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Investigating Region-wise Sensitivities for Nuclear Criticality Safety Validation

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INTRODUCTION

Criticality safety analysts estimate Upper Subcriticality Limits (USLs) for subcritical systems to account for biases and errors in modeling and simulation tools and to ensure that subcritical conditions persist during operations. This study investigates the application of the MCNP6-Whisper [1,2] calculational methods to estimate USLs for loosely-coupled systems comprised of two units and makes use of a new MCNP6 capability that allows for the calculation of multiple region-dependent sensitivity profiles in a single calculation [3]. MCNP6 can compute the region-wise sensitivity profiles for each unit, as influenced by the leakage of the other unit, and the sensitivity profile of the overall loosely-coupled system.

This investigation deliberately focused on USL estimates for small, simple systems to highlight physical and computational issues associated with these types of systems. Three basic highly enriched uranium (HEU) and plutonium components are used in the loosely-coupled models in this study: bare fast metal sphere, water-reflected fast metal sphere, and thermal solution. These three different units are paired in various combinations, and the MCNP6-Whisper calculations are performed using both the new region-wise sensitivity profile capability, and the conventional overall sensitivity profile capability. These MCNP6-Whisper calculations are performed using a range of separation distances between the loosely-coupled critical components to examine how USL estimates change as the components become increasingly isolated.

This study evaluates the Whisper-selected benchmark rankings and calculated baseline USL values for each calculated sensitivity profile at each separation distance for each application model. The results are used to provide nuclear criticality safety practitioners with greater insight into the behavior of loosely-coupled system USL estimates and to provide some preliminary recommendations for the determination of the appropriate baseline USL values with regards to nuclear criticality safety applications.

Modifications to Whisper Scripts

The *whisper_mcnp.pl* script is used to insert the required MCNP6 input for the KSEN card, specifying the reactions and energy bins for sensitivities, into the user input and then run MCNP6. The *whisper_usl.pl* script is used to extract sensitivity profiles from the MCNP6 output files and then run the Whisper program for benchmark selection and statistical analysis. These scripts assume that only one sensitivity profile for the entire problem is desired and do not permit sensitivity profiles to be obtained for different regions in the problem.

These scripts were modified and saved as *whisper_mcnp2.pl* and *whisper_usl2.pl*. These modified scripts permit users to specify regions for obtaining sensitivities in a single MCNP6 calculation. It is important to note that only one MCNP6 calculation is performed to obtain the region-wise and overall sensitivity profiles. That is, for a system containing both units A and B, the region-wise sensitivity profile (KSEN1) for unit A includes the effects of interacting with unit B; the region-wise sensitivity profile (KSEN2) for unit B includes the effects of interacting with unit A; and the sensitivity profile for the entire system (KSEN3) is what would normally be produced by MCNP6 using the *whisper_mcnp.pl* script. All three sensitivity profiles are obtained in the single MCNP6 calculation of the entire system. The *whisper_usl2.pl* script runs all three sensitivity profiles separately through Whisper (i.e., three Whisper calculations).

ANALYSIS OF TEST PROBLEMS

This study created four application models that used two criticality benchmark assemblies in each application model. Parametric studies were conducted using five different separating distances between the centers of the two units. Region-wise sensitivity profiles were calculated for each of the two interacting assemblies and the overall application system using MCNP6.2 in a single combined calculation.

These sensitivities were used by Whisper 1.1 to select and rank the most similar benchmark cases and to determine the baseline USL for each unit and for the overall coupled system. The ten benchmarks with the highest weighting were compared at each separating distance for each unit and the overall coupled system for a given model. The baseline USLs at each separating distance, for each unit and the overall coupled system, were compared to determine the differences between the regional and overall baseline USLs determined by Whisper.

Model Descriptions

All four application models used 100,000 neutrons per cycle, 500 inactive cycles, and 500 active cycles in their MCNP6.2 simulations. Truncated benchmark rankings and calculated baseline USL values were made using MCNP6.2 and Whisper-1.1 for regional and overall sensitivity profiles at each separation distance for a given model. ENDF/B-VII.1 nuclear data and standard 44-group "low-fidelity" covariance data were used in all Whisper calculations in this study.

