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United States Department of Energy
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Nuclear Criticality Safety Program

Integral Experiment Request 208
CED-2 Summary Report

Critical and Subcritical Experiment Design Team (C_EdT)

Gary A. Harms (SNL), C_EdT Lead and Publication Member
Allison D. Miller (SNL), C_EdT Experiment Member
Richard D. McKnight (ANL), C_EdT NDAG Member
Thomas M. Miller (ORNL), C_EdT Methods Member
David P. Heinrichs (LLNL), C_EdT Member

Date

SAND #

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It is with great sadness that we note the passing of our teammate and friend

Richard D. McKnight

on August 28, 2013. We could always count on Dick for his deep knowledge, his incisive reviews, and his gentle tact. He was one of the great ones and will be sorely missed. We are diminished by his loss.

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Summary

This report examines proposed Seven Percent Critical Experiment (7uPCX) experiments with fuel arrays larger than would be critical when fully reflected. In these experiments, the reactivity of the assembly will be controlled by varying the moderator/reflector level in the core tank. The analysis uses two configurations, each completely filling the 45x45 fuel rod array with fuel rods and water holes, as representative examples of the proposed experiments. The proposed configurations are compared to the experiments documented in LEU-COMP-THERM-080 of Reference 1 and to fully-reflected experiments with the same fully-loaded fuel arrays that are poisoned with boron in the moderator. The conclusion is drawn that the proposed experiments can be performed with acceptably low uncertainties given a calibrated moderator/reflector level measurement system. One of the benefits of the work described here is that a benchmark-quality critical experiment capability that uses the height of the moderator/reflector in a lattice fuel array as the approach variable will be developed.

Introduction

The experiments described here were started as part of the Nuclear Energy Research Initiative (NERI) Project 01-0124. Documentation of the overall project and results of the analytical part of the project are given in Reference 2. The sensitivity/uncertainty analysis done as part of the project is documented in Reference 3. Details regarding the goals of the experiments, the design of the experiments, and the applicability of the experiments to the desired commercial fuel element configurations are included in these references.

Quoting from Reference 2:

> *The nuclear industry interest in advanced fuel and reactor design often drives towards fuel with uranium enrichments greater than 5 wt% ^{235}U. Unfortunately, little data exists, in the form of reactor physics and criticality benchmarks, for uranium enrichments ranging between 5 and 10 wt% ^{235}U. The primary purpose of this project is to provide benchmarks for fuel similar to what may be required for advanced light water reactors (LWRs). These*

experiments will ultimately provide additional information for application to the criticality-safety bases for commercial fuel facilities handling greater than 5 wt% ^{235}U fuel.

Because these experiments are designed primarily to be reactor physics benchmarks, and not just criticality benchmarks, it is desired to include measurements of critical boron concentration, relative pin powers, relative assembly flux, burnable absorber worth, and isothermal temperature coefficients, for each configuration. Guidelines for developing an appropriate experimental configuration include bounding current pressurized water and boiling water reactor (PWR and BWR, respectively) fuel-to-water and metal-to-water ratios and maintaining consistency between experiment geometry and current PWR and BWR analysis tools used for reload designs (e.g., CASMO/SIMULATE).

The point of the last sentence of the quoted material is that some of the tools used for commercial fuel element design have difficulties addressing geometries that are different from fully-loaded commercial fuel elements. One of the goals of the work proposed here is to perform critical experiments in a square 45x45 fuel array loaded to simulate a collection of commercial fuel elements. Another benefit of these experiments will be the development of a benchmark-quality critical experiment capability that uses the height of the moderator/reflector in the fuel array as the approach variable.

The experiment matrix that was proposed in the NERI project included fully-reflected experiments with pure water moderator and experiments with fuel arrays that filled the 45x45 fuel rod array and used boric acid in the moderator to shim out the excess reactivity inherent with the fully-loaded and -reflected fuel arrays. One of the fuel rod layouts examined in the NERI report is shown in Figure 1. In that configuration, the 45x45 fuel array is loaded to simulate a 3x3 array of 15x15 PWR fuel assemblies with 1836 fuel rods and 189 water holes.

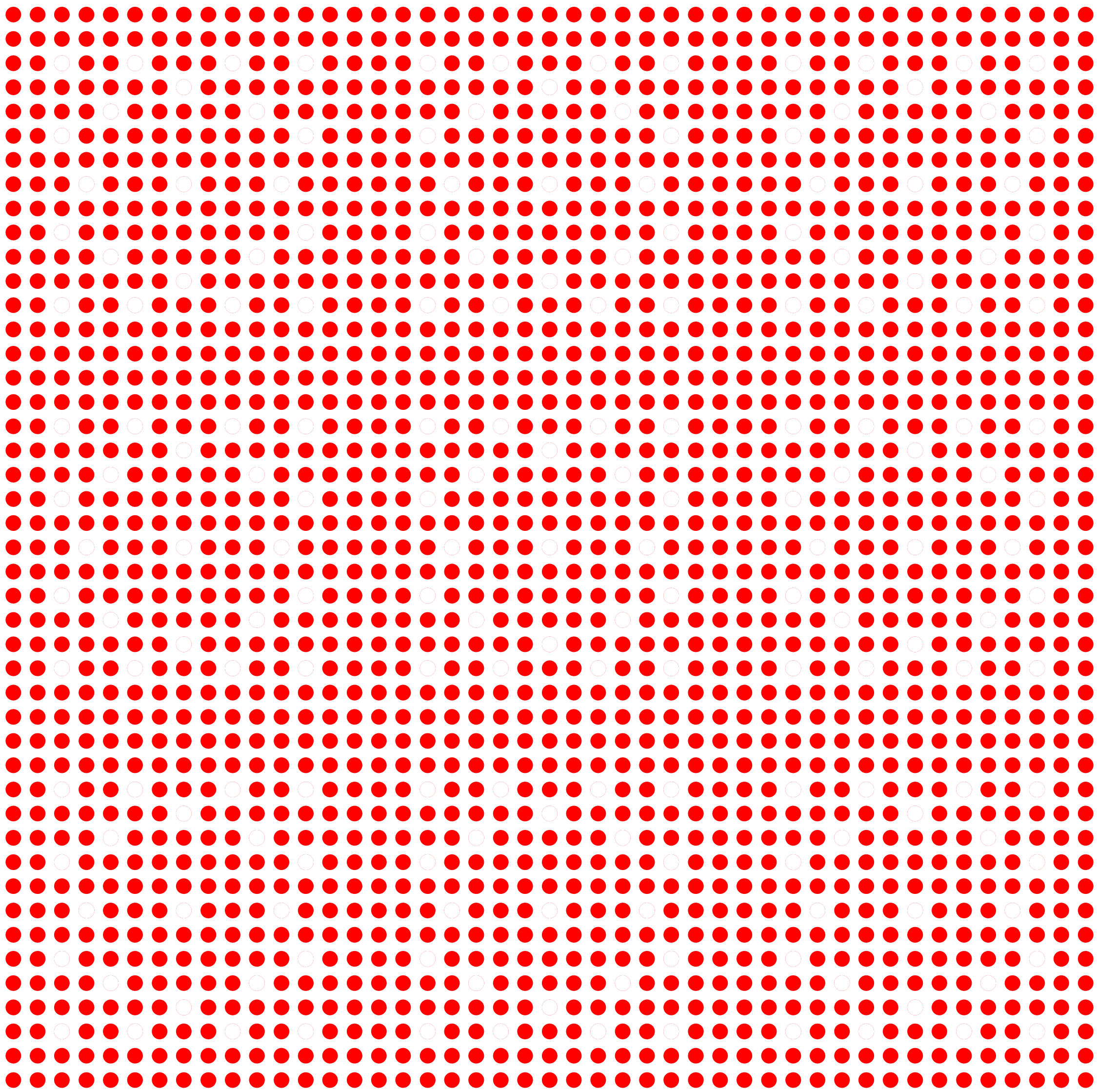

Figure 1. Fuel Rod Lay-Out Simulating a 3x3 Array of 15x15 PWR Fuel Elements.

As part of the NERI project, two grid plate sets were fabricated. The grid plates were designed so that the two sets bracketed the fuel-to-water ratios in the existing LWRs in the US. The 7uPCX configurations addressed as part of IER-135 and documented as LEU-COMP-THERM-080 (LCT080) in Reference 1 were moderated and reflected by pure water and used the grid plate set at the higher fuel-to-water ratio. In those experiments, the fuel rod array was roughly cylindrical. The experiments performed as part of IER-159 and currently being documented as LEU-COMP-THERM-078 to be added to Reference 1 are similar experiments at the lower fuel-to-water ratio.

Figure 2 shows the overall critical assembly concept that was used for the experiments performed as part of IER-135. Figure 3 shows the fuel rod layout in the assembly for one of the configurations (Case 11) investigated. This layout is a subset of that shown in Figure 1 and is near delayed critical when moderated and fully-reflected by pure water.

