ASSESSMENT OF EXISTING TRANSPORTATION PACKAGES FOR USE WITH LEU+ AND HALEU MATERIAL *

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ABSTRACT

Reactor operators, designers, and fuel vendors are pursuing increased $^{235}$U enrichments to the low-enriched uranium plus (LEU+) (enrichment between 5 and 10 wt% $^{235}$U) and high-assay low-enriched uranium (HALEU) (enrichments between 10 and 20 wt.% $^{235}$U) ranges. These fuel materials will require transportation; however, it is uncertain whether subcriticality requirements can be satisfied with existing package designs. Otherwise, tradeoffs may be required to make these packages viable, but these tradeoffs may impact their economic use for industrial quantities of material. It is also unclear whether existing benchmark data are sufficient to support code validation for these applications.

This paper presents results from studies performed to assess the usability of currently licensed transportation packages for the transport of increased enrichment unirradiated uranium fuel forms. Packages were selected for analysis from five categories: pressurized water reactor (PWR) fuel assemblies, PWR and boiling water reactor (BWR) fuel pins, BWR fuel assemblies, UO$_2$ powder and pellets, and U-metal / tristructural isotropic (TRISO) particles. Consideration of 30-inch UF$_6$ cylinders is also included in these studies.

Results provided for each package include enrichment and packaging limits (e.g., maximum transportation array sizes) and identification of potential modifications to the package or its licensing basis to account for increased enrichment material. A brief assessment of benchmark applicability is also included. Results indicate that there are viable means for increasing enrichment into the LEU+ and/or HALEU ranges for the fuel forms. Each package presents unique challenges, but in most cases, reasonable modifications can accommodate the expected realistic enrichments applicable to each package. Sources of margin to offset enrichment increases include reduced transportation array size, reduced fissile mass, burnable absorber credit, and safety analysis margin harvesting. Numerous critical benchmark experiments were identified for validation of all packages except the UF$_6$ container.

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INTRODUCTION

Advanced reactor designers, fuel vendors, and commercial light-water reactor (LWR) operators are planning for or investigating the use of fuels with enrichments greater than 5 wt% $^{235}\text{U}$. Many advanced reactor fuel forms could include enrichments ranging from 10 to 20 wt% $^{235}\text{U}$, whereas LWR operators and vendors are investigating a more limited enrichment range between 5 and 10 wt% $^{235}\text{U}$. Different terminologies exist, with some referring to the 5–10 wt% range as low-enriched uranium plus (LEU+), and others referring to the entire range of 5–20 wt% as high-assay low-enriched uranium (HALEU). In this paper, HALEU generally refers only to the 10–20 wt% $^{235}\text{U}$ range. Although this is not a universally accepted definition, it is helpful when distinguishing transportation issues associated with increased enrichments in current LWR plants (LEU+) from the higher enrichments needed for advanced reactors (HALEU). Use of these higher enrichment fuels will require updated transportation packages capable of accommodating the material’s additional reactivity.

This paper presents results from recent studies conducted at Oak Ridge National Laboratory (ORNL) assessing the potential use of selected approved transportation packages for LEU+ or HALEU contents. These studies [1,2] considered only unirradiated U fuel forms. The packages considered were selected to cover 5 categories of contents: (1) pressurized water reactor (PWR) fuel assemblies or PWR or boiling water reactor (BWR) fuel pins, (2) BWR fuel assemblies, (3) UO$_2$ powder and pellets, (4) uranium metal or tristructural isotropic (TRISO) fuel particles, and (5) uranium hexafluoride. The specific packages are (1) Traveller [3,4], (2) TN-B1 [5,6], (3) CHT-OP-TU [7,8], (4) Versa-Pac [9,10], and (5) DN-30 [11,12].