The individual units in the four application models were derived from the International Criticality Safety Benchmark Evaluation Project (ICSBEP). The Bare Fast Metal application model component is comprised of an HEU sphere taken from the ICSBEP benchmark HEU-MET-FAST-051-015 and a plutonium sphere taken from the ICSBEP benchmark PU-MET-FAST-001-001, with separation distances spanning 20 to 100 centimeters in 20-centimeter increments. The Water-Reflected Fast Metal application model is derived from the ICSBEP benchmarks HEU-MET-FAST-004-001 and PU-MET-FAST-011-001 and has a separating distance between units spanning 70 to 150 centimeters with 20-centimeter increments. The Thermal Solution application model is comprised of HEU-SOL-THERM-050-010 and PU-SOL-THERM-001-01 ICSBEP benchmarks with separating distances between the individual units from 80 to 160 centimeters with 20-centimeter increments. The Mixed Plutonium application model is made of two individual units that are derived from the ICSBEP benchmarks, PU-MET-FAST-011-001 and PU-SOL-THERM-001-001. This application model also had separation distances between the units spanning 80-120 centimeters in 20-centimeter increments.

RESULTS AND DISCUSSION

Although creating an accurate sensitivity benchmark profile is important, calculating a conservative baseline USL is of paramount importance to criticality safety analysis. As discussed below, this work shows that for loosely-coupled units, the baseline USLs determined with Whisper using region-wise sensitivity profiles may be more conservative than the Whisper baseline USL for the overall system. These results deserve attention from criticality safety analysts as performing Whisper USL estimates using only sensitivity profiles from the overall system may result in nonconservative USL estimates.

The calculated baseline USL values show the region-wise benchmark rankings bounding the overall benchmark rankings. The greater dominance of one region on the benchmark rankings of the overall system seems to coincide with the region with the greater reactivity.

Bare Fast Metal Application Model

The Bare Fast Metal application model region-wise baseline USL values' bound the overall application model's baseline USL values at each separation distance. The baseline USL values do not vary with separation distance. The benchmark rankings for each unit in Tables 1 and 2 do not vary with separation distance, and the overall benchmark rankings for this application model reflect a blending of the region-wise sensitivity profiles for the 2 units, as seen by the application model's overall benchmark rankings in Table 3.

Water-Reflected Fast Metal Application Model

The Water-Reflected Fast Metal application model baseline USL values follow the plutonium sphere region-wise baseline USL values, matching the more conservative baseline USL values. The baseline USL values, regionally and over the whole application model, vary negligibly with separation distance. However, the benchmark rankings for this application model vary with separation distance, as seen in Tables 4 and 5 for the individual units and in Table 6 for the overall system. The domination of the plutonium unit in this overall system is apparent in the benchmark rankings.

The reflected plutonium unit in this application model is more reactive than the reflected HEU unit, with k-effective values (for isolated single units) of 1.00014 $\pm$ 0.00011 and 0.99406 $\pm$ 0.00011, respectively.

Thermal Solution Application Model

The thermal solution model has benchmark rankings that are dominated by the thermal plutonium solution unit, as seen in Tables 7-9. The calculated k-effectives for individual isolated units of the thermal plutonium and HEU solutions are 1.00578 $\pm$ 0.00013 and 0.99113 $\pm$ 0.00015, respectively. This is consistent with the idea that the significantly more reactive unit in a coupled system will dominate the benchmark rankings. For this case, the baseline USL values determined by Whisper are of great interest, as seen in Figure 1.

This illustrates an incomplete dominance of the thermal plutonium solution over the baseline USL of the overall model.

Mixed Plutonium Application Model

The benchmark rankings for the mixed plutonium units are shown in Tables 10 and 11, and the rankings for the overall system in Table 12.

For the mixed plutonium system there is noticeable variation in the USL values for the fast-reflected metal plutonium unit with respect to separation distance, seen in Figure 2.