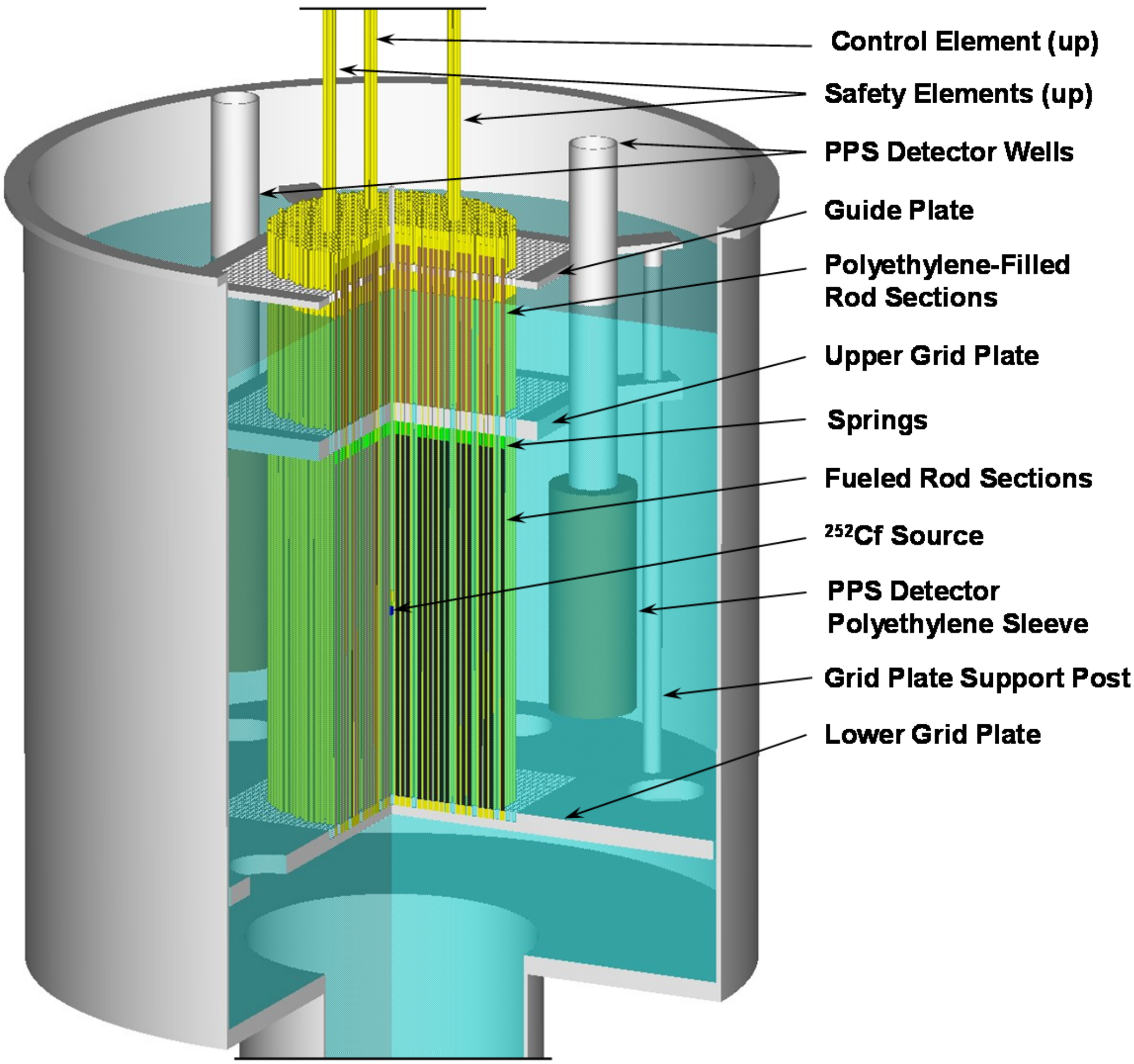

Figure 2. Critical Assembly Concept of the 7uPCX.

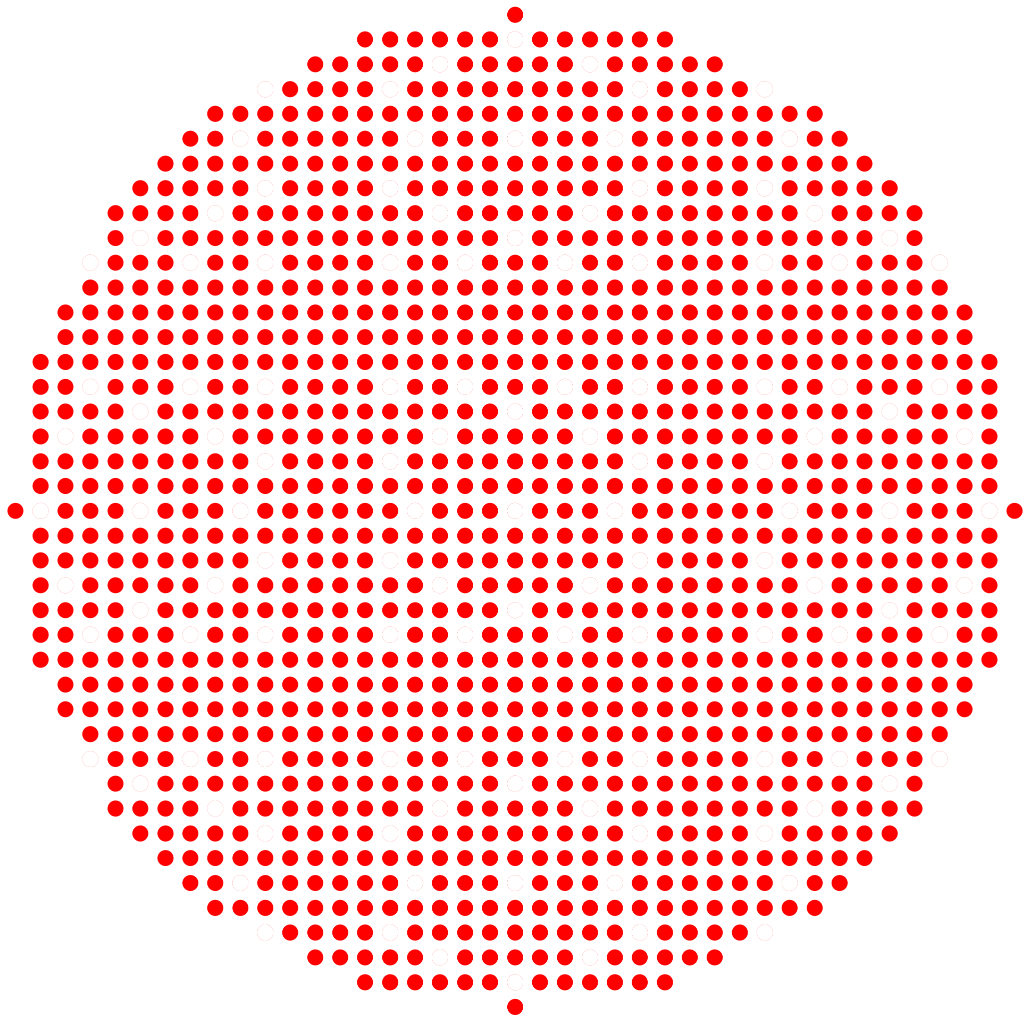

Figure 3. Fuel Rod Layout in Case 11 of LCT080.

Proposed Experiment Concept

The ownership of the experiment hardware has now transitioned to the DOE Nuclear Criticality Safety Program. Due to concerns over retention of the dissolved boron poison in the assembly, the decision has been made to defer the experiments with boric acid poisoning the moderator and reflector. The experiments described here as part of IER-208 include configurations with the 45x45 array fully loaded, similar to those included in the NERI project, but with the excess reactivity shimmed by lower moderator/reflector levels rather than by dissolved poison in the moderator/reflector. Figure 4 shows the critical assembly concept with the moderator/reflector at about the critical level for the unpoisoned fuel rod layout shown in Figure 1. Note that the neutron source and the detectors are shown in the positions used in the IER-135 experiments. They will likely be moved to lower elevations for the experiments proposed here.

