

# Applicability of ORCEF UF<sub>4</sub>/CF<sub>2</sub> Experiments to Validation of 30-Inch UF<sub>6</sub> Cylinders\*

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## ABSTRACT

Critical experiments were performed at the Oak Ridge Critical Experiments Facility (ORCEF) in the 1940s and 1950s combining blocks of UF<sub>4</sub> and Teflon (CF<sub>2</sub>) with plastic moderators. These experiments were performed with UF<sub>4</sub> and Teflon specifically to mimic the neutronic behavior of UF<sub>6</sub>. The results of these experiments were used to help define criticality safety limits at the K-25 plant. The experiments incorporated varying amounts of polymethyl methacrylate moderator to create a wide range of neutron energy spectra. The uranium was enriched to 37.5 wt% <sup>235</sup>U, and in some experiments, depleted UF<sub>4</sub> was also used. The ratio of enriched and depleted uranium was varied to create average enrichments ranging from 12.5 to 30 wt% <sup>235</sup>U. The evaluations of these experiments in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook are IEU-COMP-THERM-001, IEU-COMP-INTER-003, and IEU-COMP-MIXED-002, and document a total of 52 experiments.

These experiments are of interest in validating criticality safety calculations for UF<sub>6</sub> cylinders, and the enrichment of these experiments is also relevant to high-assay low-enriched uranium. Studies have shown a limited number of critical experiments with significant similarity to the limiting analysis conditions for these cylinders. The limiting scenarios involve intermediate neutron energy spectra, making the ORCEF experiments likely candidates for validation. Unfortunately, only a limited number of the experiments show significant similarity to representative 30-inch cylinder models. This paper investigates these results and discusses the impact of neutron energy spectrum and fissile form on similarity.

*Key Words:* Validation, benchmarks, benchmarking, uranium hexafluoride

## 1 INTRODUCTION

Recent work at Oak Ridge National Laboratory [1, 2] has investigated the impacts of increased enrichment on transportation in the front end of the commercial nuclear fuel cycle. These efforts are summarized in another paper being presented at this conference [3], and they indicate that validation of nuclear criticality safety calculations is challenging for both hypothesized accident condition (HAC) and normal conditions of transportation (NCT) models of 30-inch UF<sub>6</sub> cylinders. Consideration of water ingress

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into UF<sub>6</sub> cylinders is exempted by 10 CFR 71.55(g) [4], resulting in an intermediate neutron energy spectrum in the models.

The validation of the 30B calculations has been difficult because no critical experiments with significant similarity have been identified in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP Handbook) [5]. Documented efforts [1, 2] have focused on sensitivity/uncertainty (S/U)-based experiment selection, which requires sensitivity data files (SDFs) to be available for critical benchmark experiments. An extensive program has been carried out at the Nuclear Energy Agency to generate sensitivity data for most experiments in the ICSBEP Handbook [6], but that effort was primarily based on multigroup (MG) TSUNAMI-3D calculations. Many configurations in the ICSBEP Handbook cannot be treated accurately with MG calculations because of the limitations of SCALE's cross section processing capabilities [7].

A review of the SDFs available from the ICSBEP Handbook revealed that results from some of the experiments performed at the Oak Ridge National Laboratory Critical Experiments Facility (ORCEF) involving UF<sub>4</sub> and Teflon (CF<sub>2</sub>) blocks were not available. The complexity of the block arrangements with interleaved sheets of methyl methacrylate plastic (Plexiglas) in the IEU-COMP-INTER-003 (ICI-003) and IEU-COMP-MIXED-002 (ICM-002) evaluations precluded accurate analysis with MG techniques. Continuous-energy (CE) TSUNAMI-3D methods were introduced into SCALE 6.2 [7], so S/U-based similarity assessment of these experiments is now possible. The IEU-COMP-THERM-001 (ICT-001) evaluation contains similar experiments, and NEA SDFs are available; these experiments are also analyzed with CE TSUNAMI in this work. The KENO models of these experiments were generated for validation of  $k_{\text{eff}}$  calculations [8], and those models have been expanded into TSUNAMI-3D models. The new sensitivity data generated for the benchmarks is compared with existing application models generated by Saylor et al. [2]. These are both HAC and NCT models including 7 or 10 wt% UF<sub>6</sub>.