This suggests that the energy spectra of the neutron leakage from each unit, as a function of separation distance between units, may be of influence in systems with units of dissimilar neutron energy spectra and of negligible influence in systems where units are of similar neutron energy spectra.

CONCLUSIONS

This numerical experiment highlights that nonconservative USL estimates may be calculated for loosely-coupled multi-region critical models when using only the overall sensitivity profile of systems. This work suggests that to ensure conservative USL estimates for loosely-coupled systems, both the overall system's sensitivity profiles and region-wise sensitivity profiles should be calculated and utilized by Whisper 1.1. This study also suggests a relationship between the calculated k_{eff} of the individual units, the sensitivity profile domination of the overall model, and the baseline USL values.

In systems where the two units have similar neutron energy spectra there is little variation in the region-wise USL values or the overall system USL values with respect to separation distance between units. For the mixed plutonium system there is noticeable variation in the USL values for the fast-reflected metal plutonium unit with respect to separation distance. This suggests that the energy spectra of the neutron leakage from each unit, as a function of separation distance between units, may be of influence in systems with units of dissimilar neutron energy spectra and of negligible influence in systems where units are of similar neutron energy spectra.

ACKNOWLEDGEMENTS

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Table 1. Benchmark rankings for Bare Fast HEU Unit

Bare Fast Metal HEU Assembly	Separation Distance [cm]				
Benchmark Ranking	20	40	60	80	100
1	hmf-051-015.i	hmf-051-015.i	hmf-051-015.i	hmf-051-015.i	hmf-051-015.i
2	hmf-100-002.i	hmf-100-002.i	hmf-100-002.i	hmf-100-002.i	hmf-100-002.i
3	hmf-051-014.i	hmf-051-014.i	hmf-051-014.i	hmf-051-014.i	hmf-051-014.i
4	hmf-100-001.i	hmf-100-001.i	hmf-100-001.i	hmf-100-001.i	hmf-100-001.i
5	hmf-065-002.i	hmf-065-002.i	hmf-065-002.i	hmf-065-002.i	hmf-065-002.i
6	hmf-044-001.i	hmf-044-001.i	hmf-044-001.i	hmf-044-001.i	hmf-044-001.i
7	hmf-001-001.i	hmf-001-001.i	hmf-001-001.i	hmf-001-001.i	hmf-001-001.i
8	hmf-015-001.i	hmf-015-001.i	hmf-015-001.i	hmf-015-001.i	hmf-015-001.i
9	hmf-008-001.i	hmf-008-001.i	hmf-008-001.i	hmf-008-001.i	hmf-008-001.i
10	hmf-044-002.i	hmf-044-002.i	hmf-044-002.i	hmf-044-002.i	hmf-044-002.i

Table 2. Benchmark rankings for Bare Fast Plutonium Unit

Bare Fast Metal Plutonium Assembly	Separation Distance [cm]				
Benchmark Ranking	20	40	60	80	100
1	pmf-001-001.i	pmf-001-001.i	pmf-001-001.i	pmf-001-001.i	pmf-001-001.i
2	pmf-022-001.i	pmf-022-001.i	pmf-022-001.i	pmf-022-001.i	pmf-022-001.i
3	pmf-029-001.i	pmf-029-001.i	pmf-029-001.i	pmf-029-001.i	pmf-029-001.i
4	mmf-009-001.i	mmf-009-001.i	mmf-009-001.i	mmf-009-001.i	mmf-009-001.i
5	pmf-023-001.i	pmf-023-001.i	pmf-023-001.i	pmf-023-001.i	pmf-023-001.i
6	pmf-035-001.i	pmf-035-001.i	pmf-035-001.i	pmf-035-001.i	pmf-035-001.i
7	pmf-039-001.i	pmf-039-001.i	pmf-039-001.i	pmf-039-001.i	pmf-039-001.i
8	pmf-030-001.i	pmf-030-001.i	pmf-030-001.i	pmf-030-001.i	pmf-030-001.i
9	pmf-009-001.i	pmf-009-001.i	pmf-009-001.i	pmf-009-001.i	pmf-009-001.i
10	pmf-025-001.i	pmf-025-001.i	pmf-025-001.i	pmf-025-001.i	pmf-025-001.i