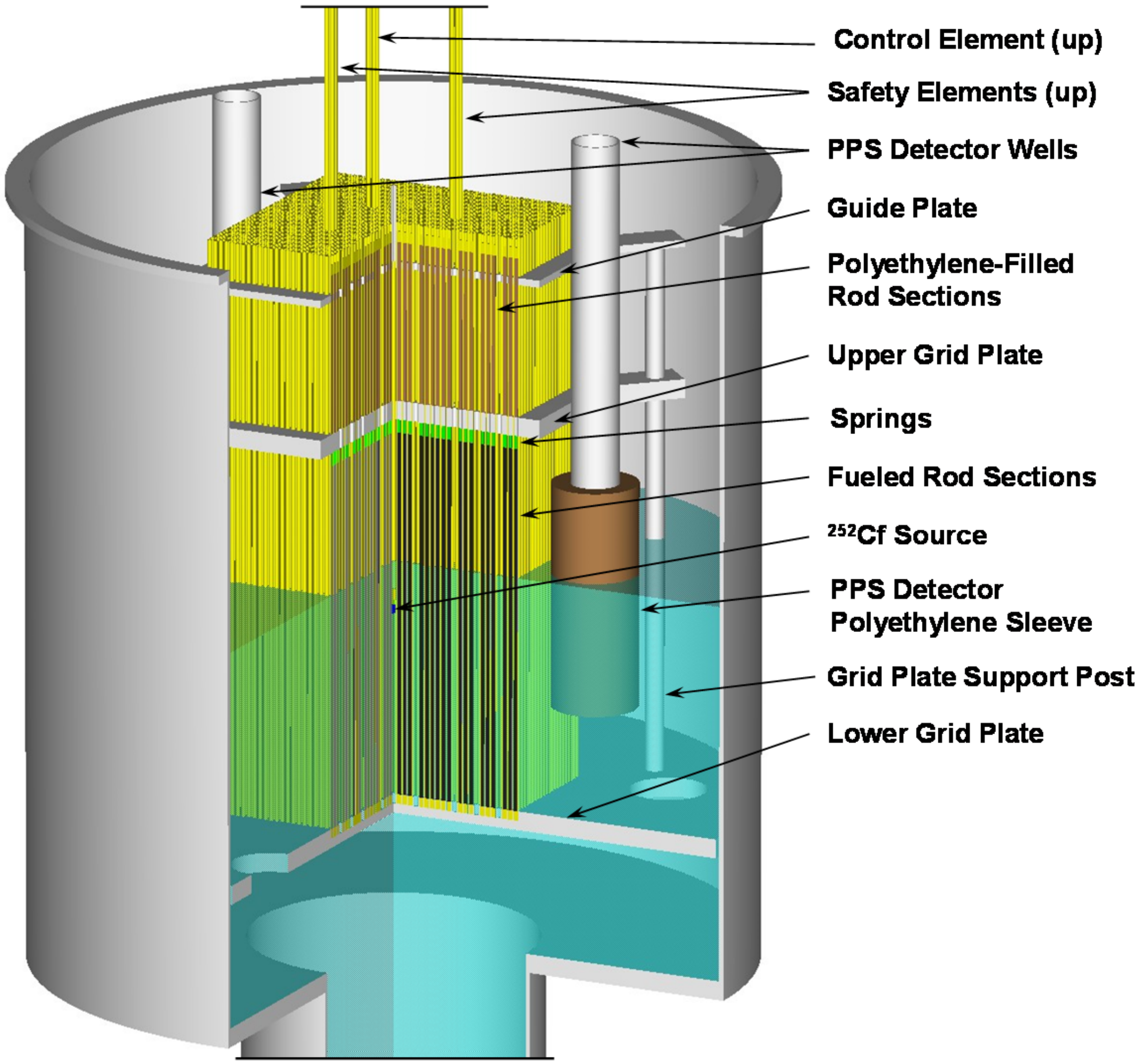

Figure 4. Critical Assembly Concept With the Array Fully Loaded.

For the purpose of investigating the experiment design, two configurations will be carried forward. The first, Configuration 1, will use the fuel rod layout shown in Figure 1 with 189 water holes distributed among 1836 fuel rods in the 45x45 array. The second, Configuration 2, will have 2025 fuel rods filling all the fuel rod positions in the array. Comparing to the experiments performed under IER-135 and documented in LCT080, Configuration 1 is similar to Case 11 and Configuration 2 is similar to Case 1.

Anticipated Critical Configurations

Detailed models of the 7uPCX configurations were prepared in both KENO-V.a from SCALE version 6.1.1 [4] and MCNP5 version 1.60 [5]. Figure 5 shows the calculated k_{eff} as a function of moderator height for Configuration 1 using KENO-V.a with ENDF/B-VII.0 cross sections. The calculated values are shown as error bars while the solid curve is a polynomial fit to these data. The horizontal line marked k_{crit} shows the calculated k_{eff} for the code and cross sections that is equivalent to delayed critical for this configuration – it includes the bias determined by comparison of calculated and measured k_{eff} for LCT080 Case 11. The vertical line marked h_{crit} shows where a polynomial fit to the k_{eff} data as a function of moderator height crosses the critical k_{eff} value. For this configuration, h_{crit} is 313.4 mm, where the height is measured from the top of the bottom grid plate of the assembly. MCNP5 gives similar results.

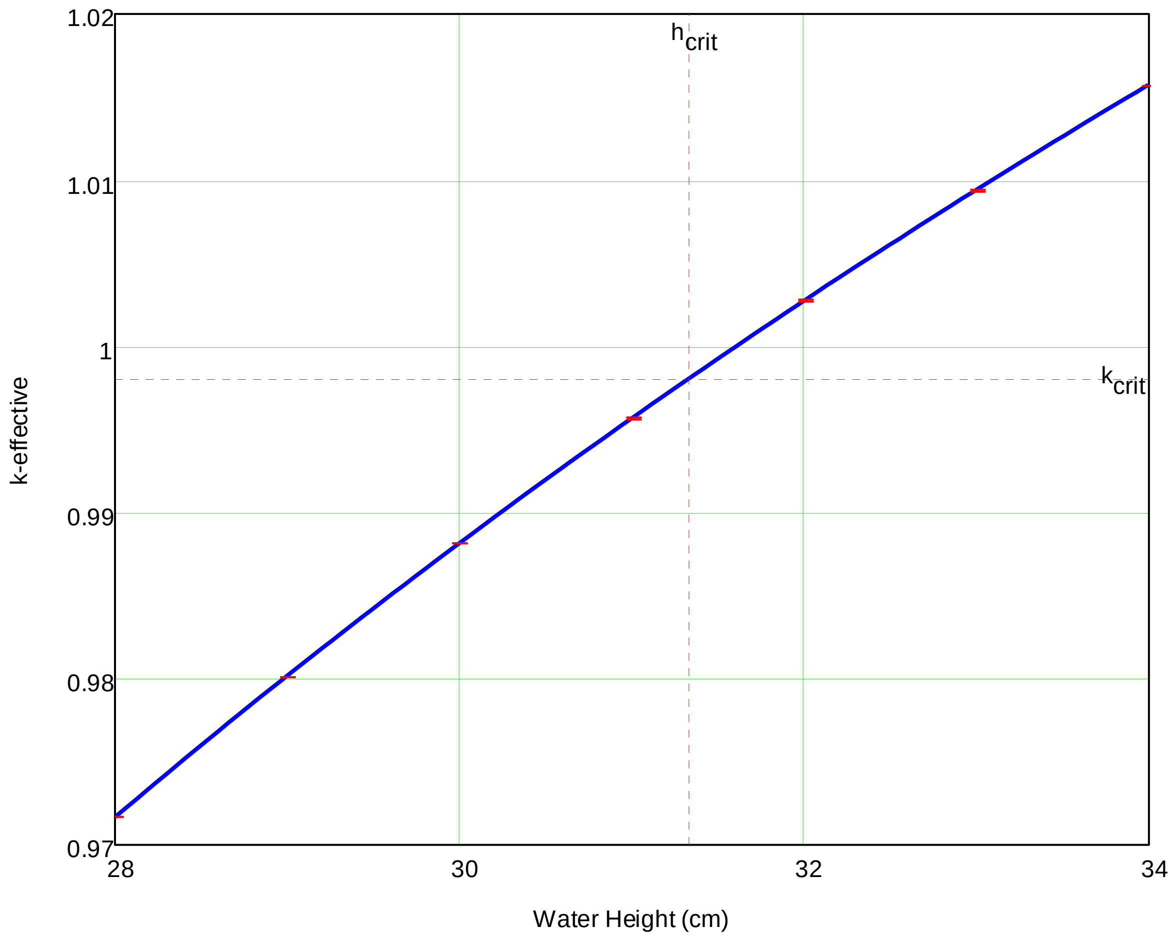

Figure 5. Calculated k_{eff} as a Function of the Moderator Height in Configuration 1.

Figure 6 shows similar data with the k_{eff} values converted to reactivity values assuming that a value of k_{crit} gives a delayed critical configuration. Here, h_{crit} is at the moderator height that has a reactivity of 0.