All five packages are described in Hall et al. [1], and both criticality safety and validation of criticality safety calculations are considered. Only the DN-30 is considered in Saylor et al. [2], although criticality safety and validation aspects are both addressed. Saylor et al. provides a more thorough analysis of the DN-30 than Hall et al., although Hall provides some analysis for the other 4 packages, as well. In all cases, the criticality assessment includes potential limitations on enrichment or array size for the transportation certificate that could allow LEU+ and/or HALEU contents in each package. These results are only intended to demonstrate measures to mitigate the reactivity increase; they do not recommend specific actions. The validation assessments were performed using the integral parameter $c_h$ from the TSUNAMI suite [13]. Only experiments included on the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [14] are considered, and the experiments must include available sensitivity data with the ICSBEP Handbook or in the ORNL Verified, Archived Library of Inputs and Data (VALID) [15].

Generally, results indicate that viable approaches exist to offset the increased reactivity associated with the higher enrichments considered in these analyses. The specific modifications vary from package to package. For all packages except the DN-30, there appear to be a sufficient number of applicable benchmark experiments to support validation.

CRITICALITY SAFETY ASSESSMENTS

An assessment of the nuclear criticality safety basis for each transportation package is considered in this section, considering LEU+ and/or HALEU contents. As mentioned above, modifications of the licensing basis are proposed for each package, except for Versa-Pac, to offset the increased
reactivity caused by the higher enrichment of the contents. Versa-Pac is already licensed to contain material up to 100% $^{235}$U enrichment, so no modifications to the licensing basis are necessary.

**Traveller**

Analysis of a fresh fuel assembly in the Traveller package was performed with fuel enriched to 5 and 8 wt% $^{235}$U. This approach allowed for calculation of the impact of the enrichment increase without direct $k_{eff}$ comparisons to the licensing models or the safety analysis report (SAR). A reactivity increase of approximately 6% $\Delta k$ resulted from the 3 wt% increase in uranium enrichment. The increase can be offset by crediting 52 integral fuel burnable absorber (IFBA) rods in the fuel assembly lattice. Reducing the array size to a single package offset half of the reactivity increase, so array size reductions in the normal conditions of transport (NCT) and hypothesized accident conditions (HAC) analyses will not be sufficient to meet regulatory requirements. This indicates that the 8 wt% enrichment modeled is a reasonable upper bound for current PWR fuel assemblies in the Traveller; further enrichment increases without some reactivity control would likely require another package or hardware change.

The fuel rod pipe contents were also considered. Unclad fuel rods were modeled at enrichments of 5 and 10 wt% $^{235}$U, resulting in $k_{eff}$ values lower than that for the 5 wt% intact assembly. This result indicates that rods with enrichments of 10 wt% or more could be transported in the Traveller in the fuel rod pipe configuration without package modifications or significant changes to its licensing basis.

**TN-B1**

A $10 \times 1 \times 10$ array of packages of the TN-B1 is identified in the current SAR [5] as the limiting array size. Therefore, this array size was used for a baseline reactivity determination. This model also included 13 burnable absorber (BA) rods in each assembly. The resulting $k_{eff}$ value of 0.9374 was used as a target in a series of calculations in which the array size was reduced as enrichment was increased. The increased enrichment models also contained 13 BA rods per assembly. The results are summarized in Table 1, indicating that the array size must be reduced to $4 \times 1 \times 4$ to accommodate enrichments approaching 10 wt% $^{235}$U. An increase in the BA loading to 24 rods could meet the $k_{eff}$ target in the original $10 \times 1 \times 10$ array with an 8 wt% enrichment. With proper iterations between core design and transportation analysis, it should be possible to optimize the tradeoff between BA loading and package array size.

