SAND2016-4267R

# United States Department of Energy
# National Nuclear Security Administration
# Nuclear Criticality Safety Program

# Integral Experiment Request 209
# CED-2 Summary Report

**Critical and Subcritical Experiment Design Team ($C_E$dT)**

**Gary A. Harms (SNL), $C_E$dT Lead, Experiment, and Publication Member**
**A. C. (Skip) Kahler (LANL), $C_E$dT NDAG Member**
**Thomas M. Miller (ORNL), $C_E$dT Methods Member**
**David P. Heinrichs (LLNL), $C_E$dT Member**

April 5, 2016

SAND2016-XXXX

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Nearly Blank Page

# Integral Experiment Request 209
# CED-2 Summary Report

## Critical and Subcritical Experiment Design Team ($C_E$dT)

**Gary A. Harms (SNL), $C_E$dT Lead, Experiment, and Publication Member**
**A. C. (Skip) Kahler (LANL), $C_E$dT NDAG Member**
**Thomas M. Miller (ORNL), $C_E$dT Methods Member**
**David P. Heinrichs (LLNL), $C_E$dT Member**

April 5, 2016

## 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-078 [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.

The experiments described here are similar to those proposed under IER-208, with the primary difference being the pitch of the fuel rods in the fuel array. Thus, this report bears a strong resemblance to the CED-2 summary report written for IER-208 and benefits from some of the design information included in that report.

## 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.

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.

