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IMPACT OF HYDROGENOUS MATERIAL MODELING IN CRITICALITY SAFETY ANALYSES OF TYPE A, FISSILE SHIPPING PACKAGES

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ABSTRACT

A large criticality uncertainty evaluated in type A, fissile transport packages is the effect of hydrogenous packing materials that may be a more effective moderator than water in the void space of the packaging. These material effects in conjunction with the geometric representations and material and fabrication tolerances compose the uncertainty of a package criticality safety analysis. When modeling hypothetical accident conditions (HAC), it is reasonable to assume that the same HAC event that might produce fuel lattice expansion would also tend to concentrate hydrogenous packing material in that same fuel region. The hydrogenous materials combined with other HAC effects may result in an increase in the package criticality uncertainty.

During transport, hydrogenous packing materials such as polyethylene cluster separators, bags, and cushioning are used to support the fuel assembly integrity, but also represent a potential for increased criticality in the system during HAC due to the repositioning of Hydrogen content. For example, a result of the fire test of the RAJ-II BWR fissile package was the melting of the fuel assembly packing materials within the inner container, which showed melted polyethylene parts and attachment of the molten polyethylene on the dummy fuel rods.

Using the SCALE 6 code, a criticality evaluation was conducted to combine the implications of polyethylene redistribution with the HAC of transport. The criticality analysis models are established to follow the melting progress of the polyethylene parts in accordance with the fire test conditions. The models incorporate optimized water moderation and lattice expansion for an arrayed system of damaged packages. For HAC, the polyethylene materials are represented by a mixture of the density weighted packing components.

Prior analyses showed the maximum increase in criticality uncertainty from modeling the polyethylene was as a uniform distribution on the fuel rod surface regardless of the condition of transport. Results of the polyethylene redistribution analysis showed that a combination of the drop, thermal, and optimized water moderation effects result in the largest contributor to criticality uncertainty; a 3% increase caused by all polyethylene packing materials melted together in the lattice expanded region at the bottom of a vertical positioned package.

INTRODUCTION

A criticality evaluation for fissile transport packages should demonstrate a maximum neutron multiplication by evaluating parameters that take into consideration combinations of transport conditions including any credible intermediate conditions. Normal and hypothetical accident transport conditions are often accounted for independently in uncertainty evaluations. However, the hypothetical accident conditions of a drop and fire event might produce combined effects in the same region of a fuel assembly, and consequently increase system criticality. In particular, the hydrogenous packing materials combined with other HAC effects may result in an unintentionally moderated region, as the hydrogenous materials may contain more hydrogen atoms per unit volume than water, hence having neutron-attenuation properties slightly better than water.

Uncertainty evaluations include identifying the optimum combination of internal moderation and interspersed moderation. Regulations TS-R-1, paragraph 671 [1] and 10 CFR Part 71.55 [2] require evaluation of loss in efficiency of moderators and presence of moderation. The moderation specification should include hydrogenous materials that may be more moderating than water. Type A, fissile transport packages for BWR fresh fuel assemblies do not typically have a built-in moderator, as burnable absorbers within the fuel assembly are credited. Therefore, not intend to be a moderator in the system, normal packing materials may provide increased moderation during normal and hypothetical accidents conditions of transport.

Within the RAJ-II BWR, fresh fuel shipping package, hydrogenous materials include ethafoam and polyethylene, and are present as packaging and packing materials used to protect the fuel assembly and avoid stressing contents components during transport. Ethafoam present as packaging and packing materials include the inner container (IC) wall foam and any additional cushioning foam. The polyethylene packing materials include the sheathing bag and cluster separators present as components integrated into the fuel contents.

There is no guarantee for a particular sequence of impacts or complete progression of a fire during a transport accident, yet often intermediate conditions or combination of accident conditions that may result in the maximum neutron multiplication are overlooked. A criticality uncertainty evaluation of the RAJ-II BWR, fresh fuel package has been done to demonstrate the impact on neutron multiplication due to the hydrogenous packing material representation.

