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Critical and Subcritical Experiment Design Team (C_EdT)

Integral Experiment Request 208
CED-1 Summary Report

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Richard D. McKnight (ANL), C_EdT NDAG Member
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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.

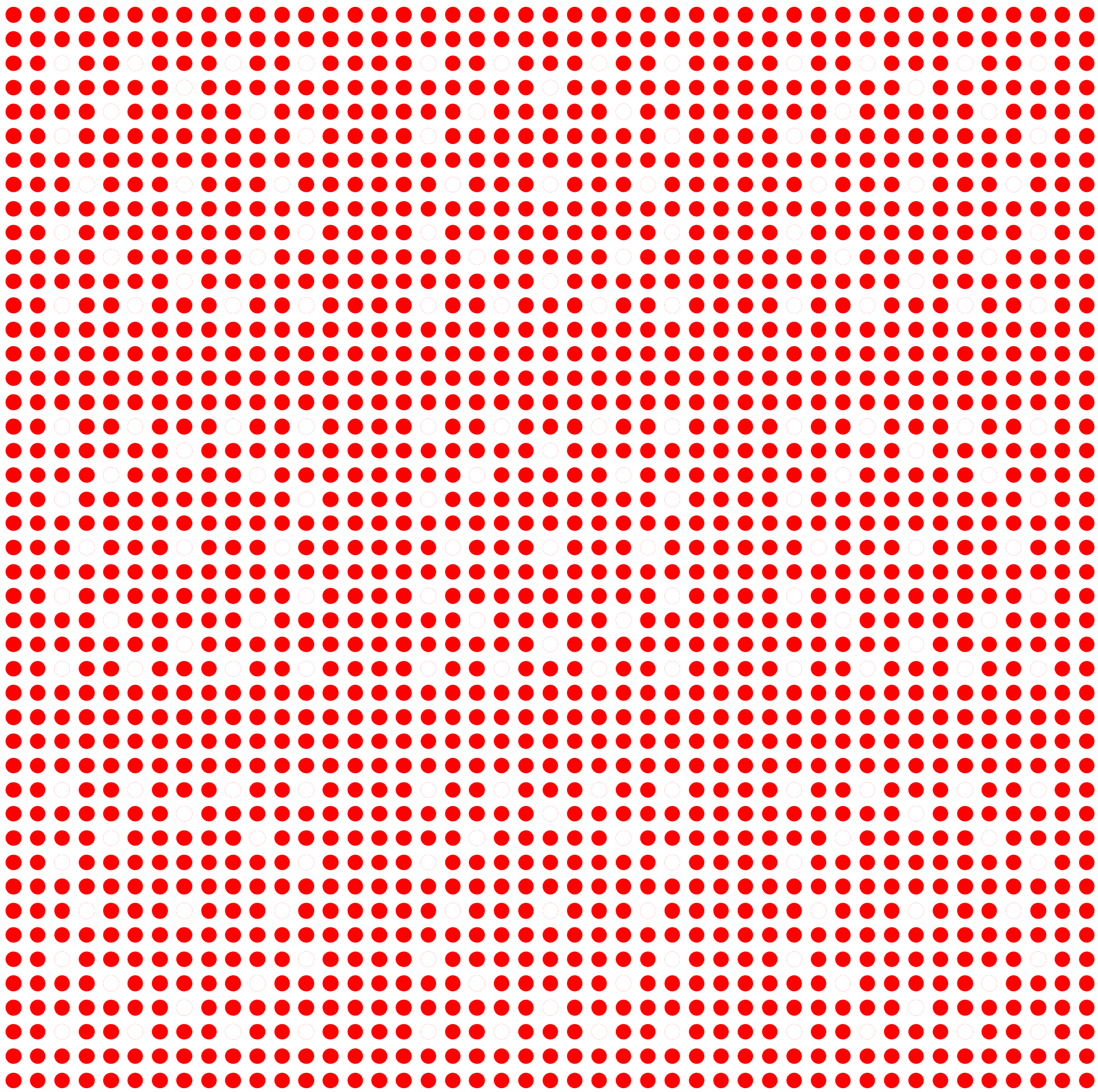

Figure 1. Fuel Rod Lay-Out Simulating a 3x3 Array of 15x15 PWR Fuel Elements.

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.