The rest of this paper describes generation of sensitivity data for the experiments using CE TSUNAMI-3D, as well as similarity assessment of the experiments with 30B application models with two enrichments. The factors contributing to similarity between the experiments and application models are highlighted, and differences reducing similarity are also identified. This information could form the basis for design of future experiments to improve the validation basis for UF<sub>6</sub> cylinders.

## 2 CODES AND METHODS

This section describes the codes and methods used in the analysis. The TSUNAMI tools within SCALE 6.2.4 [7] are used to generate SDFs and to perform similarity assessments between the 30B application models and the benchmark experiments. The metric of similarity is the  $c_k$  integral index.

The TSUNAMI-3D sequence was used to generate SDFs characterizing the potential change of  $k_{\text{eff}}$  to nuclear data changes for both application and benchmark models. The application SDFs were generated by Saylor et al. [2] using the 252-group MG library and the associated MG TSUNAMI-3D methodology [7]. The experiments used highly heterogeneous combinations of UF<sub>4</sub>/CF<sub>2</sub> blocks and sheets of plastic and therefore were analyzed with CE TSUNAMI-3D. Both CLUTCH and integrated fission probability (IFP) methods were used to generate accurate sensitivity coefficients for the experiments. The sensitivity data generated by TSUNAMI-3D were confirmed with direct perturbation calculations, regardless of calculation mode [9].

The similarity assessment between the benchmarks and application models was performed with TSUNAMI-IP. As mentioned above, the similarity metric used in this work was the  $c_k$  integral index [7, Section 6.5.1.1.1] with the explicit purpose of selecting benchmarks that manifest biases similar to the application system. The  $c_k$  index was used to assess the similarity in terms of a correlation coefficient of data-induced uncertainty in  $k_{\text{eff}}$ . This approach assumed that the covariance data are an effective proxy for the relative magnitude of the bias inherent in each nuclide/reaction present in the model [10]. Other

parameters and approaches to assessing similarity are available in TSUNAMI-IP, but they were not considered here. For this work, a  $c_k$  of 0.8 or higher was assumed to indicate sufficient similarity for a benchmark to be applicable for validation.

## 3 APPLICATIONS AND BENCHMARK EXPERIMENTS

### 3.1 Applications

As noted above, four application models from Saylor et al. [2] were used. Two enrichments—7 and 10 wt%  $^{235}\text{U}$ —were selected, as well as both the NCT and HAC models. The energy of the average lethargy causing fission (EALF) values for the 7 wt% NCT and HAC cases were 221.3 eV and 204.6 eV, respectively. For the 10 wt% cases, the EALF was 516.2 eV and 510.7 eV for the NCT and HAC models, respectively. The models contained a spherical inclusion of hydrogenated uranium residues (HUR) as a conservative modeling assumption; the concentration of all the hydrogen in the cylinder is a very unlikely but maximum reactivity assumption. The HUR spheres are also assumed to be distributed within the cylinders to maximize communication with adjacent cylinders and reactivity in array models. The total sensitivities of  $^{235}\text{U}$  and  $^{238}\text{U}$  in the  $\text{UF}_6$  filling the rest of the cylinder were higher than those in the HUR by factors of 6 and 4, respectively, so similarity assessments should be most heavily influenced by the non-HUR  $\text{UF}_6$  material. A 0.6 cm thick water film surrounded the cylinder inside the overpack [2].

### 3.2 Benchmark Experiments

The benchmark experiments specifically examined in this work are from three ICSBEP Handbook evaluations: ICI-003, ICM-002, and ICT-001. Each set of experiments is described briefly in this section.

#### 3.2.1 ICI-003

The 14 experiments included in the ICI-003 evaluation were conducted at ORCEF in 1956 and 1957. All cases were built of blocks of mixed  $\text{UF}_4$  and  $\text{CF}_2$ , with the intention of providing a basis for safety analysis of  $\text{UF}_6$  at the K-25 Gaseous Diffusion Plant [5]. The uranium used in the experiments was enriched to 37.5 wt%  $^{235}\text{U}$ . The first two cases contained no plastic, Case 3 contained a cellulose acetate plastic, and Cases 4 through 14 contained Plexiglas sheets. The combination of different numbers and thicknesses of plastic sheets allowed significant variation of the neutron energy spectra. The EALF ranged from 55.6 keV in Case 1 to 5.02 eV in Case 14. Cases included in the ICI-003 evaluation are also cross referenced as ICM-003 (Cases 9, 11, and 12) and ICT-011 (Cases 13 and 14) [5].