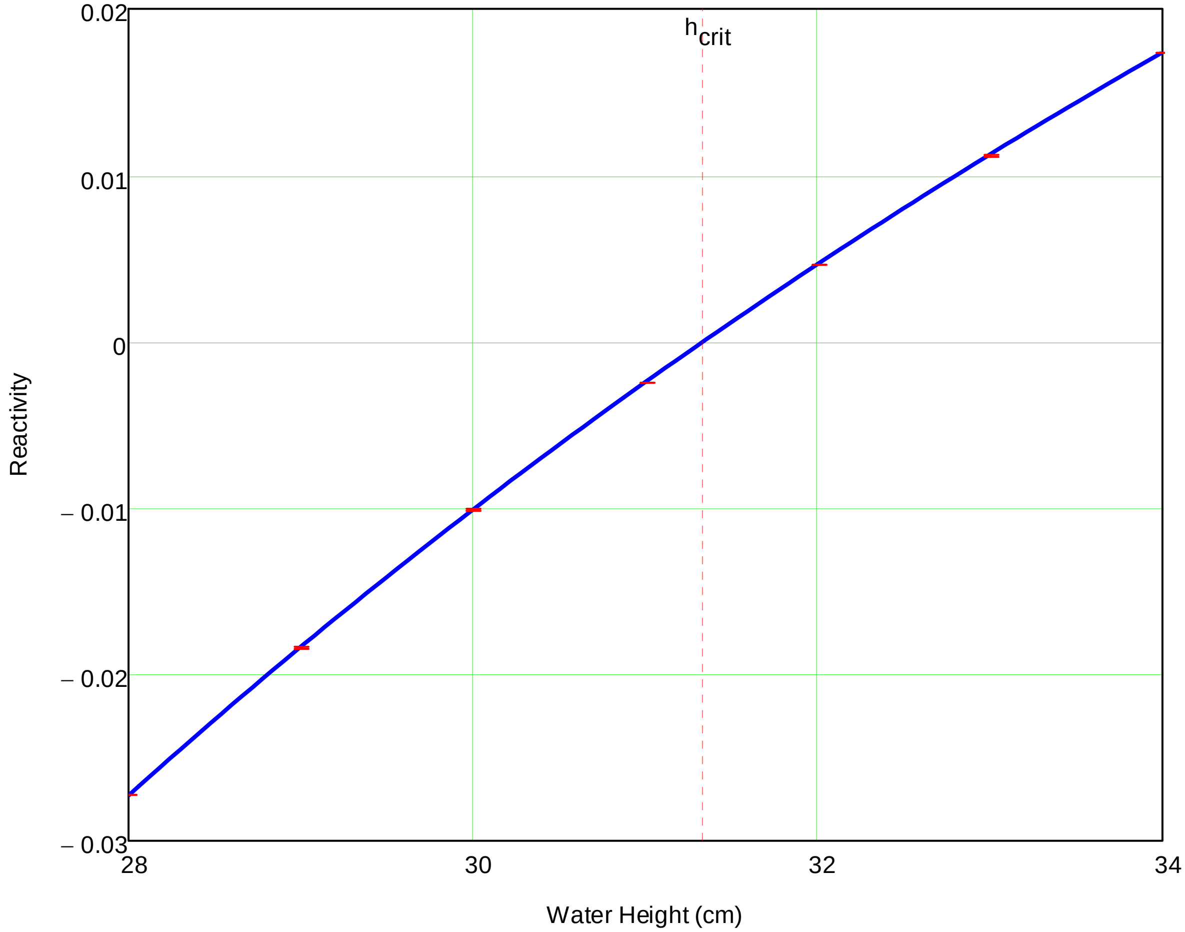

Figure 6. Reactivity as a Function of Moderator Height for Configuration 1.

The slope of the curve of reactivity versus water height at the critical water height gives the sensitivity of the k_{eff} of the assembly to the water height. For Configuration 1, the value of this sensitivity is 0.00072 per mm of water height.

Figure 7 shows the relationship between reactivity and water height for Configuration 2. Here the bias was developed from Case 1 of LCT080. In this case, the critical water height, h_{crit}, is 364.1 mm of water above the top of the bottom grid plate in the assembly.

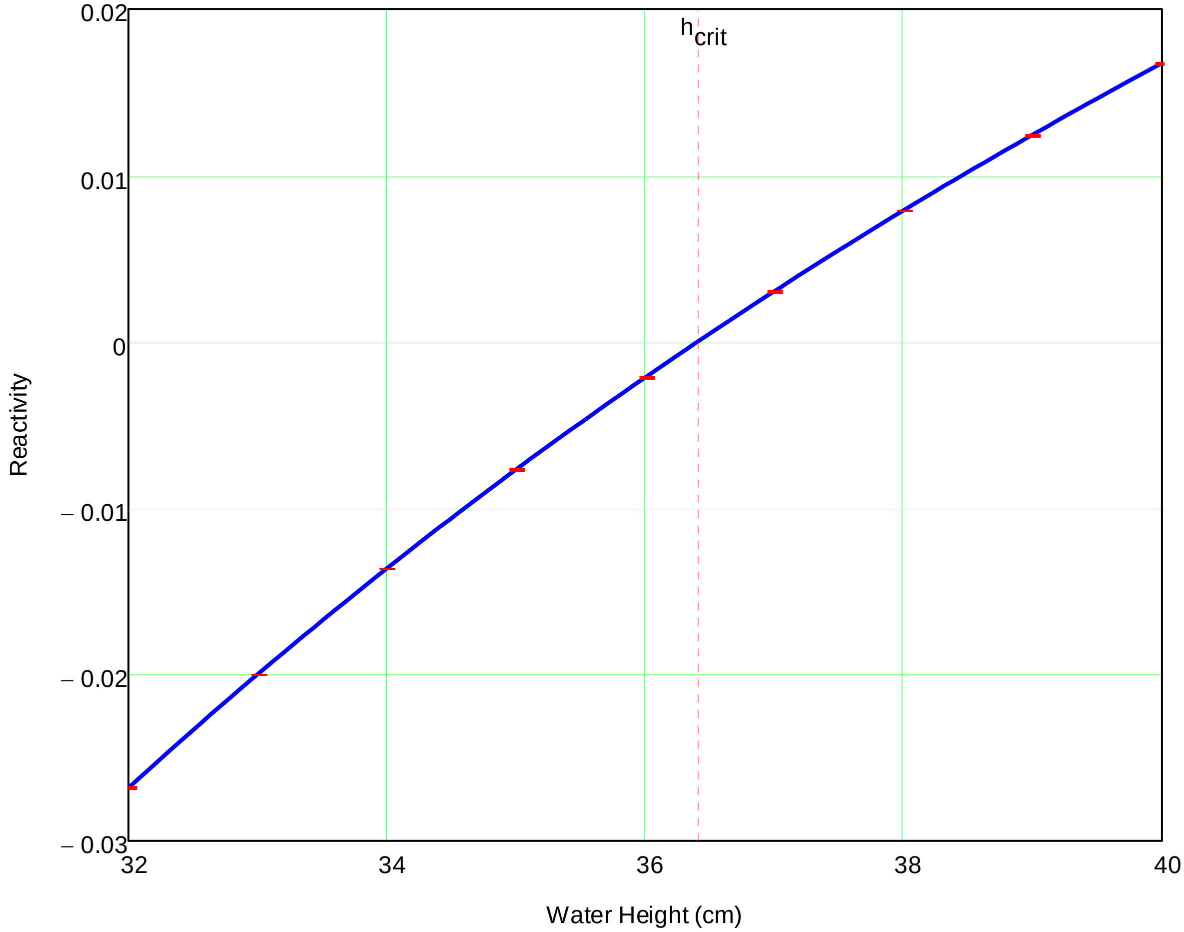

Figure 7. Reactivity as a Function of Moderator Height for Configuration 2.

The slope of the curve in Figure 7 at h_{crit} is the sensitivity of k_{eff} to the height of the moderator at delayed critical. For configuration 2, the value is 0.00052 per mm of water height

Configurations with Boron in the Moderator

Critical assembly configurations that were fully reflected, like the LCT080 experiments, with the fuel array fully loaded were examined to determine the concentration of dissolved boron in the moderator/reflector required to shim out the excess reactivity associated with the extra fuel in the assembly. These are the fully-loaded arrays envisioned in the NERI project. The first boron-poisoned configuration used the fuel rod layout shown in Figure 1. Figure 8 shows the reactivity of the assembly as a function of the concentration of boron dissolved in the moderator/reflector. The vertical dashed line labeled B_c is shown at the boron concentration that has a reactivity of zero. This is the critical boron concentration which occurs at 711 ppm boron by mass in the moderator/reflector. This configuration with the critical boron concentration will be referred to below as B0711.