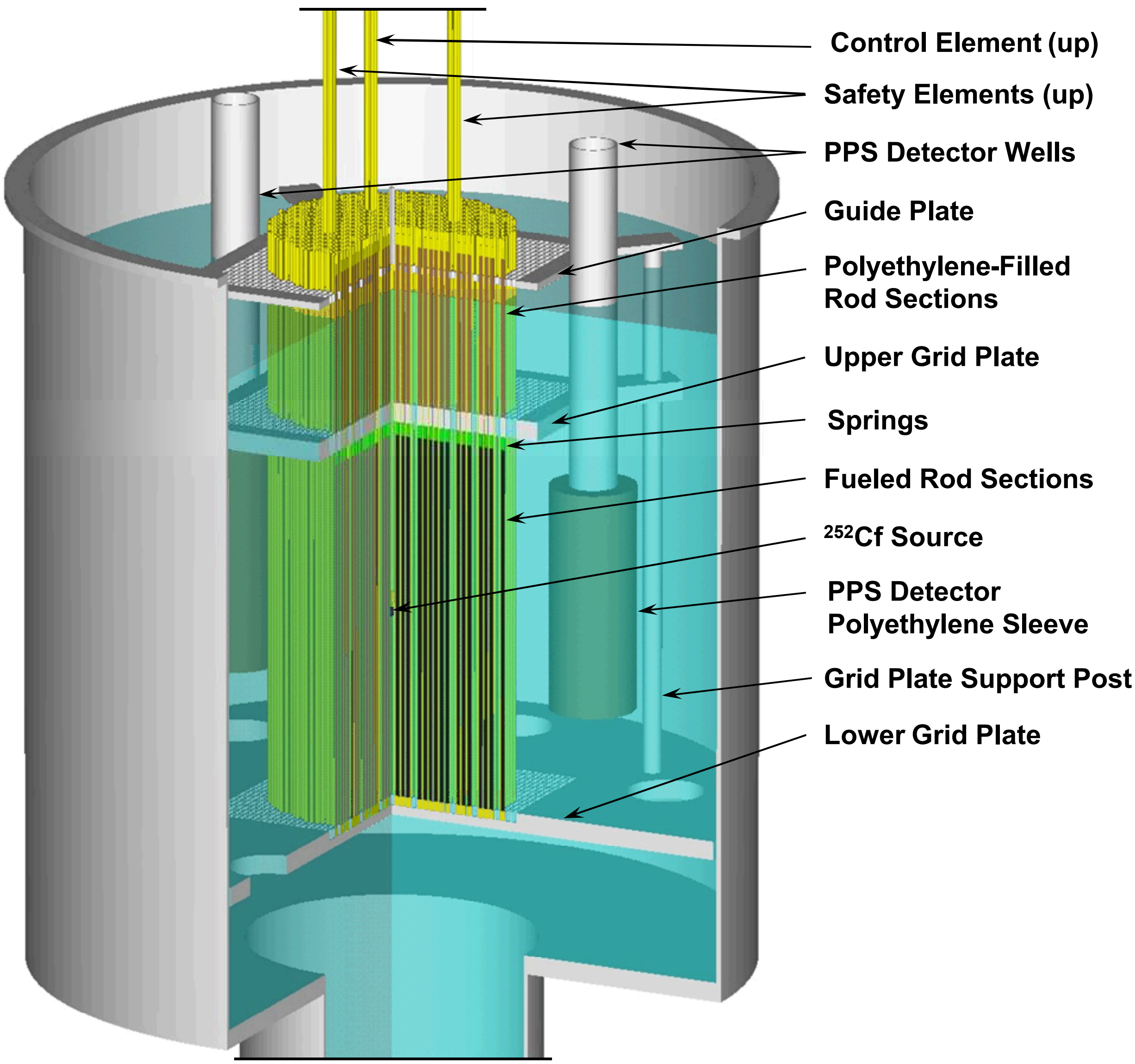

Figure 2. Critical Assembly Concept of the 7uPCX.