UNCERTAINTIES ASSOCIATED WITH HYDROGENOUS PACKING MATERIALS

An uncertainty allowance (Δk_u) is determined that covers the change in neutron multiplication due to uncertainty in a criticality parameter. Package tests representing hypothetical accident conditions include drop, impact, fire, and immersion tests. Test results define the geometric and material representations in criticality analysis modeling, and the variations of the parameters compose the associated uncertainties. Combined with material and fabrication tolerances, the total allowance for uncertainties (Δk_u) is calculated.

Transitional states during transport, including variations of flooding, package spacing, and material presence, affect uncertainty associated with the normal and hypothetical accident conditions of transport. While, neutron absorption is provided by packaging structural materials and gadolinium oxide in the uranium oxide fuel mixture, neutron moderation is provided from external or internal hydrogenous materials. Packaging materials, such as paper honeycomb, wood, and polyethylene, may provide neutron moderation, but none of these materials are intended to provide the neutron moderation required for effective neutron absorption. Packing material components (e.g., polyethylene foam, cluster separators, fuel rod spacers, and sheathing) are used to protect the fuel assembly during routine transport conditions, and the physical state of these hydrogenous materials may affect system criticality and should be considered in any uncertainty evaluation.

Axial impact tests demonstrate for BWR fuel designs the lattice may contract near the impacted end but expand slightly in the adjacent inter-grid length [3]. BWR fuels are designed to be under moderated; hence an impact event which expands the pin pitch can result in an increase in criticality. Damage to the fuel assembly contents that results from the impact tests is assumed to limit fuel lattice expansion to the inside dimension of the inner container confinement for fuel shipped without a channel. Any expansion of the fuel rod lattice is conservatively limited to a length of 50 cm along the length of the fuel assembly from the bottom impact zone [4]. The lattice expansion allows for increased moderation from external or internal hydrogenous materials, and combined with other HAC effects may result in an increase in the package criticality uncertainty.

Thermal evaluation of the RAJ-II BWR package demonstrates that temperatures for a fire during the accident transport condition in the inner container is above the polyethylene melting point range of 120-130 °C (248 to 266 °F) and ignition temperature of 349 °C (660 °F) for polyethylene materials [5]. The polyethylene foam either remains in place, melts, or combusts depending on the duration of the fire [5]. The impact absorber materials (i.e., cardboard paper honeycomb and balsa wood) may undergo complete or partial combustion during a fire; the process of charring removes hydrogen and oxygen from the solid, so that the remaining char is composed primarily of carbon. Melting polyethylene may slump into the void space in between fuel rods in a fuel bundle, and water may fill the remaining void space during immersion events.

Uncertainties associated with hydrogenous packing materials are a concern as moderation within the fuel contents. There are packaging and packing hydrogenous materials that are internal moderators (within the package) that may be more effective than water either in their normal condition or as degraded by combustion or melting in a thermal event such as a fire. The physical state of the hydrogenous materials that are part of the contents (i.e., polyethylene foam, cluster separators, fuel rod spacers, and sheathing) change as a result of the transitional HAC. The uncertainty analysis considers the effect of hydrogenous packing material distribution in the contents combined with HAC effect of lattice expansion.

MATERIAL SPECIFICATIONS

Standard SCALE polyethylene material specification POLY(H2O) is used to represent all hydrogenous packing materials (i.e., plastic sheathing, foam cushions, and melted foam) in normal and accident transport conditions. The POLY(H2O) is polyethylene CH_2, 0.92 g/cm^3 that uses hydrogen in the water with a $S(\alpha,\beta)$ thermal kernel [6]. The collision kinematics data includes thermal kinematics kernels to describe thermal scattering in moderating materials such as hydrogen in water.