#### 3.2.2 ICM-002

The 9 experiments in the ICM-002 evaluation were also conducted at ORCEF in 1956 and 1957. They were similar to the ICI-003 experiments, except that depleted  $\text{UF}_4$  blocks were included to change the average enrichment of the fissile material to 12.5, 18.8, 25, or 30 wt%  $^{235}\text{U}$  [5]. All 9 cases used Plexiglas sheets, but the spectrum was varied less than in ICI-003, because the enrichment was the primary variable of interest. Case 6 and 9 are cross referenced as ICI-004 based on their harder neutron spectrum. The EALF values for those two experiments were 2 keV and 109 eV, respectively. The other 7 cases had EALF values ranging from 10–15 eV, except for Case 5, which had an EALF of 29 eV.

#### 3.2.3 ICT-001

The 29 cases included in the ICT-001 evaluations were performed at ORCEF in the late 1940s and were generally composed of stacks of 1-inch blocks of  $\text{UF}_4/\text{CF}_2$  and 1- or 0.5-inch blocks of polyethylene. Most configurations were reflected by paraffin, although Cases 17, 18, and 19 were bare. Cases 22 through 25 included a cadmium or boron layer between the paraffin reflector and the core blocks. The uranium used in all cases was enriched to 29.83 wt%  $^{235}\text{U}$ . The ratio of  $\text{UF}_4/\text{CF}_2$  blocks and polyethylene blocks was varied from 4:1 to 1:7, with many different combinations tested. Four of the 29 cases (1, 17, 21, and 22) are cross

referenced as ICM-001. The EALF of these four cases ranged from 7.16 eV to 8.06 eV. The EALF of the 25 thermal cases ranged from 0.11 eV to 2.20 eV.

#### 4 C<sub>k</sub> RESULTS

The 52 benchmarks included in the ICI-003, ICM-002, and ICT-001 evaluations were compared to 30B cylinder models for NCT and HAC conditions. The 30B was assumed to be filled with 7 or 10 wt% UF<sub>6</sub>, creating a total of four application cases. The c<sub>k</sub> indices for the ICM-002 evaluation, including the two cases that are cross-referenced as intermediate spectrum cases ICI-004-006 and ICI-004-009, are provided in Table I. Values exceeding the c<sub>k</sub> threshold of 0.8 are shaded green. There are no cases with sufficient similarity for the 7 wt% NCT case, one for the 7 wt% HAC case, and two each for the 10 wt% cases. Across all the evaluations, no other benchmarks exceeded the 0.8 threshold for the 7 wt% models, but a total of five cases exceeded a c<sub>k</sub> of 0.8 for the 10 wt% NCT case, and 6 cases showed sufficient similarity to the 10 wt% HAC model. These benchmarks and their c<sub>k</sub> values are listed in Table II. These c<sub>k</sub> indices are large enough to indicate a significant degree of similarity between the UF<sub>4</sub>/Teflon mixtures in the experiments and the UF<sub>6</sub> material in the application if the spectra are sufficiently similar. The factors impacting the degree of similarity are examined in more detail in the remainder of this section.

Table I. c<sub>k</sub> indices for ICM-002 evaluation

Case	7 wt% NCT	7 wt% HAC	10 wt% NCT	10 wt% HAC
ICM-002-001	0.2748	0.3918	0.2946	0.3622
ICM-002-002	0.3148	0.4316	0.3340	0.4024
ICM-002-003	0.3671	0.4828	0.3799	0.4489
ICM-002-004	0.3689	0.4847	0.3799	0.4488
ICM-002-005	0.4933	0.5945	0.5309	0.5937
ICI-004-006	0.7618	0.7913	0.8696	0.8940
ICM-002-007	0.5508	0.6503	0.5459	0.6074
ICM-002-008	0.5655	0.6632	0.5605	0.6210
ICI-004-009	0.7963	0.8455	0.8342	0.8695

Table II. Benchmarks with c<sub>k</sub> values of at least 0.8

10 wt% NCT		10 wt% HAC	
Case	c <sub>k</sub>	Case	c <sub>k</sub>
ICI-004-006	0.8696	ICI-004-006	0.8940
ICI-004-009	0.8342	ICI-004-009	0.8695
ICI-003-001	0.8161	ICI-003-001	0.8369
ICI-003-002	0.8169	ICI-003-002	0.8374
ICI-003-003	0.8145	ICI-003-003	0.8361
		ICI-003-004	0.8084

Clearly, only a few cases are significantly similar to the application models—fewer than were expected. At both enrichments, the HAC cases show slightly more similarity than the NCT cases. It is also clear that c<sub>k</sub> values are higher for the 10 wt% cases than the 7 wt% cases. This is expected because the enrichment of the benchmarks ranges from 12.5 to 37.5 wt%.