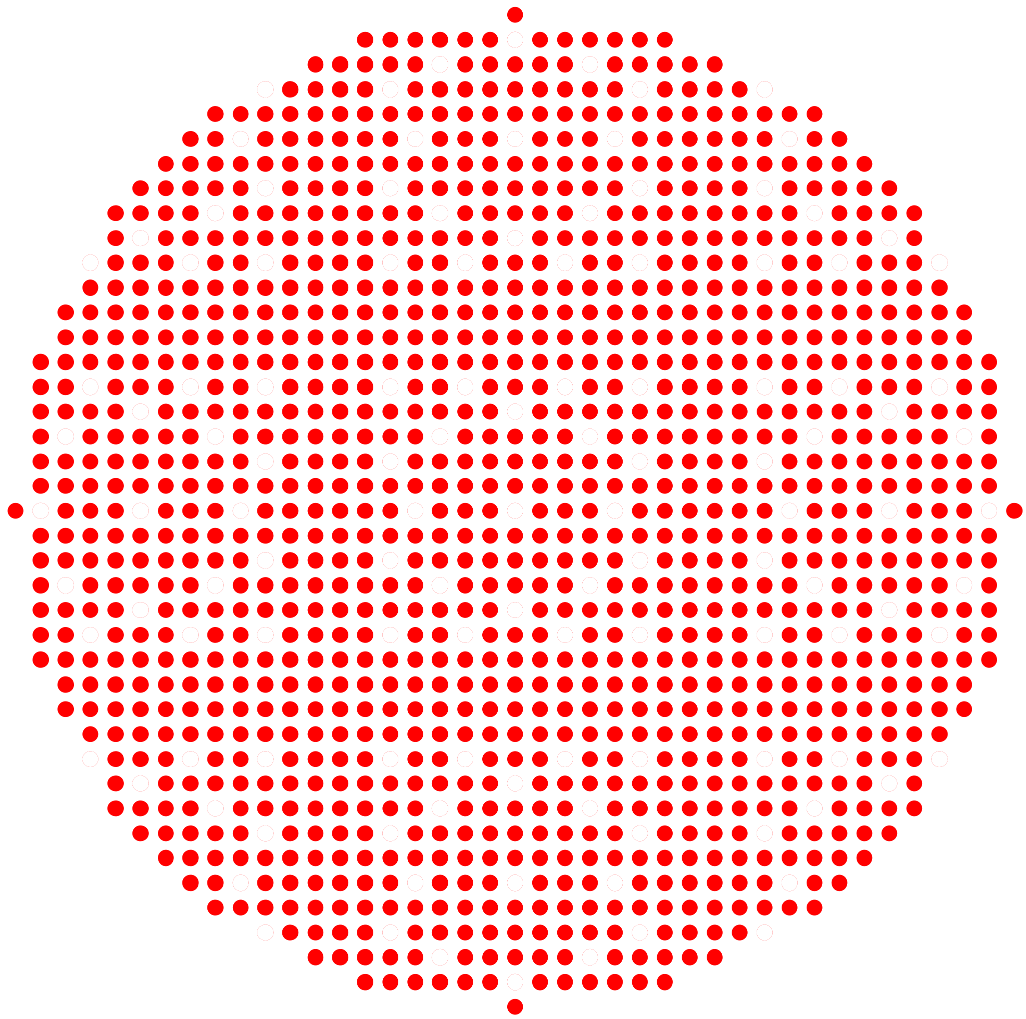

Figure 3. Fuel Rod Layout in Case 11 of LCT080.

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.