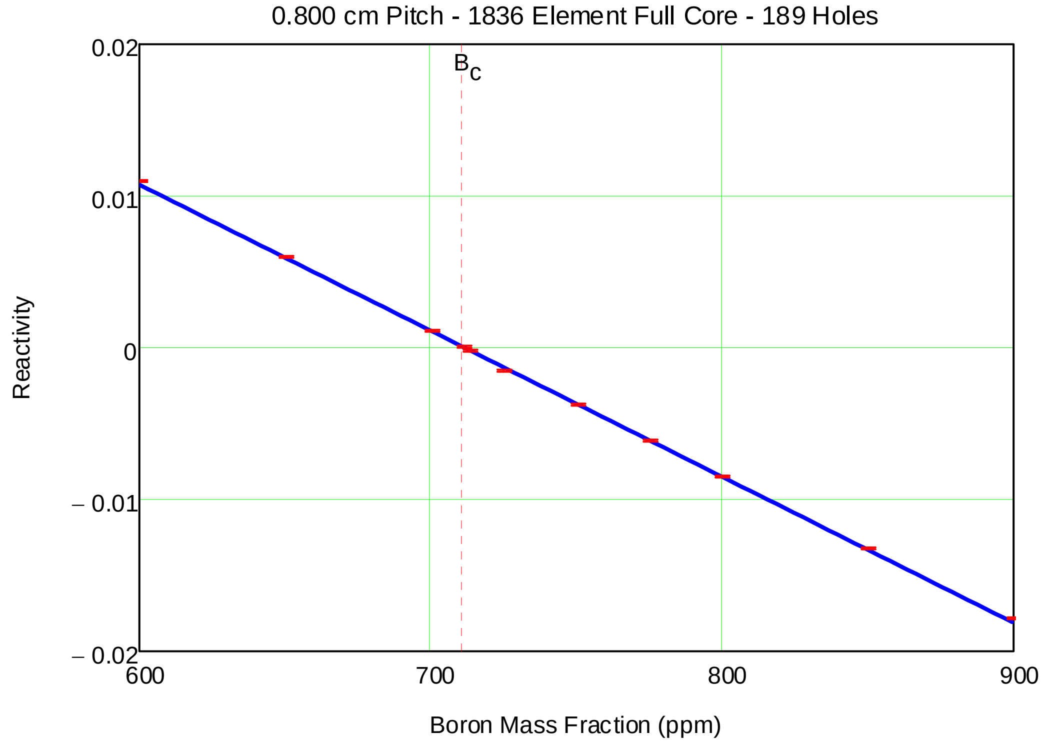

Figure 8. Reactivity as a Function of Boron Concentration in the Moderator/Reflector for Configuration B0711.

A similar configuration with all 2025 fuel rod positions filled was also investigated. Figure 9 shows the reactivity as a function of boron concentration in the moderator/reflector with the critical concentration of 456 ppm shown by the vertical dashed line. This configuration will be referred to below as B0456.

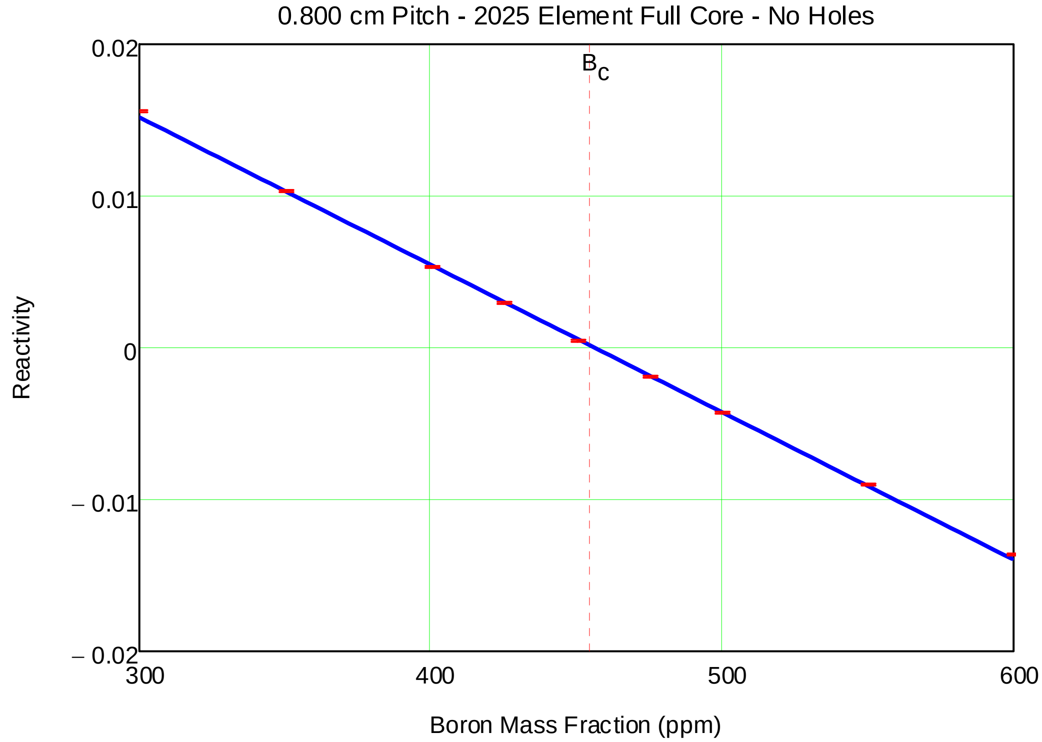

Figure 9. Reactivity as a Function of Boron Concentration in the Moderator/Reflector for Configuration B0456.

Spectral Comparisons

Figure 10 compares the neutron spectra calculated by KENO V.a using the 238-group cross sections from SCALE6.1.1 in configuration 1 with the neutron spectra in the boron-poisoned configuration B0711. For each configuration, the spectra in the fuel and the moderator in a fuel rod cell are plotted. All spectra are similar. The spectra in the fuel are slightly harder than the corresponding spectra in the cell moderator.

Figure 11 performs the same comparison for the spectra in Configuration 2 and in B0456. Again, all spectra are similar with the spectra in the fuel being slightly harder than the corresponding spectra in the cell moderator.

Table 1 presents a comparison of several neutron spectra that have been converted to 3-groups in the energy structure shown in the table. This is the same structure used for spectral comparisons in Reference 1. Also shown in the table is a comparison of the fraction of fissions in the assembly that are contributed by neutrons in each coarse group. Both sets of data are shown for the set of LCT080 Case 11, Configuration 1, and B0711 (corresponding configurations) and the set of LCT080 Case 1, Configuration 2, and B0456. The data show that the benchmark configurations from LCT080 have the softest neutron spectra in each set, the fully-reflected boron-poisoned configurations have the hardest, and the configurations with pure water moderator/reflector and the core tank incompletely filled between. The differences across each set, however, are small.

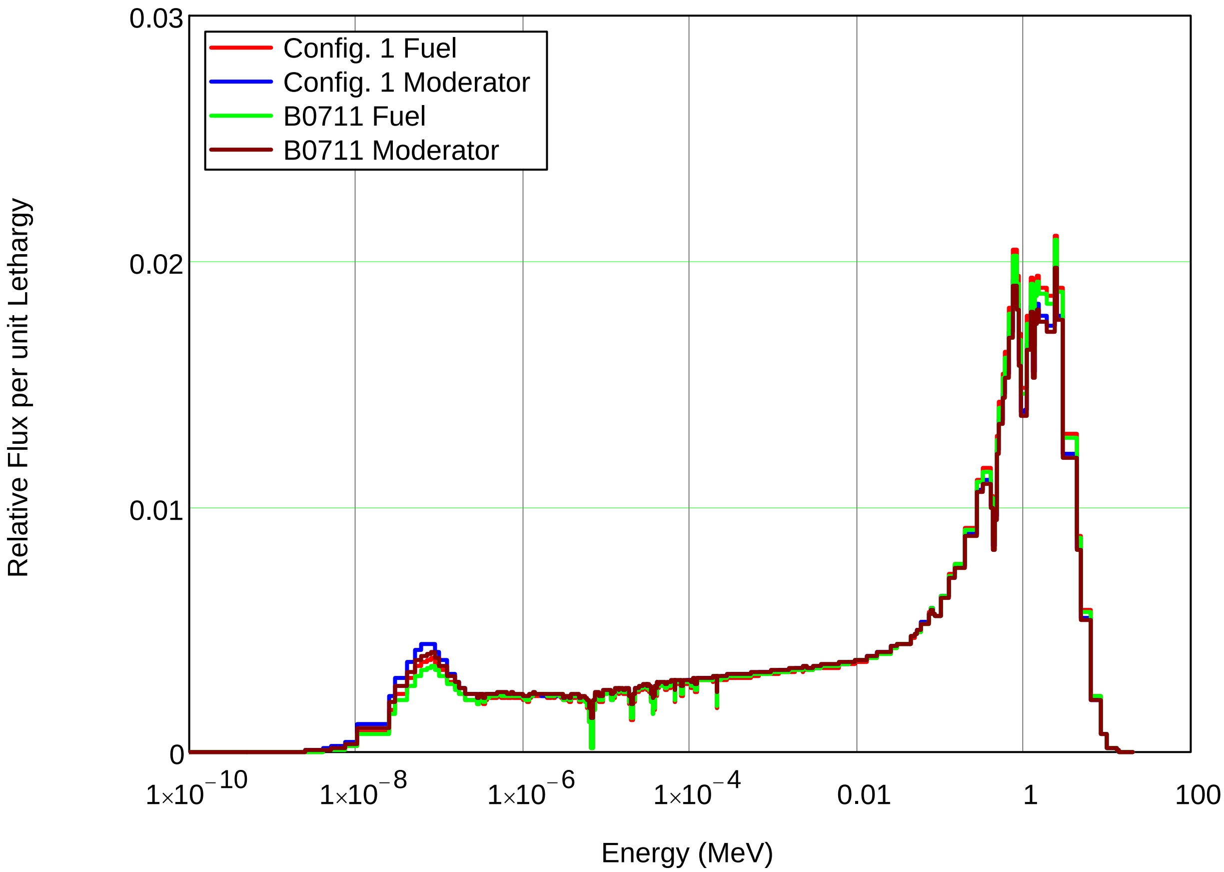

Figure 10. Comparison of the Neutron Spectra in the Fuel and the Moderator in the Fuel Rod Cells in Configuration 1 and the Corresponding System with Boron-Poisoned Moderator (B0711).