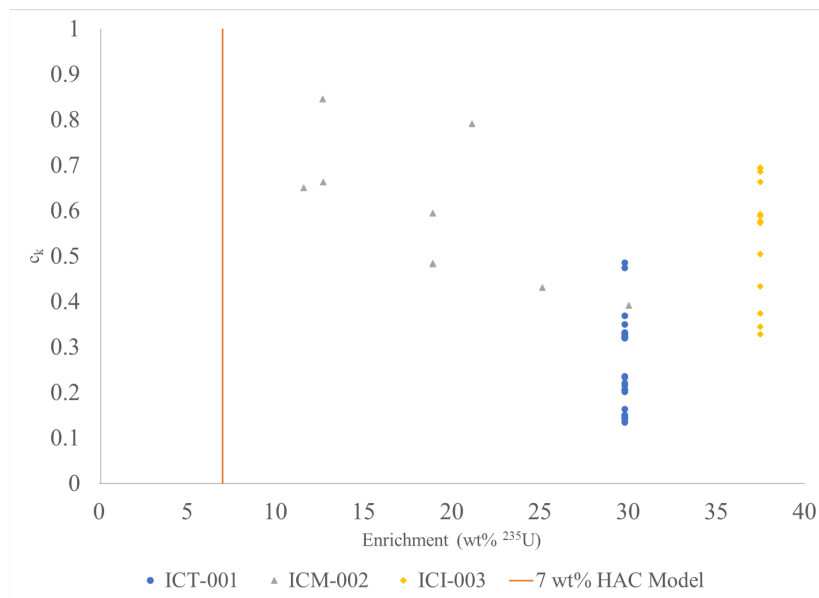
The highest c<sub>k</sub> value for both models with 7 wt% UF<sub>6</sub> comes from ICI-004-009, which has an enrichment of 12.71 wt% and an EALF of 109 eV. This is one of the lowest enrichment benchmarks,

although ICM-002-007 is lower at 11.6 wt%. The EALF for ICM-002-007 is much lower than the application at 14.2 eV, so the spectrum is clearly a factor in the similarity, along with the enrichment. The EALF for the benchmark is about half that of the application, but it is still in better agreement than many of the other benchmarks.

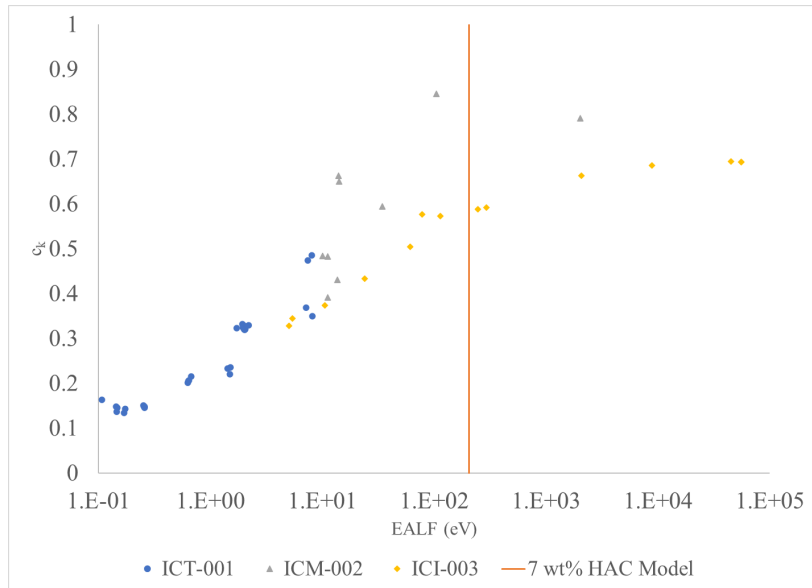
The  $c_k$  values for the 10 wt% cases are also high for ICI-004-009, but the highest values for both models come from the ICI-004-006 benchmark. This case has an enrichment of 21.16 wt% and an EALF of 2.02 keV. The EALF values for the 10 wt% application cases are approximately 500 eV, so the higher  $c_k$  values for this harder spectrum case are logical in comparison to ICI-004-009. The  $c_k$  values for the 7 wt% cases compared to the ICI-004-006 benchmark are approximately 0.76 and 0.79; while these values do not exceed 0.8, they are the second most similar benchmarks for these applications.