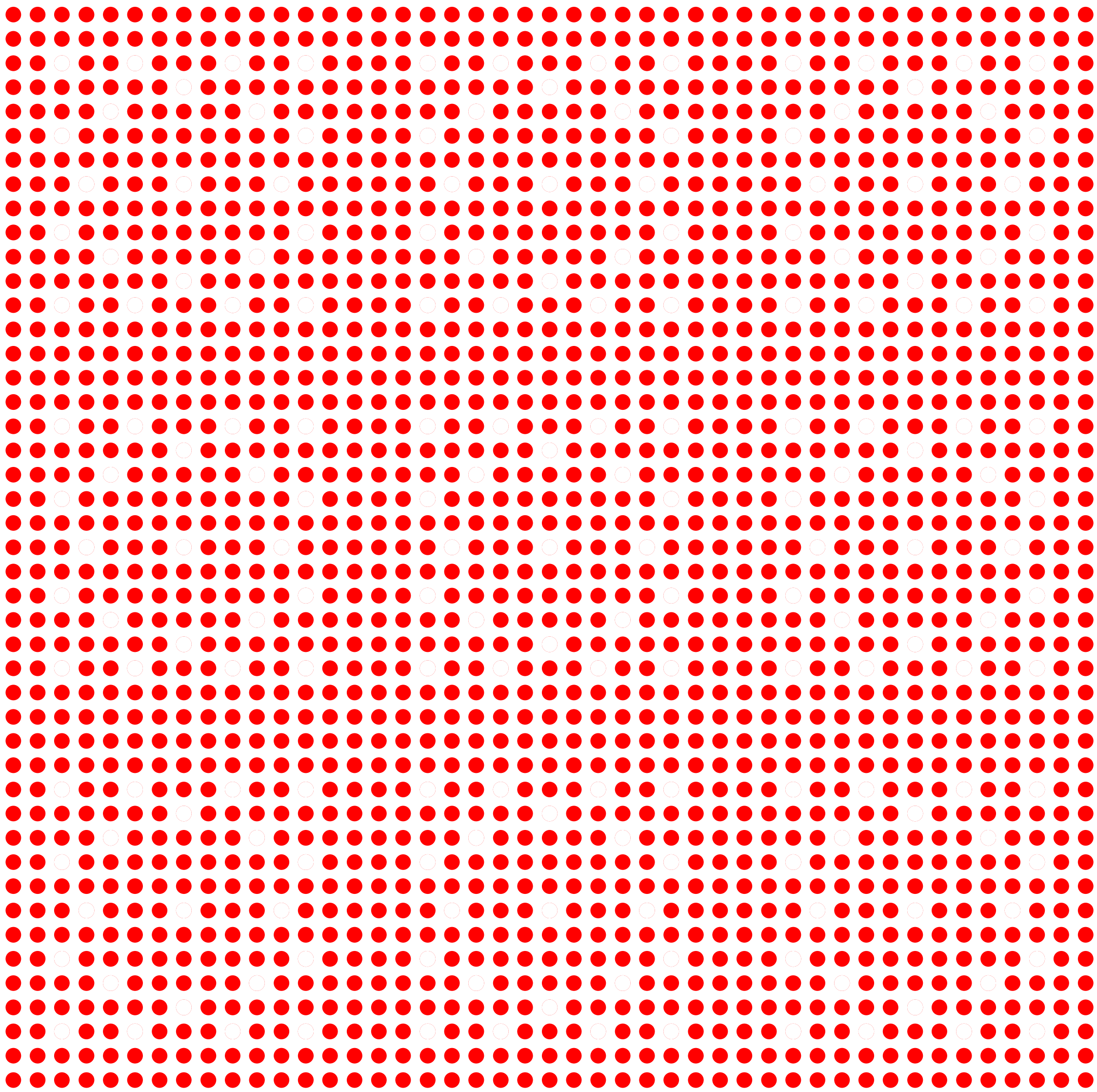

**Figure 1. Fuel Rod Lay-Out Simulating a 3x3 Array of 15x15 PWR Fuel Elements.**

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. The 7uPCX configurations addressed as part of IER-159 and documented as LEU-COMP-THERM-078 (LCT078) in Reference 1 were also moderated and reflected by pure water and used the grid plate set at the lower fuel-to-water ratio. In both sets of experiments, the fuel rod array was roughly cylindrical.

Figure 2 shows the overall critical assembly concept that was used for the experiments performed as part of IER-159. The configuration shown is Case 15 of LCT078. Figure 3 shows the fuel rod layout in the assembly for that configuration. This layout is a subset of the layout shown in Figure 1 and is near delayed critical when moderated and fully-reflected by pure water.