Table 3. Benchmark rankings for Bare Fast Metal System

Bare Metal Fast System	Separation Distance [cm]				
Ranked Benchmark	20	40	60	80	100
1	mmf-007-013.i	mmf-007-013.i	mmf-007-013.i	mmf-007-013.i	mmf-007-013.i
2	mmf-007-012.i	mmf-007-012.i	mmf-007-012.i	mmf-007-012.i	mmf-007-012.i
3	mmf-007-018.i	mmf-007-018.i	mmf-007-018.i	mmf-007-018.i	mmf-007-018.i
4	mmf-007-011.i	mmf-007-011.i	mmf-007-011.i	mmf-007-011.i	mmf-007-011.i
5	mmf-010-001.i	mmf-010-001.i	mmf-010-001.i	mmf-010-001.i	mmf-010-001.i
6	mmf-007-006.i	mmf-007-006.i	mmf-007-006.i	mmf-007-006.i	mmf-007-006.i
7	mmf-007-017.i	mmf-007-017.i	mmf-007-017.i	mmf-007-017.i	mmf-007-017.i
8	mmf-007-005.i	mmf-007-005.i	mmf-007-005.i	mmf-007-005.i	mmf-007-005.i
9	mmf-007-010.i	mmf-007-010.i	mmf-007-010.i	mmf-007-010.i	mmf-007-010.i
10	mmf-007-021.i	mmf-007-021.i	mmf-007-021.i	mmf-007-021.i	mmf-007-021.i

Table 4. Benchmark rankings for Reflected Fast Pu Unit

Reflected Fast Plutonium Assembly	Separation Distance [cm]				
Benchmark Ranking	40	60	80	100	120
1	pmf-011-001.i	pmf-011-001.i	pmf-011-001.i	pmf-011-001.i	pmf-011-001.i
2	pmf-044-004.i	pmf-042-001.i	pmf-042-001.i	pmf-044-004.i	pmf-044-004.i
3	pmf-042-001.i	pmf-044-004.i	pmf-044-004.i	pmf-042-001.i	pmf-042-001.i
4	pmf-027-001.i	pmf-027-001.i	pmf-042-002.i	pmf-027-001.i	pmf-027-001.i
5	pmf-042-002.i	pmf-042-002.i	pmf-027-001.i	pmf-042-002.i	pmf-042-002.i
6	pmf-031-001.i	pmf-031-001.i	pmf-031-001.i	pmf-031-001.i	pmf-031-001.i
7	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i
8	pmf-042-003.i	pmf-042-003.i	pmf-042-003.i	pmf-042-003.i	pmf-042-003.i
9	pmf-042-004.i	pmf-042-004.i	pmf-042-004.i	pmf-042-004.i	pmf-042-004.i
10	pmf-036-001.i	pmf-036-001.i	pmf-036-001.i	pmf-036-001.i	pmf-036-001.i

Table 5. Benchmark rankings for Reflected Fast HEU Unit

Reflected Fast HEU Assembly	Separation Distance [cm]				
Benchmark Ranking	40	60	80	100	120
1	hmf-004-001.i	hmf-004-001.i	hmf-004-001.i	hmf-004-001.i	hmf-004-001.i
2	hmf-078-001.i	hmf-078-001.i	hmf-078-001.i	hmf-078-001.i	hmf-078-001.i
3	hmf-011-001.i	hmf-011-001.i	hmf-011-001.i	hmf-007-035.i	hmf-084-011.i
4	hmf-007-035.i	hmf-084-011.i	hmf-007-035.i	hmf-011-001.i	hmf-011-001.i
5	hmf-078-011.i	hmf-007-035.i	hmf-078-011.i	hmf-091-001.i	hmf-016-002.i
6	hmf-078-009.i	hmf-016-002.i	hmf-078-017.i	hmf-078-011.i	hmf-084-002.i
7	hmf-078-017.i	hmf-091-001.i	hmf-078-009.i	hmf-078-017.i	hmf-078-005.i
8	hmf-078-005.i	hmf-078-005.i	hmf-078-005.i	hmf-078-009.i	hmf-009-002.i
9	hmf-078-015.i	hmf-078-017.i	hmf-078-015.i	hmf-078-005.i	hmf-078-017.i
10	hmf-078-013.i	hmf-078-011.i	hmf-078-013.i	hmf-078-015.i	hmf-010-002.i