<table>
<thead>
<tr>
<th>Enrichment (wt% $^{235}$U)</th>
<th>Array Size</th>
<th>$k_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$10 \times 1 \times 10$</td>
<td>$0.9374 \pm 0.0004$</td>
</tr>
<tr>
<td>5.55</td>
<td>$8 \times 1 \times 8$</td>
<td>$0.9371 \pm 0.0003$</td>
</tr>
<tr>
<td>6</td>
<td>$7 \times 1 \times 7$</td>
<td>$0.9371 \pm 0.0003$</td>
</tr>
<tr>
<td>6.7</td>
<td>$6 \times 1 \times 6$</td>
<td>$0.9377 \pm 0.0003$</td>
</tr>
<tr>
<td>7.8</td>
<td>$5 \times 1 \times 5$</td>
<td>$0.9371 \pm 0.0004$</td>
</tr>
<tr>
<td>9.8</td>
<td>$4 \times 1 \times 4$</td>
<td>$0.9374 \pm 0.0004$</td>
</tr>
</tbody>
</table>
UO₂ powder is considered in CHT-OP-TU for enrichments ranging from 5 to 18 wt% ²³⁵U. For each enrichment, the array size and oxide vessel (OV) size are selected to yield a $k_{eff}$ value of approximately 0.94 or less. The CHT-OP-TU SAR [7] is the basis for this limit. An approach using the smallest OV size and limiting the array sizes may be sufficient to accommodate enrichments up to 18 wt% ²³⁵U in CHT-OP-TU for UO₂ powder.

Calculations were also performed for pellets in CHT-OP-TU covering enrichments up to 16.5 wt% ²³⁵U. It may be necessary to use smaller vessels or limited array sizes for the pellet contents and the oxide, but criticality safety indices (CSIs) of 6 or lower may be possible for this entire enrichment range. Many cases preserve the current CSI of 2.1.

**Versa-Pac**

As mentioned above, no criticality safety assessment was performed for Versa-Pac, because it is already certified for contents up to 100 wt% ²³⁵U. Because the current license only allows 350 g of material in a single package, modifications may be desired to allow larger masses in the package.

**DN-30**

Both Hall et al. [1] and Saylor et al. [2] contain information about the criticality safety impacts of increasing the enrichment of UF₆ above 5 wt% ²³⁵U. The discussion here is taken primarily from Saylor et al. because it is a more thorough analysis of the impacts and potential limitations on the package.

The calculations presented in Saylor et al. assume that the entire inner volume of the 30B cylinder is full of UF₆, even though this violates the maximum licensed mass limit of 2,277 kg. In the Saylor et al. analysis, models are used involving a single cylinder, a finite array of cylinders, and an infinite array of cylinders. The single cylinder analysis provides an upper limit on the enrichment that could be shipped in a DN-30, but this would most likely not provide a feasible solution for industrial material quantities. The finite array models indicate transportation limits, and infinite array models have historically been used for storage analysis.

The single cylinder models included UF₆ at enrichments ranging from 6 to 20 wt% ²³⁵U and UF₆ densities ranging from 2.5 to 5.5 g/cm³. The models also include a 30 cm reflector modeled as full-density water. The reactivity of the cylinder increases with higher material densities and higher enrichments, as expected. Single cylinders cannot demonstrate subcriticality near nominal densities and enrichments of 20 wt% ²³⁵U. Other packaging options will likely be required to support industrial production of advanced reactor HALEU fuel forms.

The infinite array storage models included an infinite array of 30B cylinders with no overpack, UF₆ densities of 2 to 5.5 g/cm³, and enrichments of 5 to 10 wt% ²³⁵U. A number of different water film thicknesses and densities were tested. The water film thickness will force the cylinders farther apart in the model, so the spacing within the infinite array is also varied. The array reactivity initially increases with film thickness; after a 1 cm film thickness reactivity drops. The initial increase is driven by increasing moderation, and the subsequent drop in $k_{eff}$ is driven by increased spacing. These results indicate that storage must be licensed based on the inclusion of overpacks or some other minimum separation distance to store 30B cylinders containing UF₆ enriched to between 6 and 10 wt% ²³⁵U.
The finite array calculations include an assumption that the hydrogenated uranium residues (HUR) form a single sphere inside the cylinder instead of being uniformly distributed throughout the UF₆. This conservative assumption is made in the DN-30 SAR [11] and is maintained for consistency. Each calculation positions the HUR sphere within the cylinder to maximize reactivity through greater communication among adjacent cylinders. The HF in the cylinder is modeled as homogenously mixed with the UF₆; the DN-30 SAR modeled the HF in a spherical shell around the HUR sphere. Saylor et al. started with an \( N \) value of 7 based on the analysis from Hall et al. [1] for an enrichment of 7 wt% \(^{235}\text{U}\). This \( N \) value indicates that the HAC array must contain 14 packages, and the NCT array must contain 35. The finite array models selected were \( 7 \times 2 \) for HAC and \( 19 \times 2 \) for NCT; the NCT array of 38 is conservative compared to the minimum analysis condition of 35 cylinders.