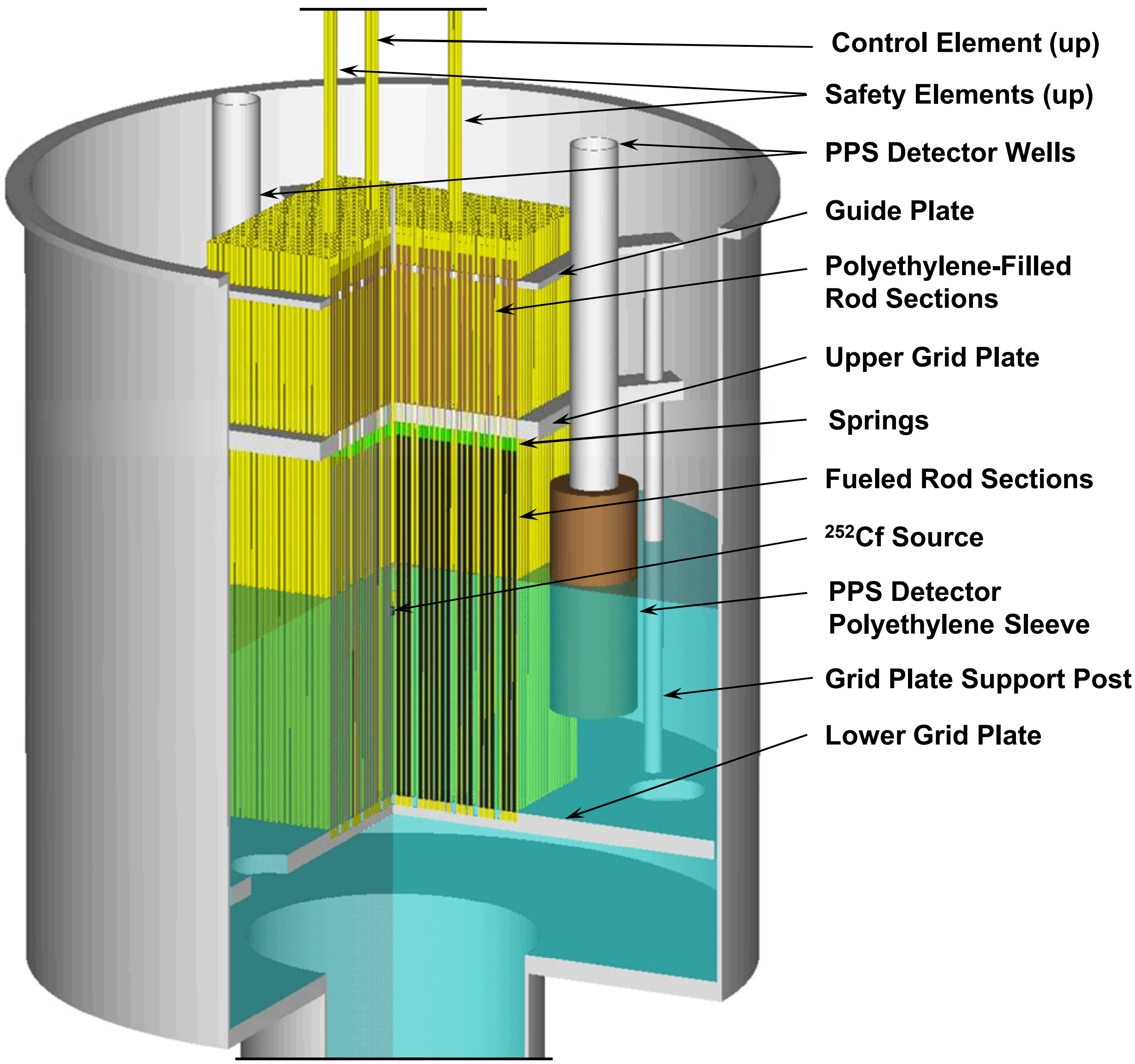

Figure 4. Critical Assembly Concept With the Array Fully Loaded.

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.

