to the clamshell dimension extending from partial length to the full length (426 cm) of the active fuel. The length of the lattice expansion becomes limiting for the package array calculations at about 125 cm.

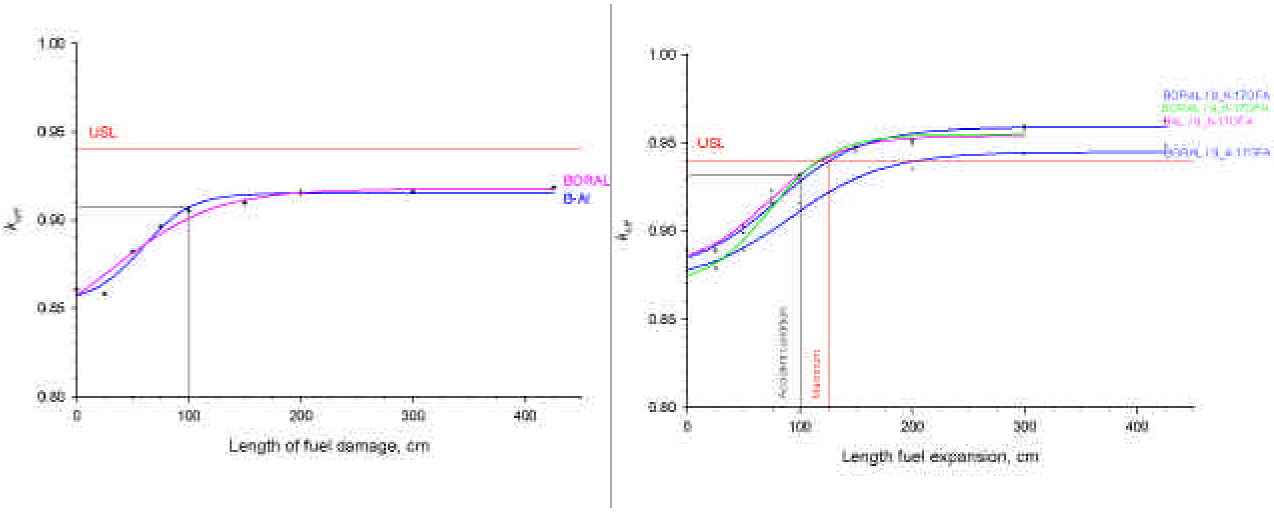

Figure 3 – Lattice expansion length sensitivity (individual package-right, package array -left)

Axial rod displacement

A reactivity peak occurs for 56 displaced rods, but effect on Keff is quite small. No statistically significant effect has been found and the displaced rods need not be considered in the evaluation.

Neutron poison

The sensitivity to the B10 areal density is evaluated for the individual package and package array with 100 cm fuel lattice expansion. The nominal Boron content is specified to minimize the sensitivity and make allowance for variations that may change the effectiveness of the neutron poison.

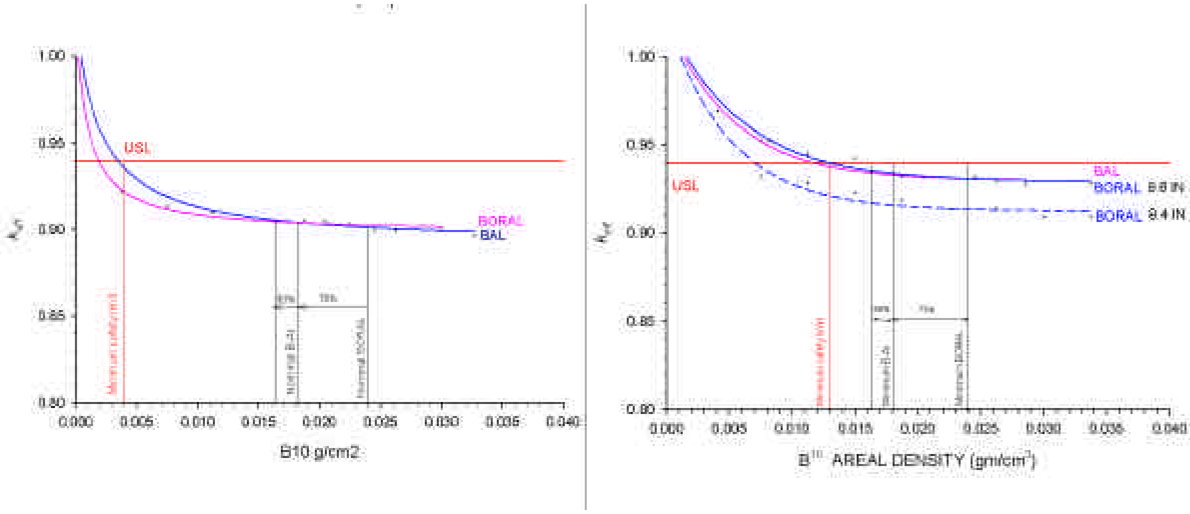

Figure 4 – Boron sensitivity, 100 cm lattice expansion-(individual package-right, package array-left)

Moderation

The individual package is compared to the package array for progressive flooding of the package void spaces to gain an understanding of the interaction potential of the package for varying moderation conditions. The difference in keff between the individual package and package array, Δk_s, indicates the interaction potential. The moderation regions are shown in Figure 3 and the configurations as evaluated are summarized in Table 2.