The analyzed HAC array is shown in Figure 1. The HUR spheres are located near the bottom of the top set of cylinders and near the top of the bottom set. The HUR spheres in the outer ring of cylinders are located near the sphere in an adjacent cylinder, for a total of three pairs of spheres. The HUR sphere in the middle cylinder is centered in the cylinder. Calculations considered a range of different water film thicknesses and UF₆ densities; the maximum calculated \( k_{\text{eff}} \) was approximately 0.88. The calculated \( k_{\text{eff}} \) of this array increases to just below 0.95 with 9 wt% UF₆ and approximately 0.92 for an enrichment of 8 wt%. Some smaller array sizes were considered to allow for increased enrichment, but the limitations imposed on the number of cylinders per shipment likely make the smaller array size, and thus higher enrichments, unfeasible.

![Figure 1. Axial and radial locations of HUR spheres in HAC array](image)

As mentioned above, the NCT array contained 38 packages in a \( 19 \times 2 \) array with UF₆ enriched to 7 wt% \(^{235}\text{U}\). The radial distribution of HUR spheres is such that there are groups of three cylinders; again the HUR sphere is centered in the middle cylinder. The array is shown in Figure 2. A variety of water film thicknesses and UF₆ densities is considered with a maximum calculated \( k_{\text{eff}} \) of approximately 0.91. This result is based on the maximum UF₆ density and a water film thickness of 0.6 cm. It should be noted that the NCT array is more limiting than the HAC array; reducing the array to the required 35 cylinders is not likely to lower \( k_{\text{eff}} \) significantly. No other enrichments were considered in Saylor et al.
Figure 2. Radial locations of HUR spheres in NCT array

VALIDATION ASSESSMENTS

**Traveller**

Validation of criticality safety calculations for PWR assemblies or PWR or BWR rods in the rod pipe configuration should not present challenges, even with enrichments up to 10 wt% $^{235}$U. The ICSBEP Handbook [13] contains more than 1,000 benchmarks for LEU pin array experiments. Many experiments from the ICSBEP intermediate enrichment category, which are defined as 10–60 wt% $^{235}$U, may also provide applicable experiments for the higher enrichment range. The Traveller models were compared to a set of almost 1,600 ICSBEP benchmarks with available sensitivity data to allow for calculation of the integral parameter $c_k$. Both the fuel assembly and the rod pipe configuration show hundreds of cases with $c_k$ values greater than 0.9, indicating strong similarity with the application system and thus applicability for validation.

**TN-B1**

The validation assessment for the TN-B1 included the base case $10 \times 1 \times 10$ array, as well as the $6.7$ wt% $^{235}$U $6 \times 1 \times 6$ array and the $8$ wt% $10 \times 1 \times 10$ array with 24 BA rods. The base case identified over 150 applicable experiments from the set of over 1,600 ICSBEP benchmarks. The $6.7$ wt% case was shown to have over 650 potentially applicable benchmarks, and the $8$ wt% case had approximately 130. The smaller array size in the $6.7$ wt% case likely contributes to the increase in similarity to many critical experiments, as discussed in some detail of Appendix C of Hall et al. [1]. Sufficient critical experiments are likely available to support validation of the TN-B1 package with the likely LEU+ enrichment range to be considered for LWR fuel assemblies.