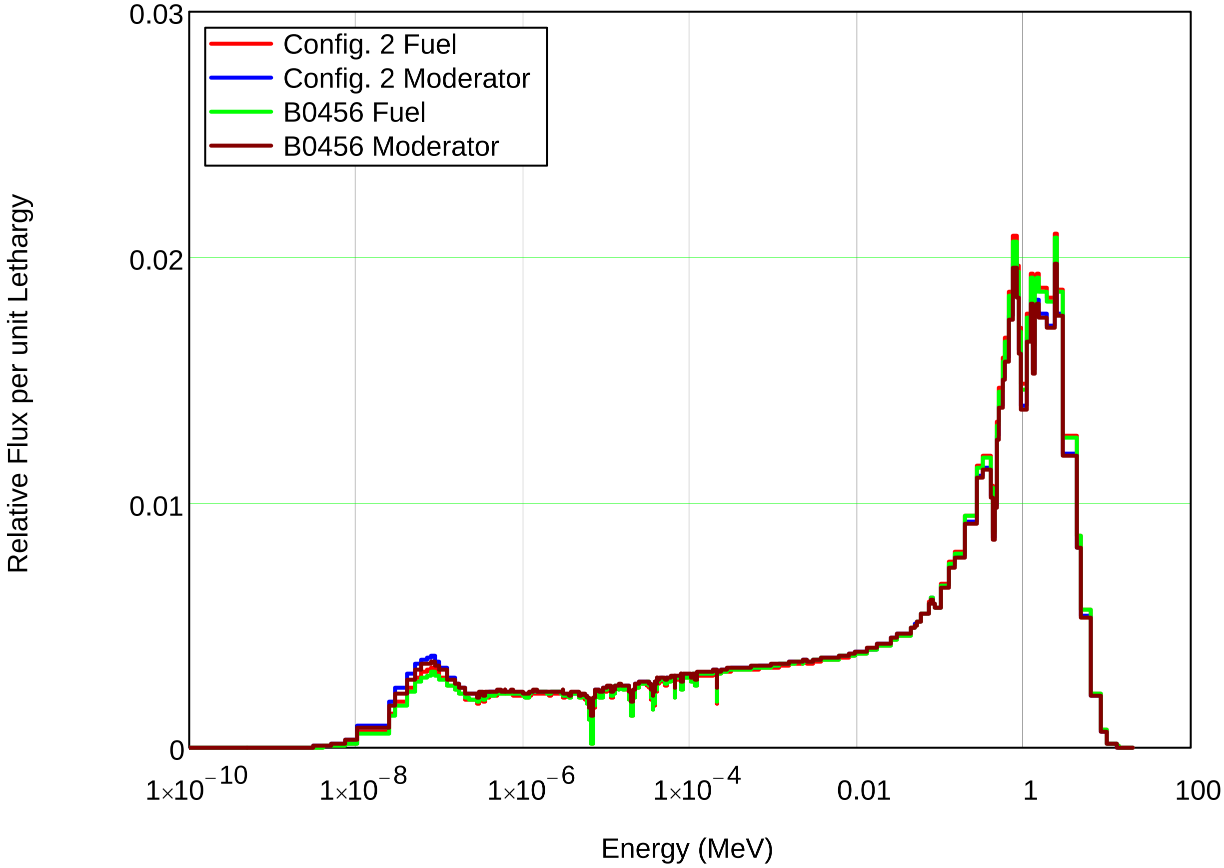

Figure 11. Comparison of the Neutron Spectra in the Fuel and the Moderator in the Fuel Rod Cells in Configuration 2 and the Corresponding System with Boron-Poisoned Moderator (B0456).

Table 1. Breakdown by Neutron Energy of the Neutron Spectrum and the Assembly Fissions for LCT080 Case 11 and Case 1, Configurations 1 and 2, and for B0711 and B0456.

Quantity	Configuration	Thermal [1]	Intermediate [2]	Fast [3]
Flux	LCT080 Case 11	9.8	36.0	54.2
	Configuration 1	9.5	36.3	54.2
	B0711	9.0	37.2	53.9
	LCT080 Case 1	8.5	36.9	54.6
	Configuration 2	8.2	37.2	54.6
	B0456	8.0	37.7	54.4
Fissions	LCT080 Case 11	79.3	14.4	6.4
	Configuration 1	77.3	15.5	7.2
	B0711	76.5	16.5	7.0
	LCT080 Case 1	76.2	16.6	7.2
	Configuration 2	74.5	17.6	7.9
	B0456	74.0	18.3	7.7

[1] Thermal: $E < 0.625$ eV
[2] Intermediate: $0.625 \text{ eV} < E < 100 \text{ keV}$
[3] Fast: $100 \text{ keV} < E$

These calculations were performed with KENO V.a from the SCALE6.1.1 package using the 238-group cross sections derived from ENDF/B-VII.0.

Material Sensitivities

The SCALE 6.1.1 sequence TSUNAMI was used to calculate the material sensitivities in Cases 11 and 1 of LEU-COMP-THERM-080, Configurations 1 and 2 described above, and the two boron-poisoned fully-reflected configurations B0711 and B0456. A comparison of the material sensitivities for Configuration 1 and B0711 is shown in Table 2. The last column shows the ratio of the sensitivity of each material in Configuration 1 to the sensitivity of the same material in B0711. Table 3 shows a similar comparison for Configuration 1 and LCT080 Case 11. Table 4 shows the comparison for Configuration 2 and B0456 and Table 5 shows the comparison for Configuration 2 and Case 1 of LCT080.

Table 2. Comparison of the Material Sensitivities of Configuration 1 and B0711.

Material	Configuration 1		B0711		Ratio
	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Config 1/B0711
UO_2 Fuel	9.808E-02	0.4%	1.195E-01	0.3%	0.80
Clad	9.167E-03	0.9%	7.390E-03	1.0%	1.24
Moderator	4.290E-01	0.5%	3.664E-01	0.5%	1.18
Grid Plates	5.347E-03	1.1%	3.499E-03	0.8%	1.50
Fuel Springs	7.280E-06	4.1%	-4.696E-05	5.0%	-0.16
Reflector	2.824E-02	24.7%	1.188E-02	17.8%	2.37

Table 3. Comparison of the Material Sensitivities of Configuration 1 and Case 11 of LCT080.

Material	Configuration 1		LCT080 Case 11		Ratio
	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Config 1/Case 11
UO_2 Fuel	9.808E-02	0.4%	8.044E-02	0.5%	1.22
Clad	9.167E-03	0.9%	6.147E-03	1.2%	1.49
Moderator	4.290E-01	0.5%	4.105E-01	0.5%	1.05
Grid Plates	5.347E-03	1.1%	2.543E-03	1.3%	2.10
Fuel Springs	7.280E-06	4.1%	-1.382E-04	2.3%	-0.05
Reflector	2.824E-02	24.7%	3.796E-02	21.1%	0.74

Table 4. Comparison of the Material Sensitivities of Configuration 2 and B0456.

Material	Configuration 2		B0456		Ratio
	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Config 2/B0456
UO_2 Fuel	8.253E-02	0.5%	9.334E-02	0.4%	0.90
Clad	9.240E-03	0.8%	8.157E-03	1.0%	1.14
Moderator	4.229E-01	0.5%	3.913E-01	0.5%	1.07
Grid Plates	4.700E-03	1.1%	3.655E-03	0.9%	1.21
Fuel Springs	1.432E-05	3.4%	-8.810E-05	3.3%	-0.13
Reflector	2.574E-02	27.0%	1.419E-02	21.4%	1.83

Table 5. Comparison of the Material Sensitivities of Configuration 2 and Case 1 of LCT080.