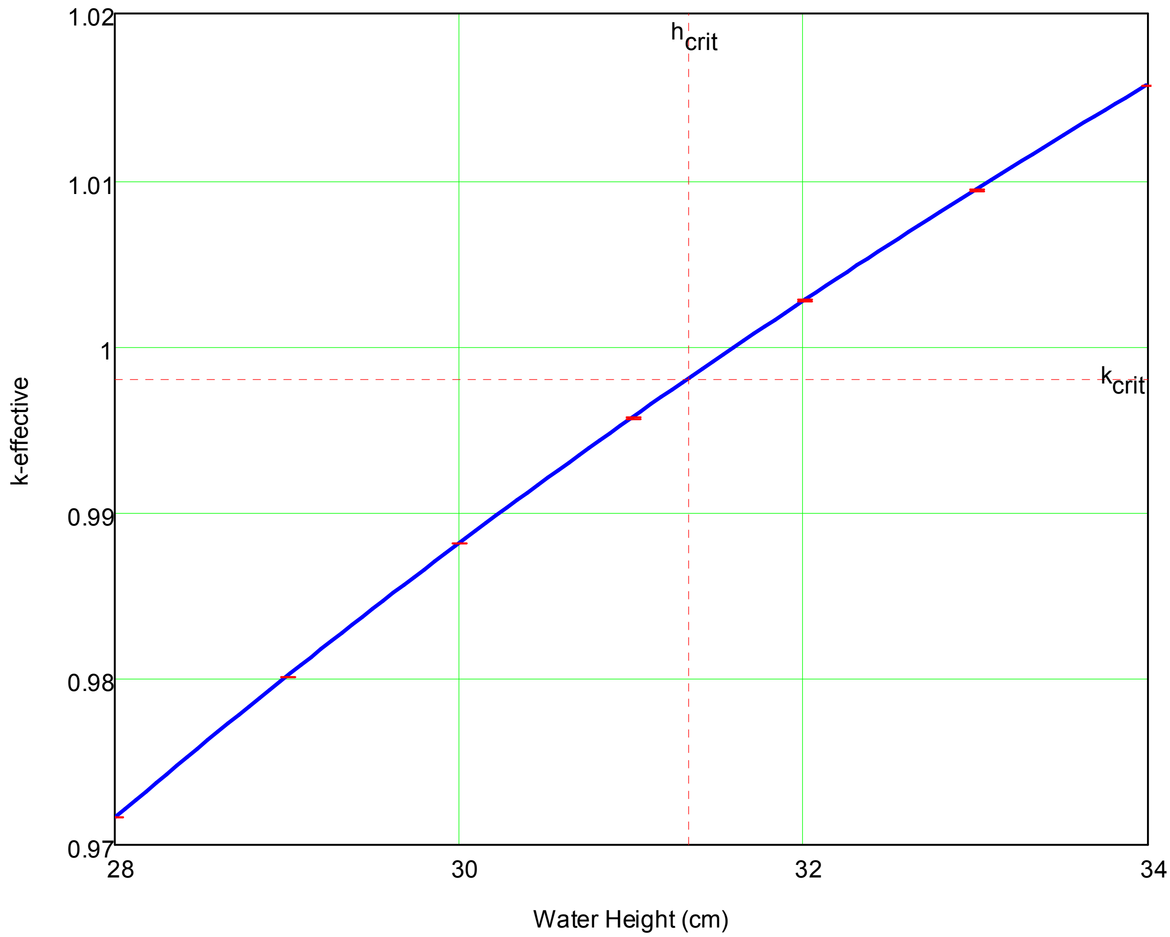

Figure 5. Calculated k_{eff} as a Function of the Moderator Height in Configuration 1.

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.

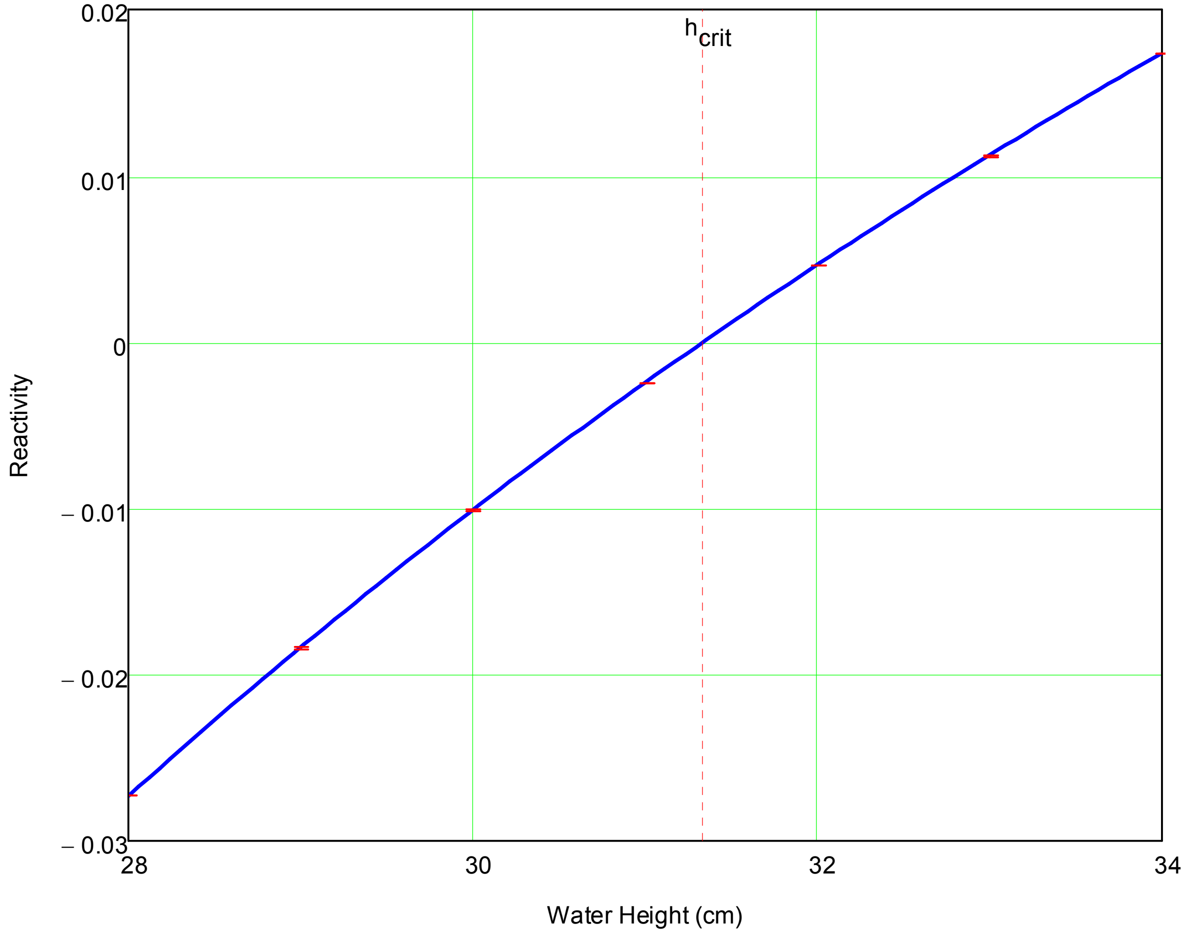

Figure 6. Reactivity as a Function of Moderator Height for Configuration 1.