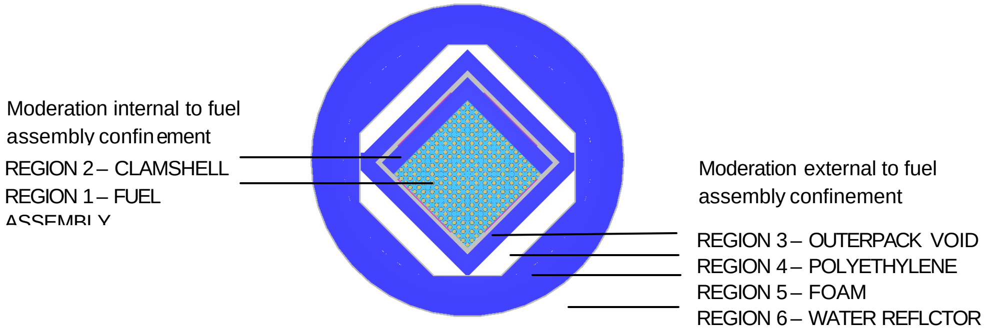

Figure 5 – Moderation regions of Traveller package

Table 2 - Interaction potential of the package for varying moderation conditions

Configuration	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Δk_s
Package 1	dry	void	void	poly	foam	void	0.0183
Package 2	moderated	void	void	poly	foam	void	0.0339
Package 3	moderated	water	void	poly	foam	void	0.0237
Package 4	moderated	water	water	poly	foam	void	0.0140
Package 5	moderated	water	water	poly	foam	water	0.0062

The maximum interaction occurs for the Package 2 configuration where the fuel assembly is moderated (Region 1) and other void space is dry including the interstitial space between the packages (Region 6). Filling the void spaces with water in Package 5 configuration effectively isolates the individual packages in an array such that k_{eff} calculated for the individual package and package array are equivalent.

The behavior of the system undergoing partial flooding depends on the level of moderator in the space between the clamshell and outerpack and inside the clamshell. There is no partial flooding scenario that is more reactive than progressive flooding the moderates only the fuel assembly envelope.

Increasing interspersed moderation only lowers the *keff* value because the array of packages is overmoderated by the presence of the polyethylene packaging material. As the water density increases and neutron absorption comes into effect, then neutron interaction between packages decreases. Increasing the water density causes the packages to become more isolated.

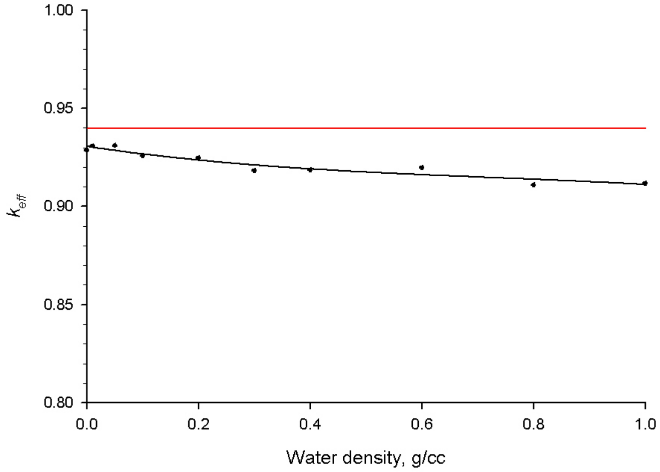

Figure 5 – Effect of interspersed moderation

CONCLUSION

Fuel rearrangement and moderation that is consistent with credible hypothetical accident test conditions were evaluated for the Traveller package design. Fuel assembly rearrangement is confined to lattice expansion near the end of the fuel assembly. The Traveller package is safe by design and remains subcritical independent of any moderation resulting from a transport accident conditions.

REFERENCES

[1] U.S. Code of Federal Regulations 10 CFR 71, Packaging and Transportation of Radioactive Material

[2] IAEA Safety Standards Series, TS-R-1 (ST-1, Revised), "Regulations for the Safe Transport of Radioactive Material", 1996 Edition (Revised).

[3] NUREG/CR-0200, Revision 6, Volume 1, Section C6, CSAS6: CONTROL MODULE FOR ENHANCED CRITICALITY SAFETY ANALYSIS WITH KENO VI

[4] L.M. Farrington, et al., "Effects of Impact Accidents on Transport Criticality Safety Cases for LWR Packages – A New Approach," Proceedings-PATRAM, September 3-7, 2001,