The reaction contributing the most to  $c_k$  is  $^{235}\text{U} (n,\gamma)$  in most cases. For a few cases compared to the 7 wt% HAC model, the top contribution is  $^{235}\text{U}$  nubar. These are all thermal experiments, and they all have  $c_k$  values below 0.2. For the 7 wt% NCT model, one thermal model has  $^{235}\text{U}$  nubar as the top contributor, and a few others have  $^{235}\text{U} \chi$  as the top contributor. As with the HAC model, the experiments with  $c_k$  values above approximately 0.2 are dominated by the  $^{235}\text{U} (n,\gamma)$  reaction. The results for the 10 wt% NCT and HAC models are driven by  $^{235}\text{U} (n,\gamma)$  for the more similar cases, but they are driven by  $^{235}\text{U}$  nubar or  $^{235}\text{U} \chi$  for some highly dissimilar cases. The individual nuclide/reaction pairs that contribute to similarity guide the analysis. In Section 5, the nuclide/reaction pairs contributing to uncertainty are examined to identify how similarity can be improved.

This brief examination of highly similar cases indicates that a more systematic review of  $c_k$  indices as a function of enrichment and EALF is warranted. The  $c_k$  values for all 52 experiments compared to the 7 wt% HAC model are shown as a function of enrichment in Figure 1 and as a function of EALF in Figure 2. Figures for the other applications are not presented here, but the general trends are very similar among all four application models.



**Figure 1.  $c_k$  values for all 52  $\text{UF}_4/\text{CF}_2$  experiments as a function of enrichment, 7 wt% HAC model.**



**Figure 2.  $c_k$  values for all 52 UF<sub>4</sub>/CF<sub>2</sub> experiments as a function of EALF, 7 wt% HAC model.**

The figures appear to show some trends, but they also indicate that the combination of enrichment and neutron energy spectrum was not sufficient to explain trends in  $c_k$ . The only experiments with a range of enrichment were from the ICM-002 evaluation, and these show a clear trend of increasing  $c_k$  with decreasing enrichment. That is, similarity improves as the enrichment of the experiment approaches the enrichment of the application. Also, two different trends are clear: the lower set corresponding to the mixed spectrum cases, and the two higher points corresponding to the intermediate spectrum experiments.

The results for ICT-001 are not as clear. There were no enrichment variations in these experiments, but there was clearly a range of similarity for the experiments to the application. For the ICT-001 cases, it is clear that increasing EALF improved similarity in general, although Figure 2 does not clearly show why the four cases with EALF values of approximately 8 eV had such different  $c_k$  values. A review of the evaluation reveals significant differences in the cases with similar EALF values. For example, Case 21 has an EALF of 8.05 and a  $c_k$  of 0.486, and it has an H:U cube ratio of 1/2:2 and a paraffin reflector. Case 22 has an EALF of 7.16 but a  $c_k$  of only 0.369. The H:U cube ratio is 1:2, and a cadmium sheet is placed between the core and the paraffin reflector. The EALF values are similar, but the detailed distributions are not, presenting the age-old peril of collapsing a distribution into a single number.

The results for ICI-003 present another puzzle. The similarity increased as EALF increased, even once it had surpassed the EALF of the target application. As mentioned above, the top contributor to similarity for the reasonably similar cases was the <sup>235</sup>U (n,γ) reaction. An examination of this sensitivity in the 14 cases in the ICI-003 evaluation shows the magnitude of the energy-integrated sensitivity increasing from Case 1 to Case 6 and varying without a clear pattern for the remaining 8 cases. The values are provided in Table III; the value for the 7 wt% HAC model is  $-0.1414 \pm 3.7 \times 10^{-5}$ . The <sup>235</sup>U (n,γ) sensitivity is most similar to the application in the first three cases of ICI-003, and it is very similar in magnitude. The  $c_k$  values for these three cases are all approximately 0.694, with very slight increases from Case 1 to Case 3. The monotonic decrease in  $c_k$  for the remaining cases appears to be at odds with the magnitude of the <sup>235</sup>U (n,γ) sensitivity. As shown in Figure 3, however, the integral value masks a persistent shift in the sensitivity to lower energies, along with the overall neutron energy spectrum. Once again, an individual value does not always accurately represent a distribution.