Since the actual densities of the polyethylene materials vary, the polyethylene material is represented as an average weighted mixture of the actual densities as follows:

$$\frac{1}{\rho_T} = \sum_i \frac{\omega_i}{\rho_i}$$

where,

ω_i is the weight fraction of material *i*,

ρ_i is the density of the mixture/component *i*, and

ρ_T is the density of the mixture.

When fuel assemblies are shipped without a channel, polyethylene inserts or polyethylene cluster separators are positioned between fuel rods at various locations along the axis of the fuel assembly to avoid stressing the axial grids during transportation. The cluster separators, as shown in Figure 1, provide a higher volume-average density polyethylene inventory. The cluster separator is composed of 30% low density polyethylene (LDPE) (0.925 g/cm^3) fingers and 70% high density polyethylene (HDPE) (0.959 g/cm^3) holder. A weight average density of 0.949 g/cm^3 is calculated for the polyethylene cluster assembly as a mixture of the actual densities since it is modeled as a single unit.

The fuel assembly is also wrapped in a polyethylene protective sheathing, with a density of 0.919 g/cm^3. The cluster separator assemblies placed along the length of the assembly and full coverage protective sheath make up the normal packing materials for a single fuel assembly.

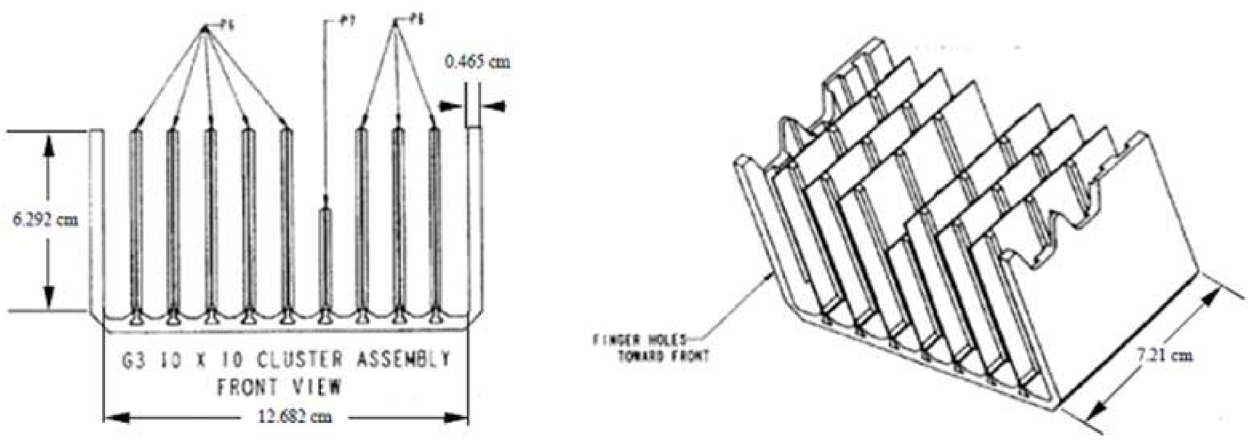

Figure 1. Polyethylene Cluster Separator

Additional hydrogenous materials in the RAJ-II package include ethafoam present as a packaging material on the IC walls, as shown in Figure 2, and packing material as additional cushioning foam placed in the IC to support the contents. There exists a range of nominal densities dependent on manufacturer; hence the ethafoam is characterized by a limiting upper density of 0.080 g/cm^3 based on the hydrogen content limit.