Table 6. Benchmark rankings for Reflected Fast Metal System

Reflected Fast Metal System	Separation Distance [cm]				
Benchmark Ranking	40	60	80	100	120
1	pmf-011-001.i	pmf-011-001.i	pmf-011-001.i	pmf-011-001.i	pmf-011-001.i
2	pmf-042-001.i	pmf-042-001.i	pmf-042-001.i	pmf-044-004.i	pmf-042-001.i
3	pmf-044-004.i	pmf-027-001.i	pmf-027-001.i	pmf-042-001.i	pmf-044-004.i
4	pmf-027-001.i	pmf-044-004.i	pmf-044-004.i	pmf-027-001.i	pmf-027-001.i
5	pmf-042-002.i	pmf-042-002.i	pmf-042-002.i	pmf-042-002.i	pmf-042-002.i
6	pmf-031-001.i	pmf-031-001.i	pmf-031-001.i	pmf-031-001.i	pmf-031-001.i
7	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i
8	pmf-042-003.i	pmf-042-003.i	pmf-042-003.i	pmf-042-003.i	pmf-042-003.i
9	pmf-042-004.i	pmf-042-004.i	pmf-042-004.i	pmf-042-004.i	pmf-042-004.i
10	pmf-036-001.i	pmf-036-001.i	pmf-036-001.i	pmf-036-001.i	pmf-036-001.i

Table 7. Benchmark rankings for Thermal HEU Solution Unit

Thermal HEU Solution Assembly	Separation Distance [cm]				
Benchmark Ranking	45	65	85	105	125
1	hst-050-010.i	hst-050-010.i	hst-050-010.i	hst-050-010.i	hst-050-010.i
2	hst-050-001.i	hst-050-001.i	hst-050-001.i	hst-050-001.i	hst-050-001.i
3	hst-050-008.i	hst-050-008.i	hst-050-008.i	hst-050-008.i	hst-050-008.i
4	hst-050-002.i	hst-050-002.i	hst-050-002.i	hst-050-002.i	hst-050-002.i
5	hst-050-004.i	hst-050-004.i	hst-050-004.i	hst-050-004.i	hst-050-004.i
6	hst-050-006.i	hst-050-006.i	hst-050-006.i	hst-050-006.i	hst-050-006.i
7	hst-009-001.i	hst-009-001.i	hst-009-001.i	hst-009-001.i	hst-009-001.i
8	hst-009-002.i	hst-050-011.i	hst-009-002.i	hst-050-011.i	hst-050-011.i
9	hst-050-011.i	hst-009-002.i	hst-050-011.i	hst-009-002.i	hst-009-002.i
10	hst-050-003.i	hst-050-005.i	hst-050-009.i	hst-050-005.i	hst-050-005.i

Table 8. Benchmark rankings for Thermal Plutonium Solution Unit

Thermal Plutonium Solution Assembly	Separation Distance [cm]				
Benchmark Ranking	45	65	85	105	125
1	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i
2	pst-002-005.i	pst-011-165.i	pst-011-165.i	pst-002-005.i	pst-010-009.i
3	pst-010-009.i	pst-010-009.i	pst-010-009.i	pst-010-009.i	pst-002-005.i
4	pst-011-165.i	pst-002-005.i	pst-002-005.i	pst-010-002.i	pst-011-165.i
5	pst-010-002.i	pst-010-002.i	pst-010-002.i	pst-011-165.i	pst-010-002.i
6	pst-002-006.i	pst-002-006.i	pst-002-004.i	pst-002-006.i	pst-002-004.i
7	pst-002-007.i	pst-002-004.i	pst-002-006.i	pst-002-007.i	pst-002-006.i
8	pst-002-004.i	pst-002-007.i	pst-002-007.i	pst-002-004.i	pst-002-007.i
9	pst-002-003.i	pst-002-003.i	pst-002-003.i	pst-002-003.i	pst-002-003.i
10	pst-001-002.i	pst-001-002.i	pst-001-002.i	pst-001-002.i	pst-001-002.i