Table III. Energy-integrated  $^{235}\text{U}$  (n, $\gamma$ ) sensitivity for ICI-003

Case	Sensitivity	Case	Sensitivity
ICI-003-001	-0.1222	ICI-003-008	-0.1664
ICI-003-002	-0.1225	ICM-003-009	-0.1800
ICI-003-003	-0.1280	ICI-003-010	-0.1546
ICI-003-004	-0.1611	ICM-003-011	-0.1869
ICI-003-005	-0.1761	ICM-003-012	-0.1837
ICI-003-006	-0.1918	ICT-011-013	-0.1758
ICI-003-007	-0.1836	ICT-011-014	-0.1759

The uncertainty in all reported sensitivities is 0.03% or less.

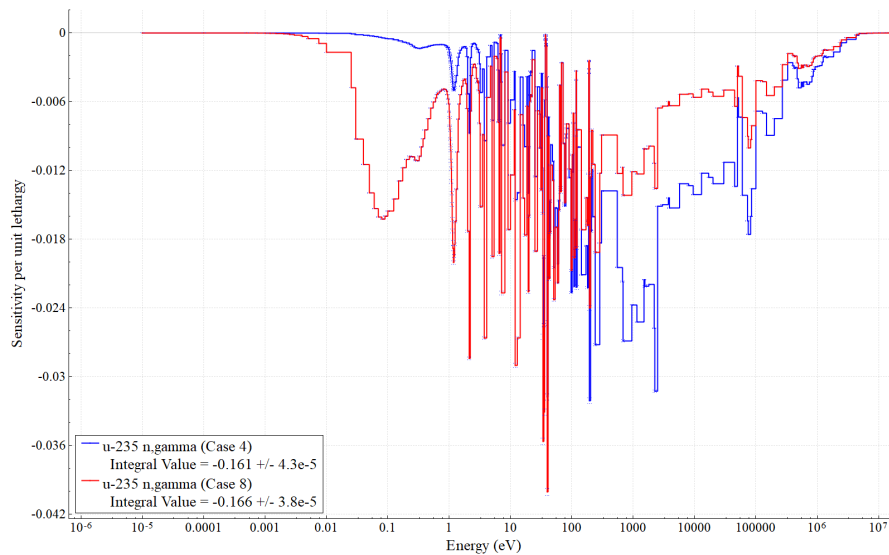


Figure 3.  $^{235}\text{U}$  (n, $\gamma$ ) sensitivity for ICI-003-004 and ICI-003-008.

Clearly, some of the ORCEF  $\text{UF}_4/\text{CF}_2$  experiments are useful for validation of 30-inch  $\text{UF}_6$  cylinder safety analysis calculations. In general, the  $^{235}\text{U}$  (n,  $\gamma$ ) reaction is very important for the most similar experiments. There are general trends to higher  $c_k$  values resulting from better agreement between the application enrichment and neutron energy spectrum and the benchmark values. This is not surprising and is not in itself particularly helpful. More analysis is needed to identify the parameters that would indicate which highly similar experiments would be most useful for validation of criticality safety calculations for these systems.

## 5 UNCERTAINTY CONTRIBUTIONS

There is no way to calculate the reason why  $c_k$  values are not higher. The TSUNAMI-IP extended  $c_k$  edit provides the contribution of each nuclide/reaction pair to  $c_k$ , but the answer to “what’s missing?” is more difficult to assess. Generally, the most successful approach is to examine the uncertainty contributions from each nuclide/reaction pair and analyze the differences in the sensitivities for these top uncertainty contributors between the application and benchmark models. The top five contributors to uncertainty for the four application models and the data-induced uncertainty from each of them are provided in Table IV. In each case, these five contributors represent between 94% and 96% of the total data-induced uncertainty, so it is reasonable to focus on this subset of uncertainty contributors.