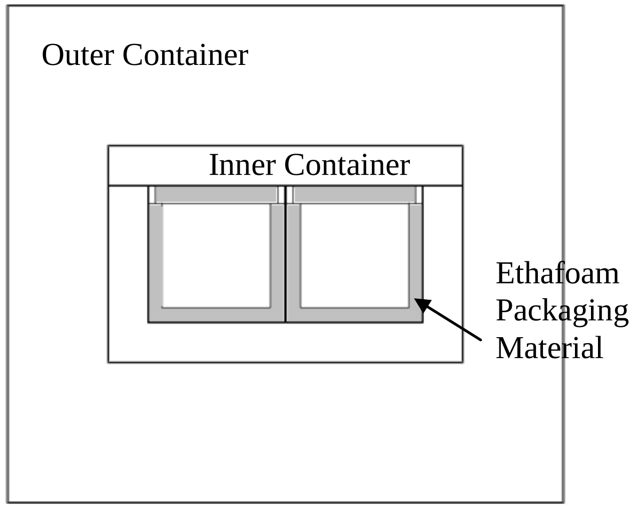

Figure 2. RAJ-II Package with Ethafoam Packaging

HYDROGENOUS MATERIAL SENSITIVITY EVALUATIONS

The RAJ-II BWR packaging used in the evaluation of hydrogenous material sensitivity consists of inner and outer containers that retain the contents within a fixed geometry relative to other such packages in an array. The modeled system is a 9x9 array of damaged RAJ-II packages, with the combined HAC effects of fuel bundle lattice expansion to the inner container confinement boundary and water moderation maintained in the fuel envelop.

When the fuel assembly is packed into the packaging, the packing materials such as cluster separators, sheathing/bags, and ethafoam cushioning are used for fuel protection during transport. Placement of additional packing materials is not strictly instructed; therefore redistribution of packing materials is possible during transport accidents. To determine the impact of hydrogenous material, a criticality uncertainty evaluation was conducted to combine the implications of hydrogenous material redistribution with the HAC of transport. The criticality analysis models are established to follow the melting progress of the materials in accordance with the fire test conditions. The evaluation of the hydrogenous materials assesses the representation of the material in the model as a uniform wrap around each rod in the bundle and as redistribution of material accumulation during transitional melting stages.

<u>Uniform Wrap</u>

Evaluations performed for the Japanese RAJ-II package safety report determined that polyethylene material uniformly wrapped around each rod had a greater impact on the neutron multiplication than transitional melting phases [7]; hence the uniform wrap is set as the base polyethylene material modeling technique. The base case for comparison contains the normal packing materials (i.e., cluster separator and sheathing bag) for normal conditions of transport (NCT).

The packing materials are represented in the model as a polyethylene wrap uniformly thick around each fuel rod over the active fuel length. The volume of packing material assumed to be distributed within the fuel bundle is used to determine the uniform poly outer radius around each fuel rod. This volume of material consists of the cluster separators and protective sheath for all transport conditions. The effective density of the polyethylene is a volume-weighted average of the cluster separator and plastic sheath; modeled as a single material wrapped around each rod, a combined weight average density of 0.947 g/cm^3 is calculated for the polyethylene normal packing material.

Transitional Melting Stages
The criticality analysis models were established to follow the melting progress of the polyethylene parts in accordance with temperature rising under the fire test conditions. The process of melting and moving of the polyethylene parts is categorized by two melting stages (Stages 2 and 3) and one normal stage (Stage 1). For each melting stage, two cases are evaluated representing horizontal and vertical placement of the package.

For an undamaged package model, the polyethylene materials are assumed to be in original shapes and positions. Therefore Stage 1 represents a before melting state where the normal packing materials are inserted between each row of rods.

As for the damaged package model, several cases are evaluated following the polyethylene material variations as a fire may continually melt the material with progressing presence. The volume of polyethylene to be melted or wrapped on rods is evaluated in two stages. Stage 2 represents an intermediate melting phase, where only the ethafoam cushioning material around the assembly in the IC is fully melted. Stage 3 represents full melt, where all hydrogenous materials in the IC including ethafoam cushioning and normal packing materials are fully melted. Based on stage, the volume of melted polyethylene is calculated, defined at the average weighted packing material density of 0.947 g/cm^3 calculated prior. The volume of polyethylene to melt is smeared over the defined IC space (minus the occupying rod space), fully filling a uniform level in the IC.