Material	Configuration 2		LCT080 Case 1		Ratio
	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Config 2/Case 1
UO_2 Fuel	8.253E-02	0.5%	7.448E-02	0.6%	1.11
Clad	9.240E-03	0.8%	7.015E-03	1.2%	1.32
Moderator	4.229E-01	0.5%	4.008E-01	0.5%	1.06
Grid Plates	4.700E-03	1.1%	2.931E-03	1.3%	1.60
Fuel Springs	1.432E-05	3.4%	-1.571E-04	2.3%	-0.09
Reflector	2.574E-02	27.0%	3.559E-02	22.7%	0.72

A ranking of the k_{eff} sensitivities listed in Tables 2 through 5 from highest to lowest is moderator, UO_2 fuel, reflector, clad, grid plates, and fuel springs. Table 6 repeats the sensitivity ratios for the two configurations compared with Configuration 1 taken from the last columns of Tables 2 and 3. Table 7 repeats the sensitivity ratios for the two configurations compared with Configuration 2 taken from the last columns of Tables 4 and 5.

Table 6. Ratio of the Material Sensitivities of Configuration 1 to B0711 and LCT080 Case 11.

Material	B0711 Sensitivity Ratio	LCT080 Case 11 Sensitivity Ratio
UO_2 Fuel	0.80	1.22
Clad	1.24	1.49
Moderator	1.18	1.05
Grid Plates	1.50	2.10
Fuel Springs	-0.16	-0.05
Reflector	2.37	0.74

Table 7. Ratio of the Material Sensitivities of Configuration 2 to B0456 and LCT080 Case 1.

Material	B0456 Sensitivity Ratio	LCT080 Case 1 Sensitivity Ratio
UO_2 Fuel	0.90	1.11
Clad	1.14	1.32
Moderator	1.07	1.06
Grid Plates	1.21	1.60
Fuel Springs	-0.13	-0.09
Reflector	1.83	0.72

The material k_{eff} sensitivities of Configurations 1 and 2 to the moderator are somewhat higher than for the boron-poisoned configurations B0711 and B0456 and nearly the same as for the LCT080 configurations. The k_{eff} sensitivities of Configurations 1 and 2 to the UO_2 fuel are somewhat lower than for the boron-poisoned configurations and higher than for the comparable LCT080 configurations. Configurations 1 and 2 are more sensitive to the reflector than the corresponding boron-poisoned configurations by about a factor of two. They are less sensitive to the reflector than the LCT080 configurations. Configurations 1 and 2 are slightly more sensitive to the clad material than either of the corresponding boron-poisoned and LCT080 configurations.

The grid plate and fuel spring sensitivities are small for all configurations. Of academic note (but little practical value) is the fact that the k_{eff} sensitivity of the fuel spring material has the opposite sign in configurations 1 and 2 from the corresponding boron-poisoned and LCT080 configurations. This occurs because the springs are outside the effective fueled volume and part of the reflector for Configurations 1 and 2 while they are between the fueled volume and the reflector in the other configurations.

The sensitivity comparisons shown above indicate that the proposed configurations are not wildly different from the corresponding boron-poisoned and LCT080 configurations. It is possible to meet the NERI project goal of performing experiments in the fully-loaded 45x45 array with material sensitivities that are similar to the material sensitivies in the poisoned experiments.

Experiment Uncertainties

Table 8 gives a comparison of the expected benchmark k_{eff} uncertainties in Configuration 1 with the benchmark k_{eff} uncertainties determined for LCT080 Case 11. In addition, the sensitivity of the proposed configurations to the moderator/reflector height was combined with an assumed uncertainty in the measured height of 0.5 mm to obtain a k_{eff} uncertainty associated with height measurement uncertainties. The corresponding k_{eff} uncertainty in the LCT080 benchmarks was zero because they were fully reflected. The last entry for each configuration gives the overall k_{eff} uncertainty. For both configurations, this is the sum in quadrature of all the components. The estimated benchmark k_{eff} uncertainty for the proposed Configuration 1 is numerically identical the value given for LCT080 Case 11 to the precision shown.

Table 8. Comparison of the Expected Benchmark k_{eff} Uncertainties for Configuration 1 with Those for LCT080 Case 11.

Uncertainty Source	Configuration 1 Δk_{eff}	LCT080 Case 11 Δk_{eff}
Pitch of Fuel Rods	0.00060	0.00076
Clad OD	-0.00010	-0.00010
Clad ID	-0.00002	-0.00001
Fuel Pellet OD	0.00000	0.00000
Water Depth	0.00036	0.00000
Rod Fuel Mass	0.00002	0.00002
Rod Fuel Length	-0.00010	0.00005
Enrichment	0.00012	0.00012
^{234}U	-0.00001	-0.00001
^{236}U	-0.00001	-0.00001
UO_2 Stoichiometry	-0.00058	-0.00048
Measured Fuel Impurities	-0.00010	-0.00012
Undetected Fuel Impurities	-0.00004	-0.00006
Clad Composition	-0.00023	-0.00027
Grid Plate Composition	-0.00018	-0.00011
Water Composition	-0.00003	-0.00014
Temperature	-0.00008	-0.00005
Sum in Quadrature	**0.00098**	**0.00098**

Table 9 provides a similar k_{eff} uncertainty comparison between Configuration 2 and LCT080 Case 1. Again, the estimated benchmark k_{eff} uncertainty for the proposed Configuration 2 is similar to the value given for LCT080 Case 1.

Table 9. Comparison of the Expected Benchmark k_{eff} Uncertainties for Configuration 2 with Those for LCT080 Case 1.

Uncertainty Source	Configuration 2 Δk_{eff}	LCT080 Case 1 Δk_{eff}
Pitch of Fuel Rods	0.00070	0.00078
Clad OD	-0.00012	-0.00012
Clad ID	-0.00002	-0.00002
Fuel Pellet OD	-0.00001	0.00000
Water Depth	0.00026	0.00000
Rod Fuel Mass	0.00002	0.00002
Rod Fuel Length	-0.00008	0.00006
Enrichment	0.00012	0.00012
^{234}U	-0.00001	-0.00001
^{236}U	-0.00001	-0.00001
UO_2 Stoichiometry	-0.00053	-0.00045
Measured Fuel Impurities	-0.00009	-0.00013
Undetected Fuel Impurities	-0.00004	-0.00007
Clad Composition	-0.00022	-0.00028
Grid Plate Composition	-0.00016	-0.00013
Water Composition	-0.00001	-0.00023
Temperature	-0.00007	-0.00005
Sum in Quadrature	**0.00098**	**0.00101**

Assembly Modifications for the Proposed Experiments.

Figure 12 shows details of the existing moderator level control and moderator level measurement standpipes on the critical assembly. The large black tube on the right of the figure has a variable-height overflow inside the tube. The height of the overflow tube is set by the control mechanism that can be seen at the top of the black tube. The level measurement stand pipe is on the left of the figure. An ultrasonic level measurement system is inside that standpipe. Both standpipes are connected to the bottom of the core tank. Some of that plumbing is visible in the figure. The level control standpipe is mounted on the dump tank of the assembly. Moderator that overflows through the standpipe exits directly into the dump tank.

Figure 12. Photograph of the Critical Assembly showing the Moderator Level Control Standpipe and the Moderator Level Measurement Standpipe.

Moderator Level Control

The 7uPCX critical assembly has the capability to perform experiments with moderator/reflector height as the free parameter. In order to perform the proposed experiments, it will be necessary to modify the variable overflow standpipe to accommodate the range of levels needed to perform these experiments. This will be done by modifying the design of the internals of the moderator level control standpipe. The modifications have been designed and will be implemented when the project is authorized to move forward.