Table IV. Top uncertainty contributors for application models

7 wt% NCT		7 wt% HAC	
Nuclide/reaction	Uncertainty (%)	Nuclide/reaction	Uncertainty (%)
$^{235}\text{U} (n,\gamma)$	0.643	$^{235}\text{U} (n,\gamma)$	0.588
$^{238}\text{U} (n,\gamma)$	0.411	$^{238}\text{U} (n,\gamma)$	0.387
$^{56}\text{Fe} (n,\gamma)$	0.360	$^{56}\text{Fe} (n,\gamma)$	0.319
$^{235}\text{U}$ nubar	0.222	$^{235}\text{U}$ nubar	0.231
$^{238}\text{U} (n,n')$	0.199	$^{235}\text{U}$ fission	0.119
10 wt% NCT		10 wt% HAC	
Nuclide/reaction	Uncertainty (%)	Nuclide/reaction	Uncertainty (%)
$^{235}\text{U} (n,\gamma)$	1.043	$^{235}\text{U} (n,\gamma)$	0.973
$^{238}\text{U} (n,\gamma)$	0.400	$^{238}\text{U} (n,\gamma)$	0.379
$^{56}\text{Fe} (n,\gamma)$	0.323	$^{56}\text{Fe} (n,\gamma)$	0.295
$^{238}\text{U} (n,n')$	0.251	$^{235}\text{U}$ nubar	0.189
$^{235}\text{U} \chi$	0.186	$^{238}\text{U} (n,n')$	0.171

As mentioned in Section 4, the  $^{235}\text{U} (n,\gamma)$  reaction, is the dominant contributor to uncertainty. Therefore, the highly similar experiments have large  $c_k$  contributions from this reaction in this isotope.

The ICI-004-009 experiment is the most similar case to both 7 wt% models. The largest uncertainty in ICI-004-009 comes from  $^{235}\text{U} (n, \gamma)$  and is 0.660%  $\Delta k$ , which is somewhat larger than the 0.588%  $\Delta k$  in the application model. This results from the larger integral sensitivity in the benchmark, because the benchmark model has more sensitivity at higher energies where the uncertainty is greater. The second largest contributor to uncertainty in both application models and the benchmark is  $^{238}\text{U} (n, \gamma)$ . The uncertainty contribution is larger in the application models because of the lower enrichment and correspondingly higher  $^{238}\text{U}$  concentration. The  $^{238}\text{U} (n,\gamma)$  uncertainty contribution for ICI-004-009 is only 0.292%  $\Delta k$ . This reaction also explains why  $c_k$  values are lower for the NCT model than the HAC model, given the higher uncertainty contribution in the NCT model. There is no iron in the ICI-004-009 benchmark; this lack of structural material is another impactful difference between benchmark and application models. In the benchmark model, the third largest contributor to the data-induced uncertainty is  $^{19}\text{F}$  elastic scatter; this reaction is not in the top 5 uncertainty contributors of the application models. The  $^{19}\text{F}$  elastic scattering reaction is the fourth highest contributor to  $c_k$  in the 7 wt% HAC case, contributing only 0.025 to  $c_k$ .

The top contributor to uncertainty for ICI-004-006 is  $^{235}\text{U} (n, \gamma)$ , with an uncertainty contribution of over 1.3%  $\Delta k$ . This results in a  $c_k$  contribution of 0.780 for the HAC model, which is almost enough to reach the 0.8 similarity threshold without any other nuclide/reaction pairs. The benchmark again suffers for the lack of  $^{56}\text{Fe}$  and too much sensitivity to  $^{19}\text{F}$ . The application system is 10 wt%  $^{235}\text{U}$ , so the  $^{238}\text{U}$  contribution is more similar than that of the 7 wt% case. The  $c_k$  for the ICI-004-006 benchmark with the 10 wt% HAC application is over 0.89, so there is little need to search for areas of improvement. The addition of steel would improve the similarity to above 0.9 if it could be implemented in a manner that did not significantly alter the neutron spectrum.

## 6 FISSILE FORM

Historically, part of the similarity of application models and benchmark experiments has been based on the qualitative similarity of experiment components and parameters, and the physical form of the fissile material has often been one of the considerations. It is not clear that this is necessarily a constraint for S/U-based validation because the primary focus is on the cross sections being exercised. The ICT-015 and -016

evaluations [5] contain experiments with  $\text{UO}_2$  material incorporated into wax blocks. These systems achieved a range of moderation ratios with different  $\text{UO}_2$  loadings, and they provide a test bed for comparison for different fissile forms with the  $\text{UF}_4/\text{CF}_2$  ORCEF experiments. SDFs have recently been generated at Oak Ridge National Laboratory (ORNL) for 70 cases from ICT-015 and ICT-016, though these files have also not been reviewed for addition to the Verified, Archived Library of Inputs and Data (VALID).