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

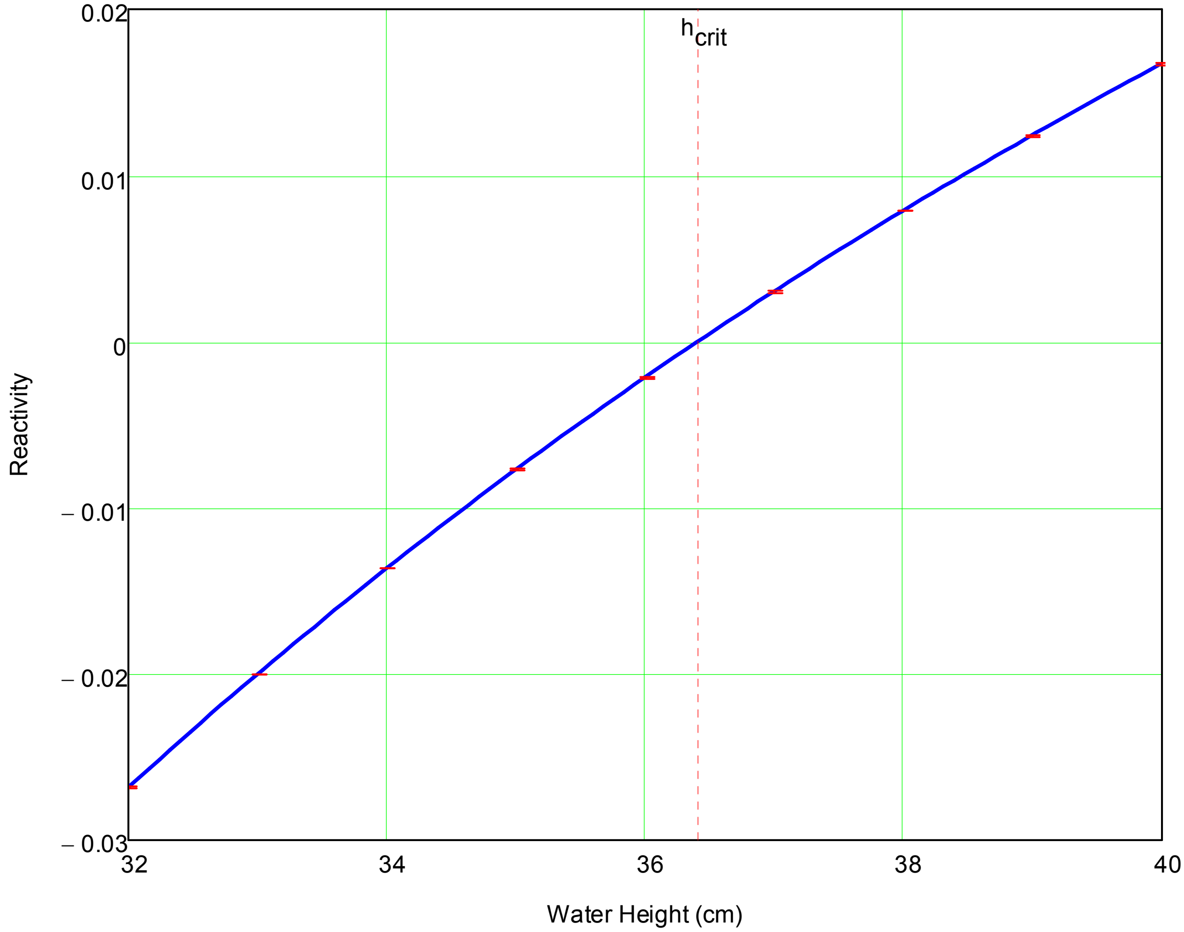

Figure 7. Reactivity as a Function of Moderator Height for Configuration 2.

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.