The volume of each melting material is calculated and then adjusted to conform to the calculated weighted packing material density of 0.947 g/cm^3. The two melting materials are the ethafoam cushioning and normal packing materials. Adjusting the material density results in a change in the volume of material and hence the space occupied in the inner container. The conversion is calculated by setting the masses of each model equal and solving for the volume at the adjusted density (e.g., $\rho_1 * V_1 = \rho_2 * V_2$, where V_2 is unknown).

Stage 1: normal, before melting model
Representing a normal condition of transport, prior to melting, Stage 1 is modeled with normal packing materials and ethafoam cushioning material in the nominal position. Additionally, the fuel bundle is modeled at the normal pitch without an expanded bottom lattice region. Cluster separators or inserts are placed into the assembly, between the rods. For modeling, these pieces are assumed to be uniform polyethylene plates between each row of rods over the effective fuel length. The polyethylene plates are composed of the cluster separators and the sheathing bag, as the bag represents a small fraction of the volume, this allows a simplified model. For comparison, there are two stage 1 cases; one with the ethafoam is modeled nominally on the IC walls (Figure 4) and one case without ethafoam (Figure 3).

Separator plate thickness calculation, shown below, is based on an estimated total mass of the packing materials. The single plate thickness calculated as 0.087cm is distributed over the length of the fuel between each row of rods in the assembly including the outer edge. There are two single plates for each rod cell, hence a total plate thickness 0.174cm between each row of rods and a single plate thickness on the outer edge of the lattice; this results in a conservative overestimation of the polyethylene by approximately 23g. By modeling a plate on each side of the rod cell, the lattice cell approximation correctly calculates the cross-sections and fluxes of present materials.

where,
t_{plate} = polyethylene single plate thickness
M = mass of packing
ρ = density of packing
N = # of rods in a row
m = # of plates (2 per rod cell) = 2N
p = pitch
L = active fuel length