The results of the similarity assessment are striking: all 70 cases have  $c_k$  values between 0.82 and 0.92 when compared with ICT-011-013 and ICT-011-014, both of which are from the ICI-003 evaluation. A plot of the  $c_k$  values for all 70 ICT-015 and ICT-016 cases considered here vs. EALF is shown in Figure 4. Again, a general trend of increasing  $c_k$  is apparent as the EALF increases toward the EALF of ICT-011-014, which is used as the application in this case. These results are not definitive, but they provide a strong suggestion that highly similar experiments could be designed for  $\text{UF}_6$  applications without using  $\text{UF}_6$  as the fissile material. This would be a very advantageous application of S/U-based validation to a difficult validation problem.

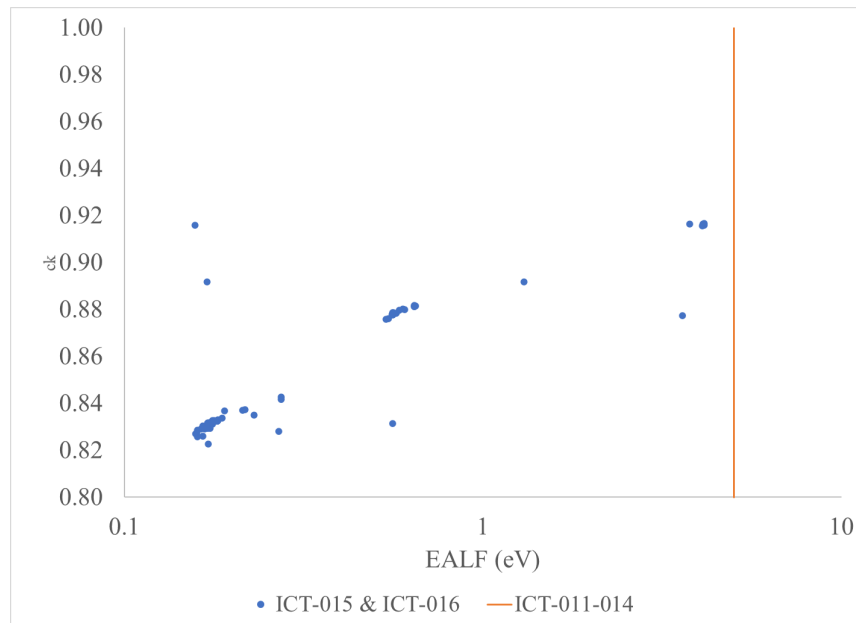


Figure 4.  $c_k$  values for selected ICT-015 and ICT-016 cases compared to ICT-011-014.

## 7 CONCLUSIONS

The obviously applicable critical experiments available in the ICSBEP Handbook [5] to validate criticality safety calculations for  $\text{UF}_6$  cylinders are limited. Experiments with some potential applicability were performed at ORCEF in the 1940s and 1950s and are documented in the ICT-001, ICM-002, and ICI-003 evaluations. These experiments were designed to mimic  $\text{UF}_6$  by combining  $\text{UF}_4$  and  $\text{CF}_2$ , and they used a range of interstitial plastic sheets or polyethylene blocks to vary the neutron energy spectrum. Recently, it was hoped that these experiments would yield high similarity to recent  $\text{UF}_6$  application models, including uranium enriched to 7 and 10 wt%  $^{235}\text{U}$  [2]. However, only one case was identified as being similar to the 7 wt% HAC case, and no cases surpassed a  $c_k$  value of 0.8 for the 7 wt% NCT model. The results were slightly better with the 10 wt% cases, with 5 and 6 cases identified above a  $c_k$  of 0.8 for the NCT and HAC cases, respectively.

Further investigation demonstrated that enrichment and neutron energy spectrum are inherently obvious parameters to use when predicting similarity but they cannot necessarily be used blindly. A detailed

assessment of similarity is possible by combining the positive indications in the extended  $c_k$  edit from TSUNAMI-IP, and indications of mismatches between application and experiment can be gleaned from the significant contributors to data-induced uncertainty.

Finally, a very brief study was conducted to assess the similarity of two sets of thermal experiments fueled with different fissile forms. While this analysis was very limited in scope, the preliminary indication confirms that identical fissile material may not be required for significant similarity. Further work is clearly warranted in this area generally, and in the validation of  $UF_6$  cylinders in transportation and storage scenarios specifically.

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