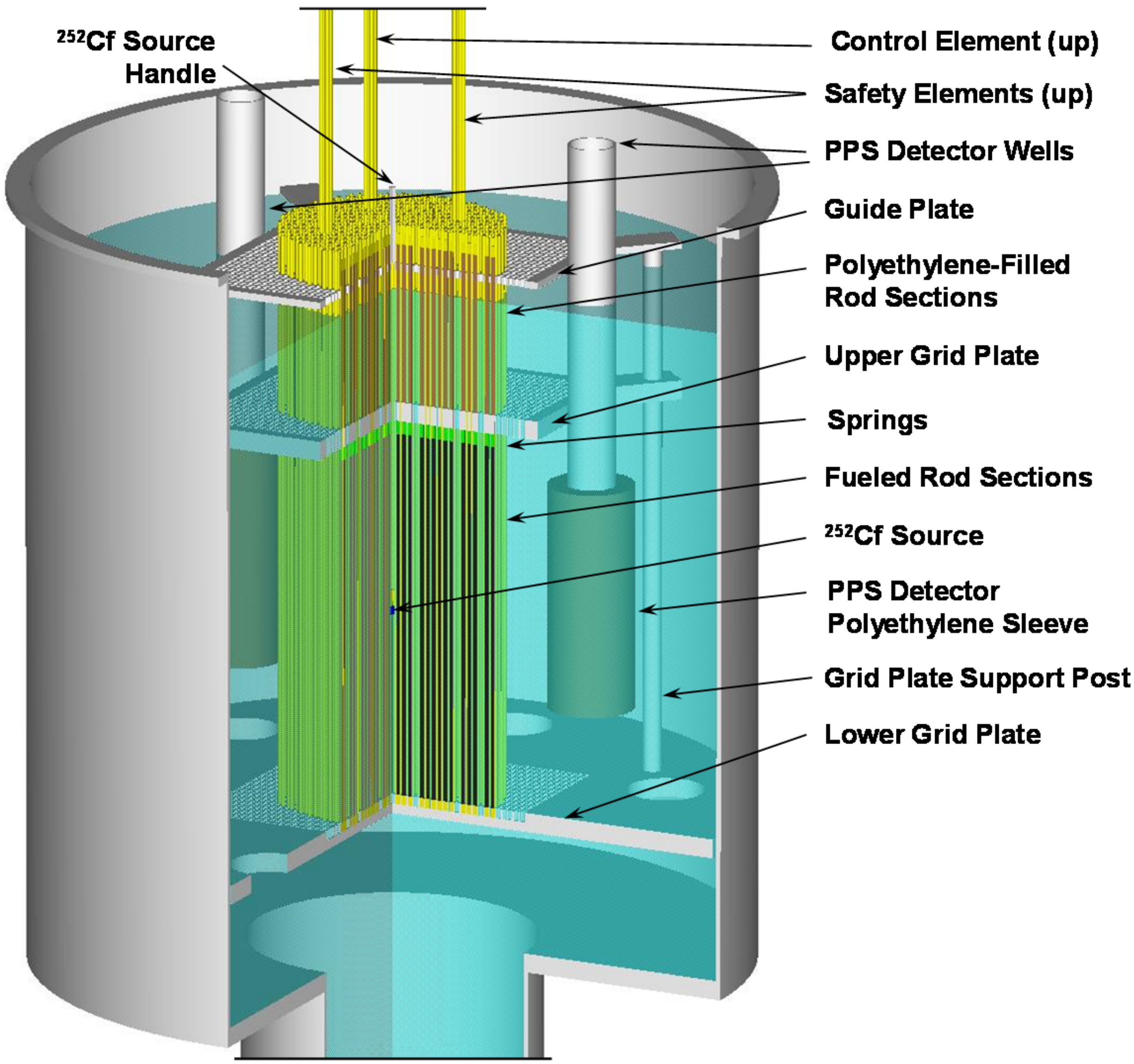


**Figure 2. Critical Assembly Concept of the 7uPCX.**

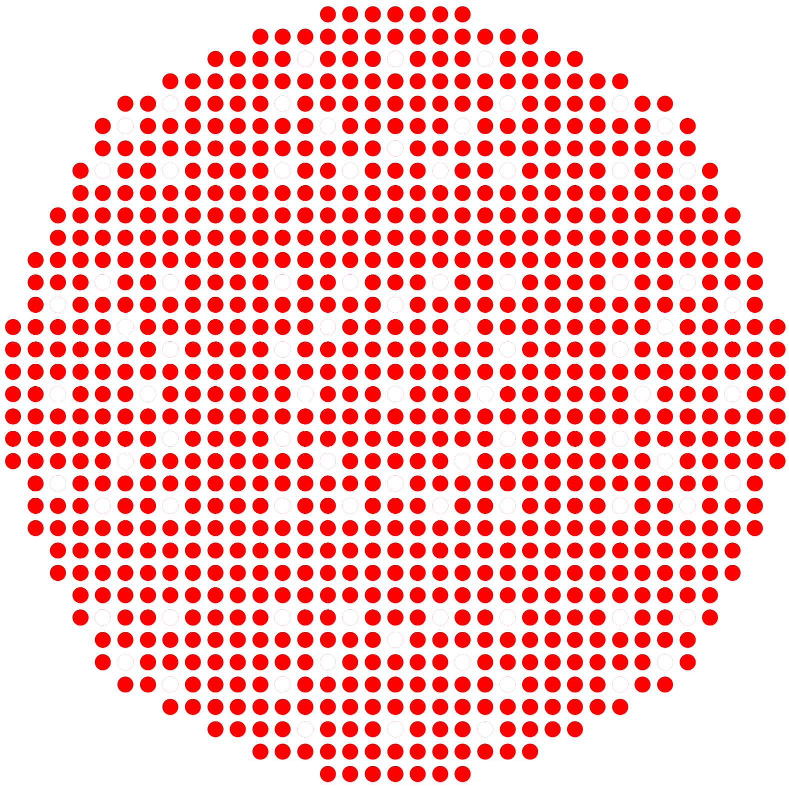

**Figure 3. Fuel Rod Layout in Case 15 of LCT078.**

## 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-209 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-159 experiments. They will likely be moved to lower elevations for the experiments proposed here.