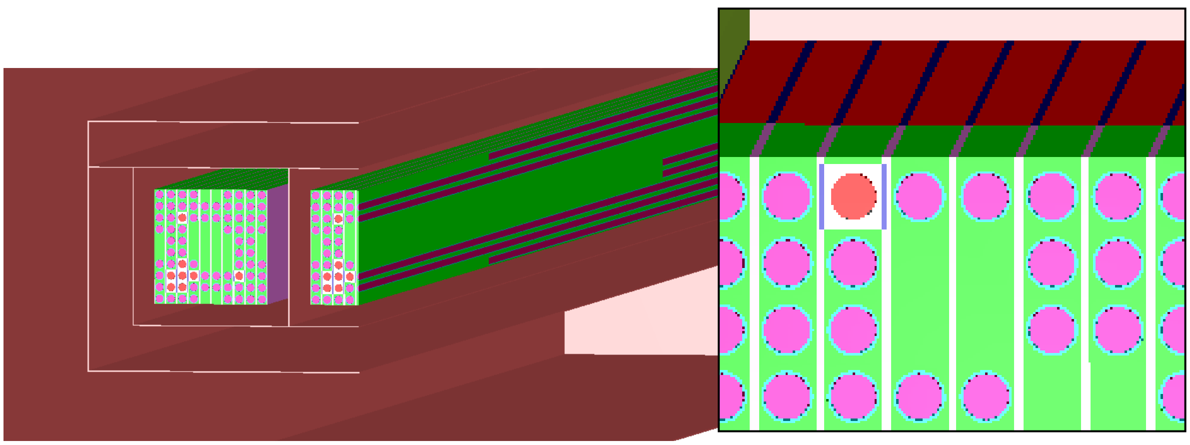

Figure 3. Poly Redistribution Model, Stage 1 Nominal without Ethafoam

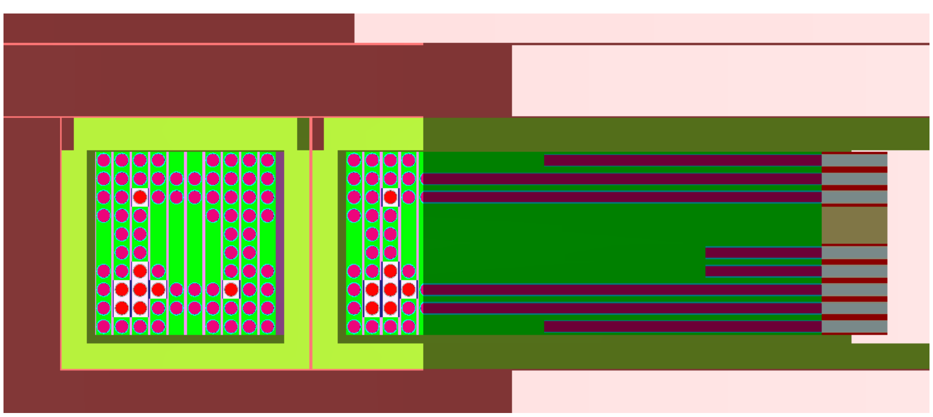

Figure 4. Poly Redistribution Model, Stage 1 Nominal with Ethafoam

Stage 2: Ethafoam Melt

The inner container ethafoam packaging materials are completely melted for stage 2. Hence ethafoam material nominally positioned on the bottom, four sides and upper lid are accumulated at the bottom part of the inner container, whether the model is oriented vertically or horizontally. Due to melting of material, the fuel assemblies are moved downward and in contact with the bottom wall of the inner container. Therefore, the fully melted material fills part of the assembly and inner container evenly. Fuel rods are now covered with a uniform poly wrap composed of the packing materials.

For the horizontal model, fuel rods of the bottom row of the assembly are submerged in polyethylene, where the height of the polyethylene is defined by the nominal pitch of the assembly. However, for the expanded lattice the polyethylene fills the first row at the expanded lattice pitch. To calculate the height of the polyethylene in the package, the available space is calculated based on full row heights. The available space is defined by the internal wall of the IC minus any space occupied by fuel bundle components. A volume greater than the polyethylene melt volume is determined, and the next full row height is used to set the polyethylene melt level in the horizontal package. This method allows the inclusion of additional polyethylene; however this is a conservative modeling method. For simpler modeling, the addition of 2395cc of poly is added to the melt material to fully fill the bottom row of the assembly, and create a uniform polyethylene level in the IC for the height of the first row of rods at the normal pitch, see Figure 5.

For the vertical model, the poly melt height is calculated based on available space within the assembly to match the volume of melted material rounded to the nearest whole number. Hence a height of 22 cm is filled in with polyethylene, with the addition of 116cc of polyethylene for simpler modeling to the nearest whole number. The model is oriented with the expanded lattice at the bottom, so the polyethylene material fills in the expanded lattice region first, see Figure 5. The expanded lattice represents a more optimal moderator-to-fuel ratio as compared to the nominal fuel lattice; hence the inclusion of material more moderating than water will have a greater impact on k_{eff}.

For both package orientations, exposed fuel rods are still covered with a uniform poly wrap composed of the normal packing materials.