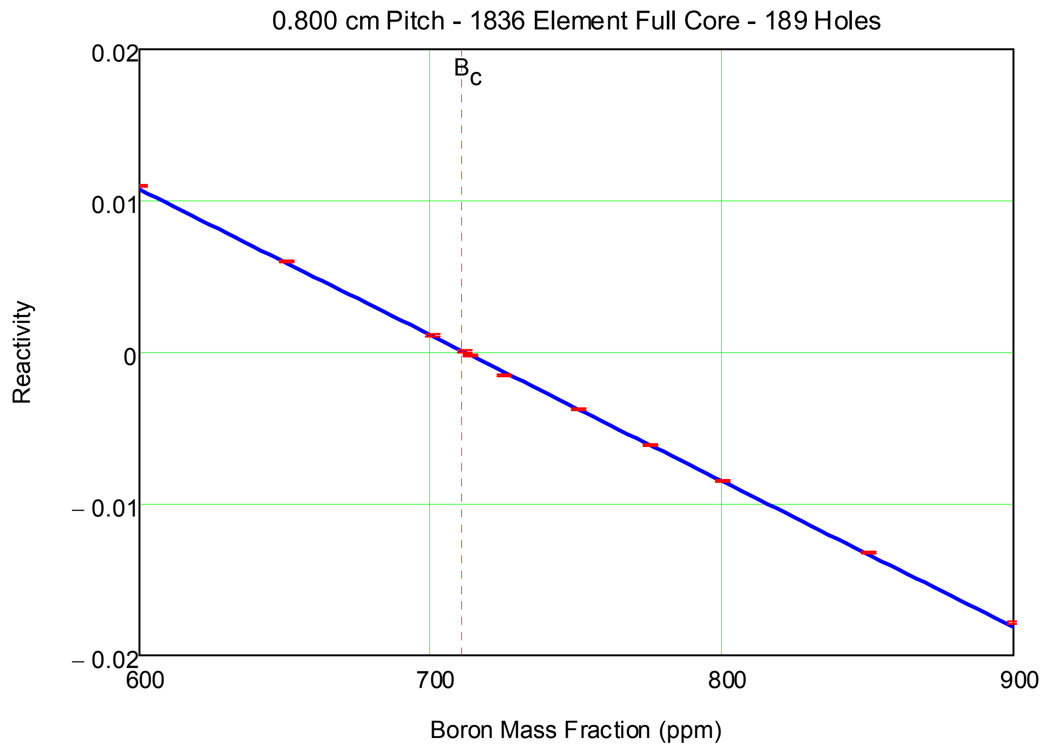

Figure 8. Reactivity as a Function of Boron Concentration in the Moderator/Reflector for Configuration B0711.

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.