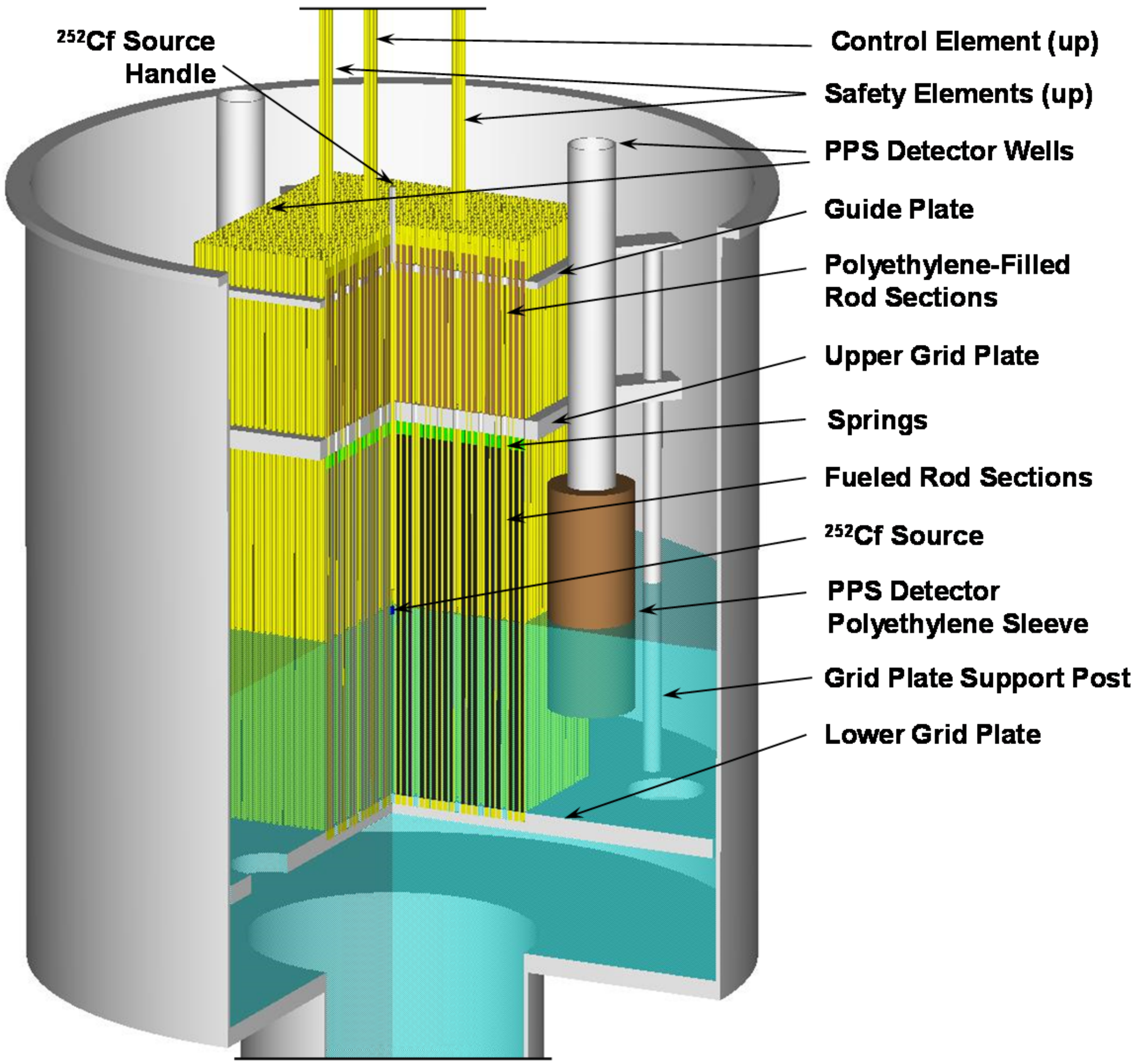


**Figure 4. Critical Assembly Concept With the Array Fully Loaded.**

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-159 and being documented in LCT078, Configuration 1 is similar to Case 15 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 from SCALE6.1.1 with 238-group 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 in the $k_{eff}$ calculation determined by comparison of calculated and measured $k_{eff}$ for LCT078 Case 15. 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 255.5 mm, where the height is measured from the top of the bottom grid plate of the assembly. MCNP5 gives similar results using continuous-energy ENDF/B-VII.0 cross sections and the same biasing technique.