**CHT-OP-TU**

Validation of CHT-OP-TU calculations were examined for the oxide powder contents using $5$ wt% and $8$ wt% $^{235}$U enrichments to provide a baseline and an indication of the impact on the number of applicable experiments caused by an enrichment increase. The base case model with $5$ wt% enriched powder resulted in over 300 potentially applicable experiments, which increased to over 500 with the $8$ wt% enrichment. The higher enrichment leads to a slightly harder neutron spectrum and increases similarity with the large number of available pin array experiments.
Validation of the pellet case considered two enrichments: 6.9 wt% and 16.5 wt% $^{235}$U. The 6.9 wt% pellets were modeled in the 7.5-inch OV and the 16.5 wt% pellets in the 6-inch OV. The arrays of OVs were also different, with 18 packages considered for the 7.5-inch OV, and 48 packages considered for the 6-inch OV. The results for the 6.9 wt% pellets in the 7.5-inch OV indicate over 650 ICSBEP experiments with $c_k$ values over 0.9, and almost 150 ICSBEP experiments with such high similarity for the smaller OV with 16.5 wt% material.

These results indicate that validation of calculations for the CHT-OP-TU package should not present difficulties for the oxide or pellet options at a range of LEU+ and HALEU enrichments.

Versa-Pac
No assessment of the Versa-Pac validation basis was made because the package is already licensed to carry content up to pure $^{235}$U.

DN-30
The finite array models used for HAC and NCT analysis involving the DN-30 package create validation challenges because of the system’s intermediate spectrum. A broad set of over 3,000 ICBSEP experiments was surveyed in an attempt to find benchmarks with $c_k$ values as high as 0.8 for these cases. No cases were identified with $c_k$ values of 0.8 or higher, which has historically been viewed as the minimum integral parameter for validation [13]. Subsequent to the work in Saylor et al. [2], this set was expanded further in Marshall and Greene [16]; however, the $^{235}$U/C$^{18}$O experiments examined did not significantly improve the number of apparently applicable experiments. Increasing enrichment appears to improve experiment applicability, so this problem is not made worse with increasing enrichment. Eliminating the spherical HUR accumulation in favor of distributing the HUR homogenously throughout the cylinder also appears to improve experiment applicability. Validation of criticality calculations in design basis arrays for the 30B UF$_6$ cylinder presents a technical challenge.

One option to address this issue is to adopt an additional reactivity margin to account for potential nonconservative results if appliable experiments were in fact available. The determination of an appropriate margin can be facilitated with the use of sensitivity/uncertainty methods to identify the potential impact of unvalidated nuclides or energy regions. Another possible option is to switch validation techniques to a data assimilation–based approach such as in the TSURFER [13] module in SCALE. This approach has not been used in the United States in a direct bias determination at this point, and the approach also presents technical challenges. Further study is warranted to identify the best available approaches for validating criticality safety calculations for 30B UF$_6$ cylinders.

CONCLUSIONS
Work performed at ORNL since the most recent PATRAM symposium includes an assessment of five currently licensed packages for inclusion of LEU+ and/or HALEU contents. The Versa-Pac is already licensed for a limited quantity of fully enriched material, whereas the other four packages are currently only certified for contents with enrichments of 5 wt% $^{235}$U or less. Approaches have been identified for the other four packages that could be used to accommodate some material with higher enrichments. Generally, these changes are related to licensing calculation modifications, although hardware modifications can also be made to improve capacity. Validation of the criticality calculations is not expected to be made significantly more difficult with increased enrichment.
Challenges remain for validation of the 30B cylinders, but these are not unique to LEU+ or caused by contents.

This work is important to support deployment of advanced reactor fuel cycles and integration of LEU+ material into LWR power plants. Economic constraints must be addressed in future work to determine the optimal tradeoffs between reduced shipment sizes and hardware modification.

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REFERENCES