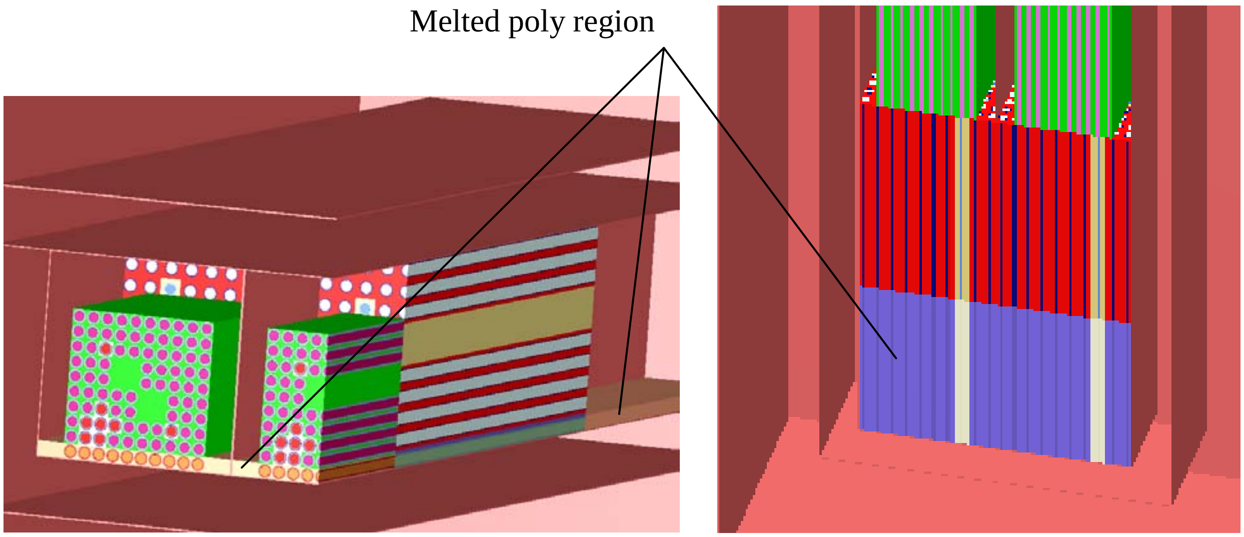

Figure 5. Poly Redistribution Horizontal and Vertical Model, Stage 2

Stage 3: full melt
With extended time, the materials are assumed to fully melt and accumulate at the bottom of the inner container, filling a portion of the assembly and uncovering the upper portion of the assembly from any polyethylene. Due to melting of material, the fuel assemblies are moved downward and in contact with the bottom wall of the inner container, and the fully melted material fills part of the assembly and inner container evenly. Stage 3 is represented by the assembly covered with all melted hydrogenous materials, including the ethafoam and normal packing materials.

For the horizontal model, fuel rods of the bottom two rows of the assembly are submerged in polyethylene, where the height of the polyethylene is defined by the nominal pitch of the assembly. However, for the expanded lattice the polyethylene fills two rows at the expanded lattice pitch. For simpler modeling, the addition of 456cc of poly is added to the melt material to fully fill two rows of the assembly and create a uniform level in the IC for the height of two rows of rods at the normal pitch, see Figure 6.

For the vertical model, the poly melt height is calculated to match the volume of melted material to the nearest whole number. Hence a height of 63 cm is filled in with polyethylene, with the addition of 146cc of polyethylene for simpler modeling. The model is oriented with the expanded lattice at the bottom, so the polyethylene material fills in the expanded lattice region first then the region of the nominal pitch lattice, see Figure 6.