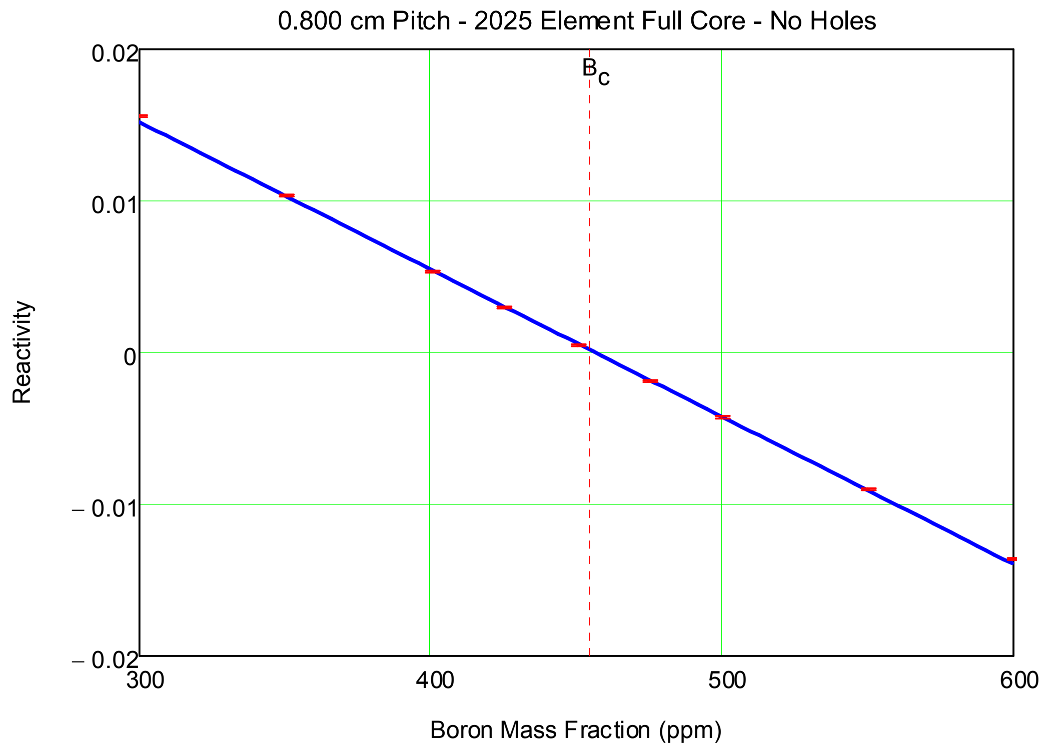

Figure 9. Reactivity as a Function of Boron Concentration in the Moderator/Reflector for Configuration B0456.

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 1. 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 2 shows a similar comparison for Configuration 1 and LCT080 Case 11. Table 3 shows the comparison for Configuration 2 and B0456 and Table 4 shows the comparison for Configuration 2 and Case 1 of LCT080.

Table 1. 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 2. 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 3. 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 4. Comparison of the Material Sensitivities of Configuration 2 and Case 11 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 1 through 4 from highest to lowest is moderator, UO_2 fuel, reflector, clad, grid plates, and fuel springs. Table 5 repeats the sensitivity ratios for the two configurations compared with Configuration 1 taken from the last columns of Tables 1 and 2. Table 6 repeats the sensitivity ratios for the two configurations compared with Configuration 2 taken from the last columns of Tables 3 and 4.

Table 5. 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 6. 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 the 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. Also, the risk of assuming that the k_{eff} uncertainties in Configurations 1 and 2 are of the same character as those in the other configurations is low.

Experiment Uncertainties

Table 7 gives a comparison of the expected benchmark k_{eff} uncertainties in Configuration 1 with the benchmark k_{eff} uncertainties determined for LCT080 Case 11. The uncertainties for Configuration 1 for the parameters that gave the highest three uncertainties in the LCT080 benchmarks – the fuel rod pitch, the number of oxygen atoms per uranium atom in the fuel, and the clad composition – were directly calculated for the proposed configurations by applying the methods used in LCT080. 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 the LCT080 configuration, this is the sum in quadrature of all the components. For Configuration 1, it is an estimate obtained by summing in quadrature the four elements listed in the second column with the elements in the LCT080 column excluding the first four. The estimated benchmark k_{eff} uncertainty for the proposed Configuration 1 is similar to the value given for LCT080 Case 11.

Table 7. 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
UO_2 Stoichiometry	-0.00057	-0.00048
Clad Composition	-0.00022	-0.00027
Moderator height (0.5 mm uncertainty)	0.00036	0.00000
Clad OD	–	-0.00010
Clad ID	–	-0.00001
Fuel Pellet OD	–	0.00000
Rod Fuel Mass	–	0.00002
Rod Fuel Length	–	0.00005
Enrichment	–	0.00012
234U	–	-0.00001
236U	–	-0.00001
Measured Fuel Impurities	–	-0.00012
Undetected Fuel Impurities	–	-0.00006
Grid Plate Composition	–	-0.00011
Water Composition	–	-0.00014
Temperature	–	-0.00005
Sum in Quadrature	**0.00097[(a)]**	**0.00098**

(a) The sum in quadrature of the first four values listed in the second column and the fifth through seventeenth values listed in the third column.

Table 8 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 8. 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
UO_2 Stoichiometry	-0.00053	-0.00045
Clad Composition	-0.00016	-0.00028
Moderator height (0.5 mm uncertainty)	0.00026	0.00000
Clad OD	–	-0.00012
Clad ID	–	-0.00002
Fuel Pellet OD	–	0.00000
Rod Fuel Mass	–	0.00002
Rod Fuel Length	–	0.00006
Enrichment	–	0.00012
234U	–	-0.00001
236U	–	-0.00001
Measured Fuel Impurities	–	-0.00013
Undetected Fuel Impurities	–	-0.00007
Grid Plate Composition	–	-0.00013
Water Composition	–	-0.00023
Temperature	–	-0.00005
Sum in Quadrature	**0.00100**[(a)]	**0.00101**

(a) The sum in quadrature of the first four values listed in the second column and the fifth through seventeenth values listed in the third column.

Assembly Modifications for the Proposed Experiments.

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 may be necessary to adjust/modify the variable overflow standpipe to accommodate the range of levels needed to perform these experiments.

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 within the capability of the existing level measurement system and will be used to specify the minimum accuracy required for any new system.

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 may be 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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