Table 9. Benchmark rankings for Thermal Solution System

Thermal Solution System	Separation Distance [cm]				
Benchmark Ranking	45	65	85	105	125
1	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i
2	pst-007-010.i	pst-010-002.i	pst-010-002.i	pst-010-002.i	pst-010-002.i
3	pst-010-002.i	pst-007-010.i	pst-007-010.i	pst-007-010.i	pst-007-010.i
4	pst-002-006.i	pst-010-009.i	pst-010-009.i	pst-010-009.i	pst-010-009.i
5	pst-010-009.i	pst-002-006.i	pst-002-006.i	pst-002-006.i	pst-002-006.i
6	pst-002-005.i	pst-002-005.i	pst-002-005.i	pst-002-005.i	pst-002-005.i
7	pst-007-005.i	pst-007-005.i	pst-002-004.i	pst-002-004.i	pst-007-005.i
8	pst-007-009.i	pst-002-004.i	pst-007-005.i	pst-001-002.i	pst-002-004.i
9	pst-001-002.i	pst-001-002.i	pst-001-002.i	pst-007-005.i	pst-001-002.i
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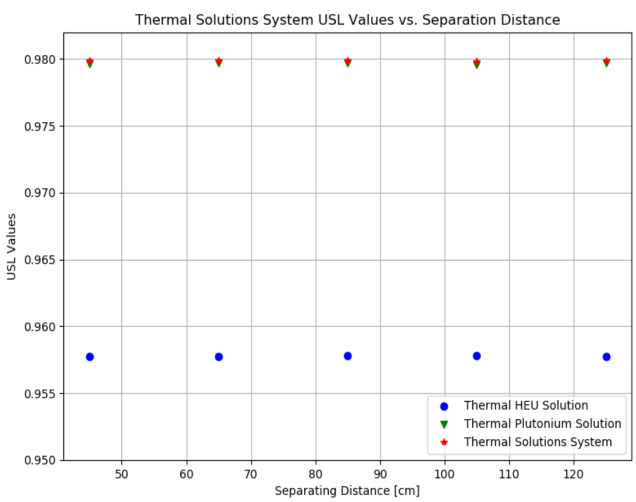

Fig. 1 Thermal Solution System's baseline USL values versus unit separation distance

Table 10. Benchmark rankings for Fast Metal Plutonium Unit in Mixed Plutonium System

Fast Metal Plutonium Assembly	Separation Distance [cm]				
Benchmark Ranking	50	70	90	110	130
1	pmf-044-004.i	pmf-042-002.i	pmf-044-004.i	pmf-044-004.i	pmf-044-004.i
2	pmf-044-005.i	pmf-042-003.i	pmf-044-005.i	pmf-044-005.i	pmf-044-005.i
3	pmf-024-001.i	pmf-044-005.i	pmf-042-002.i	pmf-042-002.i	pmf-031-001.i
4	pmf-036-001.i	pmf-027-001.i	pmf-042-001.i	pmf-031-001.i	pmf-024-001.i
5	pmf-031-001.i	pmf-044-004.i	pmf-031-001.i	pmf-042-001.i	pmf-036-001.i
6	pmf-044-003.i	pmf-042-001.i	pmf-042-003.i	pmf-042-003.i	pmf-042-001.i
7	pmf-042-002.i	pmf-042-004.i	pmf-027-001.i	pmf-027-001.i	pmf-044-003.i
8	pmf-042-001.i	pmf-011-001.i	pmf-011-001.i	pmf-042-004.i	pmf-042-002.i
9	pmf-027-001.i	pmf-042-005.i	pmf-042-004.i	pmf-036-001.i	pmf-027-001.i
10	pmf-042-004.i	pmf-031-001.i	pmf-036-001.i	pmf-011-001.i	pmf-011-001.i