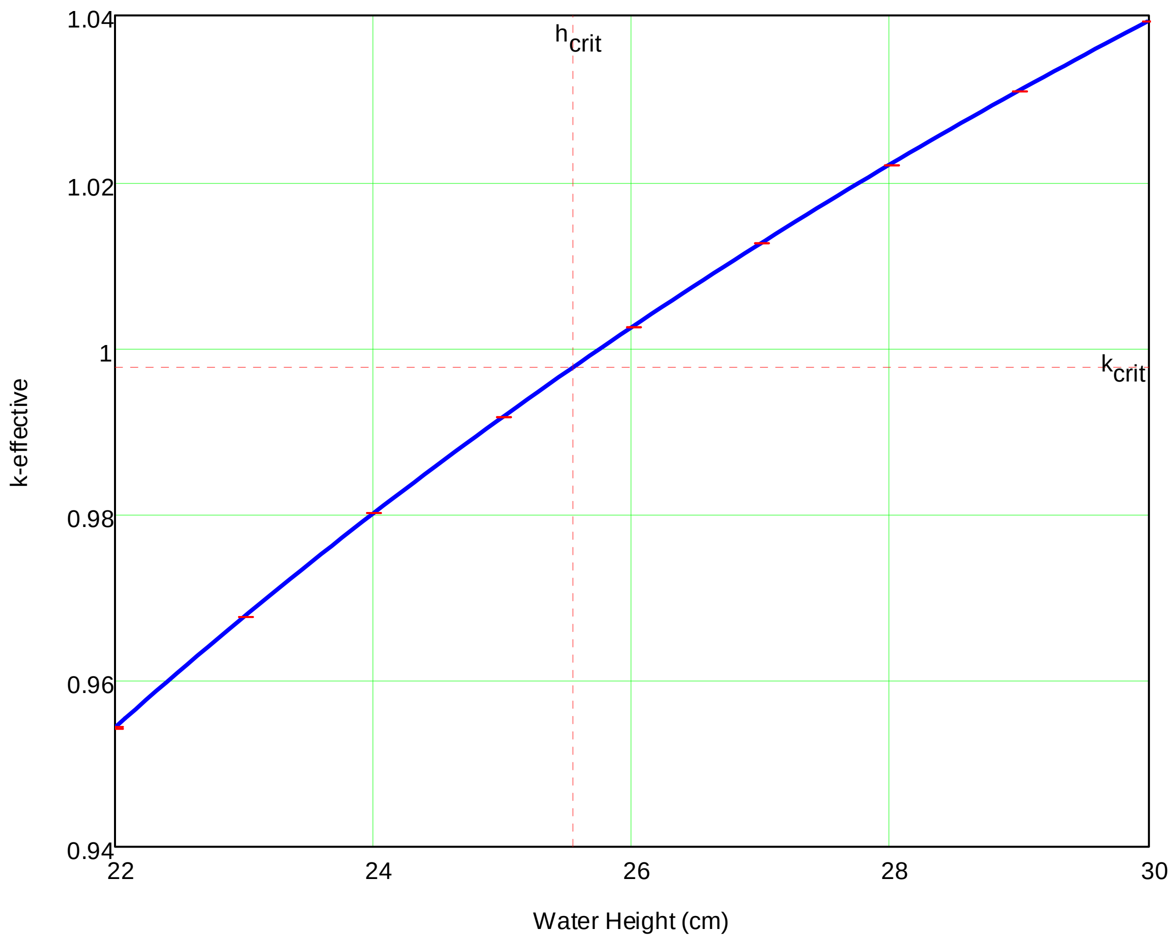


**Figure 5. Calculated $k_{eff}$ as a Function of the Moderator Height in Configuration 1.**

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.