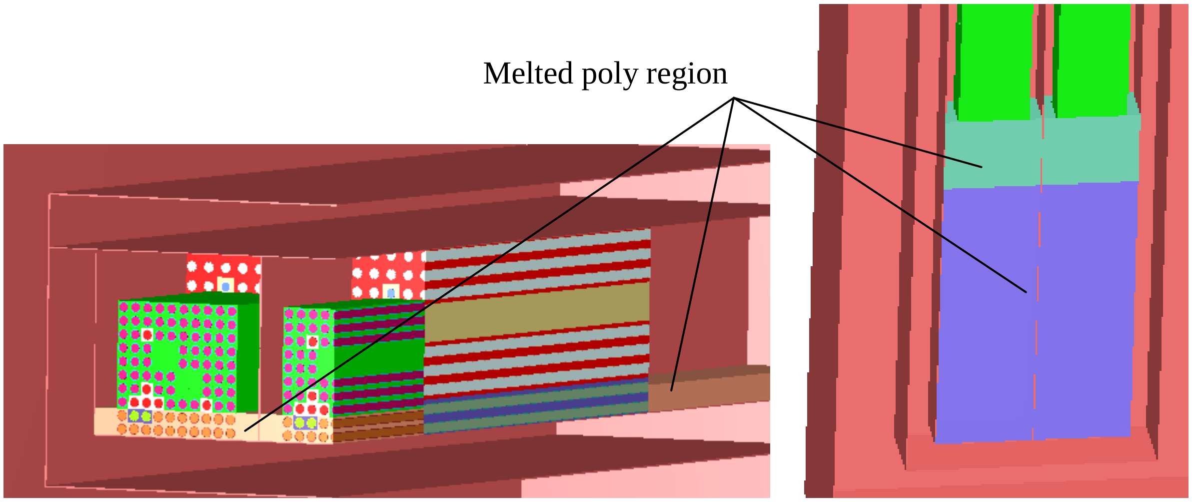

Figure 6. Poly Redistribution Horizontal and Vertical Model, Stage 3

RESULTS

Results of the polyethylene redistribution stages are shown in Table 1 for NCT and Table 2 for HAC. The Δk_u is the combination of k_{eff} and sigma by the error propagation method. Results show that an increase in hydrogenous material in the lattice expanded region has the greatest impact on k_{eff}, this due to an optimization of the moderator-to-fuel ratio. The combination of hypothetical accidents conditions of transport have the largest positive effect on criticality uncertainty associated with modeling and geometric representations. For package arrays, the positive impact on k_{eff} due to hydrogenous packing material redistribution in conjunction with other HACs is 1.87% for NCT and 2.79% for HAC. The largest positive reactivity from any redistribution stage is statistically combined as additional uncertainty to the total package uncertainty.

Table 1. Polyethylene Redistribution Results for Normal Conditions of Transport

Analysis Condition	Analysis Model	Fuel Bundle		
		k_{eff}	σ	Δk_u
NCT package array	Full wrap Horizontal / vertical	0.82792	0.00036	--
NCT package array	Stage 1: nominal – plates +ethafoam Horizontal / vertical	0.84605	0.00033	0.01862
NCT package array	Stage 1: nominal – plates Horizontal / vertical	0.82581	0.00031	-0.00163

Table 2. Polyethylene Redistribution Results for Hypothetical Accident Transport Conditions

Analysis Condition	Analysis Model	Fuel Bundle		
		k_{eff}	σ	Δk_u
HAC package array	Full wrap Horizontal / vertical	0.87473	0.00044	--
HAC package array (Intermediate state)	Stage 2: initial melt Horizontal	0.88072	0.00037	0.00656

HAC package array (Intermediate state)	Stage 2: initial melt Vertical	0.88610	0.00042	0.01198
HAC package array (Intermediate state)	Stage 3: full melt Horizontal	0.87410	0.00034	-0.00007
HAC package array (Intermediate state)	Stage 3: full melt Vertical	0.90206	0.00034	0.02789

CONCLUSIONS

Prior criticality safety analyses showed the maximum increase in criticality due to modeling the polyethylene as a uniform distribution on the fuel rod surface regardless of the condition of transport. However, when hydrogenous material effects are evaluated in a combined HAC model, results may vary dependent on the package assessment and should be evaluated as such. Results of the hydrogenous material redistribution analysis showed that a combination of the effects from drop, thermal, and optimized water moderation result in the largest contributor to criticality uncertainty; a 3% increase in criticality uncertainty caused by hydrogenous packing and packaging materials melted together and concentrated in the lattice expanded region of damaged fuel contents. The expanded lattice has a large impact on the criticality of the system, as the expanded pitch represents a more optimal moderator-to-fuel ratio as compared to the nominal fuel pitch; hence the inclusion of hydrogenous materials will have a greater impact on k_{eff}.

Combined HAC effects, including drop impacts causing lattice expansion, fire events causing material redistribution, and immersion causing further moderation, are important in criticality safety evaluations of fissile transport packages, as the hydrogenous materials may provide unintended increased moderation in the system and an added increased criticality uncertainty when assessed with multiple HAC contributors. Additionally, the criticality evaluation of hydrogenous materials in the package, that are more moderating than water, may set limits for the total polyethylene mass allowed in the transport package.

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