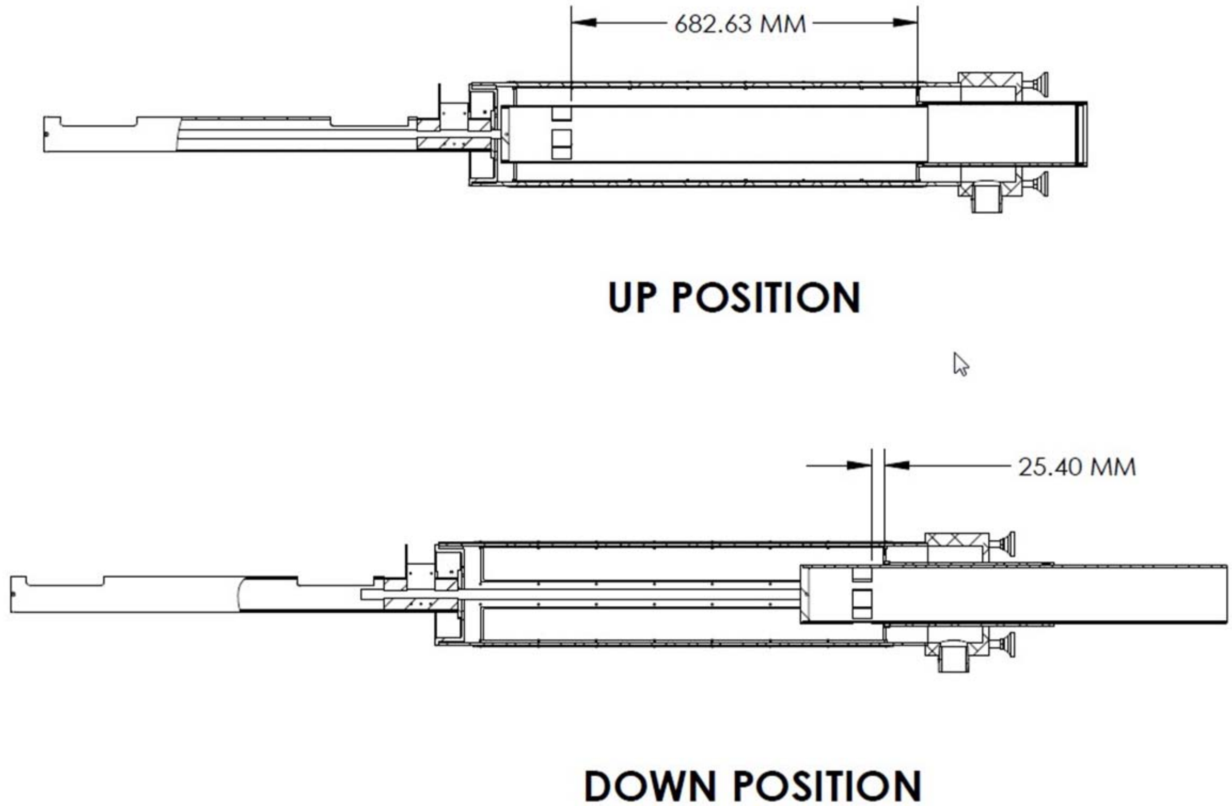

Figure 13. Sketch of the Redesigned Moderator Level Control Standpipe.

Moderator Level Measurement

The assembly has a moderator level measurement system that was installed in the late 1980s and is currently operable. It has a readout resolution of 0.1 mm on the moderator height and is believed to be linear from experience gained in that period. It is not currently calibrated to the accuracy needed to perform benchmark measurements of the water height. A method will be required to calibrate this system relative to the moderator height at the center of the assembly core. Though this existing system appears to be functional currently, the addition of a new system to perform the same measurement with components known to be currently available may be considered.

A method for the calibration of the moderator level measurement system will be required. To keep the k_{eff} uncertainty introduced by uncertainties in the level measurement system from significantly affecting the overall experiment uncertainty, this k_{eff} uncertainty should be kept below about 0.0005 (about half of the total LCT080 uncertainties) if possible. Using the sensitivities of k_{eff} to the moderator height given previously (0.00072 mm^{-1} for Configuration 1 and 0.00052 mm^{-1} for Configuration 2), the accuracy required of the level measurement system is about 0.7 mm for Configuration 1 and about 1 mm for Configuration 2. These accuracies seem to be well within the capability of the existing level measurement system and will be used to specify the minimum accuracy required for any new system.

An ultrasonic detection system with the specifications to achieve the desired accuracy has been identified. A calibration protocol for the system has been determined. A single level detection system has been ordered and will be tested to determine whether it can be calibrated to meet the needed accuracy and reproducibility levels.

By design, the bottom of the fuel column in the 7uPCX fuel rods is at the same elevation as the top of the lower grid plate. The water level in the critical assembly is measured relative to the top of the lower grid plate. Currently the water level is measured in a stand pipe on the outside of the core tank. The crucial quantity in the geometry of a water-level benchmark experiment is the average water depth across the core tank. Assumptions are necessary that the water level is parallel to the reference surface on the lower grid plate. With the water-level measurement being made at the outside the core tank, it is essential that the water level measurement be calibrated relative to the center of the core. It is also necessary that the lower grid plate be level and that this be verified during the experiments.

One way to accomplish the necessary level measurement and level verification is to have several calibrated level sensors at the outside of the core. The current plan is to measure the level of the moderator at more than one point around the core in stand pipes near the wall of the core tank.

The stand pipes are necessary to limit wave action at the sensor during core filling operations. The stand pipes will be designed to rest on the lower grid plate with openings at the bottom to admit moderator during filling. Because the ultrasonic level detectors will respond to either the water surface or the surface of the grid plate, the detectors can be zeroed with no moderator above the lower grid plate. The fabrication of a number of gages that set a detection surface a calibrated distance above the lower grid plate is planned. In this way, the level detection system can be calibrated and checked for linearity. With multiple calibrated systems around the periphery of the core tank, the system level can be checked and the moderator level at the center of the core determined by averaging the measurements.

Biases

The proposed experiments are expected to behave similarly to the experiments documented in LCT080. However, because the proposed experiments will not be fully reflected, it is expected that the surroundings of the assembly could affect the k_{eff} results of the experiments. A more detailed description of the assembly surroundings than was given in LCT080 will be required.

Critical Assembly Surroundings

The LCT080 configurations were fully reflected with at least 6 inches of water in all directions from the core. A simple but conservative analysis was used in the evaluation to show that the surroundings of the assembly did not affect k_{eff} in the assembly. In the proposed experiments, the fact that the moderator level is well below the top of the fuel column exposes parts of the assembly fuel directly to the effects of reflection from the reactor room walls, ceiling, and floor. The detailed MCNP model of the assembly was modified to include the reactor room floor, ceiling, and walls. The reactivity difference between k_{eff} calculated with and without the reactor room are shown in Table 9. The reactivity difference is less than 0.0001 for both configurations.

This small bias can be taken into account in the benchmark model k_{eff} for the proposed benchmark configurations.

Upper Assembly Parts

Some of the upper details of the assembly were eliminated from the LCT080 benchmark models because there was a significant amount of water reflector between the active fuel in the core and those parts. The LCT080 benchmark models were modified to include the lower water heights of configurations 1 and 2. The reactivity difference between these models and the detailed models of the assembly are also shown in Table 10. The reactivity differences are larger than for the effects of the reactor room but small nonetheless. The small values obtained can be accommodated in the benchmark model k_{eff} without significant effects on the neutron spectrum of the benchmark model.

Table 10. k_{eff} Bias From Two Major Model Simplifications

Simplification	Configuration 1		Configuration 2	
	Δk_{eff}	Uncertainty	Δk_{eff}	Uncertainty
Remove Reactor Room	-0.00005	0.00003	-0.00008	0.00003
Use LCT080 Benchmark Model Simplifications	0.00024	0.00003	0.00014	0.00003

Compliance with C_EdT Manual Requirements

Table 5.1 in the C_EdT manual [Reference 6] provides an example of required input and calculated values for design, execution and documentation of criticality (k_{eff}) measurement experiments. Table 11 replicates the columns of the table applicable to the current CED-2 status for IER-208. Also shown in the table is a brief response for this IER.

Table 11. C_EdT Manual Example Requirements for CED-2 of a Criticality Measurement Experiment. The first and second columns are replicated from Table 5.1 of the manual.

Input Parameters	**Final Design CED-2** [d]	**Notes**
Masses (m, σ_m)	✓, ✓	Values and uncertainties are included in the LCT080 evaluation.
Compositions (N, σ_N)	✓, ✓	Values and uncertainties are included in the LCT080 evaluation.
Dimensions (x, σ_x)	✓, ✓	Most values and uncertainties are included in the LCT080 evaluation. The exception is the measurement of the moderator height which is discussed above.
Positions (y, σ_y)	✓, ✓	Values and uncertainties are included in the LCT080 evaluation.
Calculated Parameters	**Final Design CED-2** [d]	
Eigenvalue (k_{eff}, σ_k)	✓, ✓	Critical moderator heights are estimated above. Experiment uncertainties are estimated above. The differences from the LCT080 biases are also discussed.
Material Worth [a] (Δk_{eff}, $\sigma_{\Delta k}$)	✓, ✓ [a]	Material sensitivities are discussed above. Because there is no investigation of a particular material, no material worths are calculated.
Neutron Energy Spectrum	✓	
Neutron Balance [b, c] (by Isotope, Region)	✓ [c]	
Isotope Sensitivities [c] (by Reaction)	✓ [c]	SCALE models available for use in TSUNAMI, if desired.

Notes a through c are from the table in the reference.
[a] If relevant.
[b] Production, Absorption and Leakage Fractions.
[c] Perhaps not required, but desirable.
[d] The first check mark indicates the value is required. A second check mark, if present, indicates the uncertainties in the parameter are required.

Conclusion

Integral Experiment Request 208 considers critical experiments in the 7uPCX assembly with fuel arrays larger than the fully-reflected arrays considered in LCT080 with the assembly reactivity controlled by the moderator/reflector height in the assembly. The analysis presented here shows that, given a moderator/reflector measurement system calibrated to the accuracy discussed, such experiments can be performed with acceptably low k_{eff} uncertainties. As part of this work, a benchmark-quality critical experiment capability will be developed that uses the height of the moderator/reflector in a lattice fuel array as the approach variable.

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