Table 11. Benchmark rankings for Thermal Plutonium Solution Unit in Mixed Plutonium System

Thermal Plutonium Solution Assembly	Separation Distance [cm]				
Benchmark Ranking	50	70	90	110	130
1	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i
2	pst-010-009.i	pst-011-165.i	pst-011-165.i	pst-011-165.i	pst-011-165.i
3	pst-011-165.i	pst-010-009.i	pst-010-009.i	pst-010-009.i	pst-010-009.i
4	pst-010-002.i	pst-002-005.i	pst-002-005.i	pst-002-005.i	pst-002-005.i
5	pst-002-005.i	pst-010-002.i	pst-010-002.i	pst-010-002.i	pst-010-002.i
6	pst-002-004.i	pst-002-004.i	pst-002-006.i	pst-002-004.i	pst-002-004.i
7	pst-002-006.i	pst-002-006.i	pst-002-004.i	pst-002-006.i	pst-002-006.i
8	pst-002-007.i	pst-002-007.i	pst-002-007.i	pst-002-003.i	pst-002-003.i
9	pst-002-003.i	pst-002-003.i	pst-002-003.i	pst-002-007.i	pst-002-007.i
10	pst-001-002.i	pst-001-002.i	pst-001-002.i	pst-011-163.i	pst-011-163.i

Table 12. Benchmark rankings for Mixed Plutonium System

Mixed Plutonium System	Separation Distance [cm]				
Benchmark Ranking	50 cm	70 cm	90 cm	110 cm	130 cm
1	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i	pst-001-001.i
2	pst-010-002.i	pst-010-002.i	pst-010-002.i	pst-010-002.i	pst-010-002.i
3	pst-010-009.i	pst-010-009.i	pst-010-009.i	pst-010-009.i	pst-010-009.i
4	pst-002-006.i	pst-002-005.i	pst-002-006.i	pst-002-005.i	pst-002-005.i
5	pst-002-005.i	pst-002-006.i	pst-002-005.i	pst-002-006.i	pst-002-004.i
6	pst-007-010.i	pst-002-004.i	pst-007-010.i	pst-002-004.i	pst-002-006.i
7	pst-002-004.i	pst-007-010.i	pst-002-004.i	pst-007-010.i	pst-007-010.i
8	pst-001-002.i	pst-001-002.i	pst-001-002.i	pst-002-003.i	pst-002-003.i
9	pst-007-005.i	pst-007-005.i	pst-002-003.i	pst-001-002.i	pst-001-002.i
10	pst-002-003.i	pst-002-003.i	pst-002-007.i	pst-002-007.i	pst-007-005.i

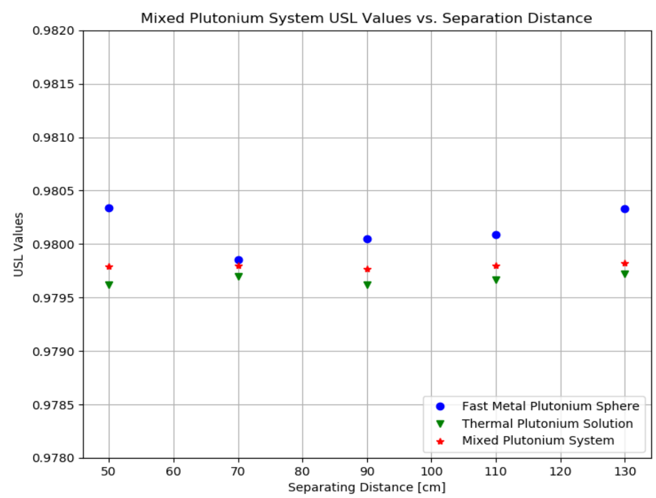

Fig 2. Mixed Plutonium System's baseline USL values versus unit separation distance