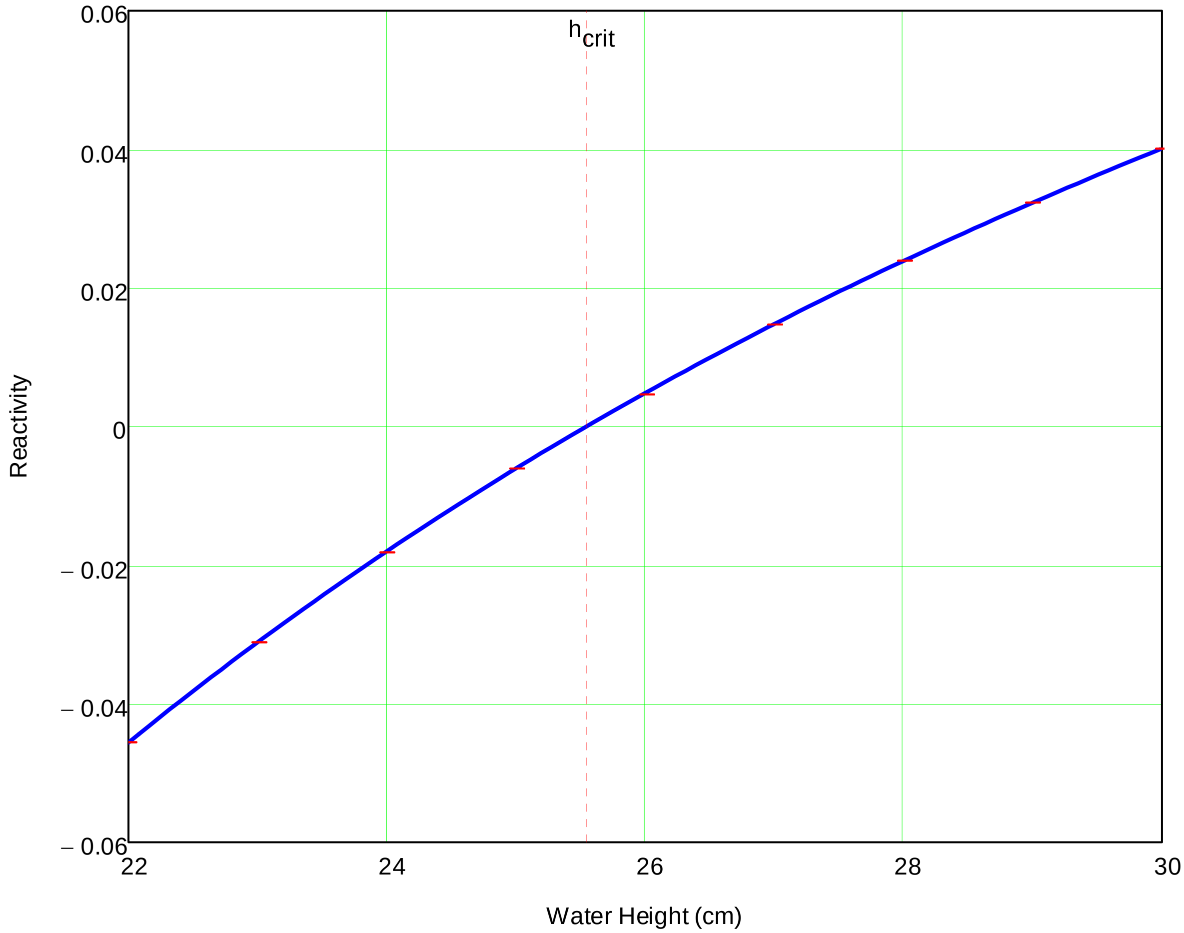


**Figure 6.  Reactivity as a Function of Moderator Height for Configuration 1.**

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 0.00108 per mm of water height at the water height that gives a reactivity value of 0.  This sensitivity is higher than the value of 0.00072 per mm obtained for the equivalent configuration with the tighter pitch of IER-208.

Figure 7 shows the relationship between reactivity and water height for Configuration 2.  Here the bias in the $k_{eff}$ calculation was developed from Case 1 of LCT078.  In this case, the critical water height, $h_{crit}$, is 277.4 mm of water above the top of the bottom grid plate in the assembly.

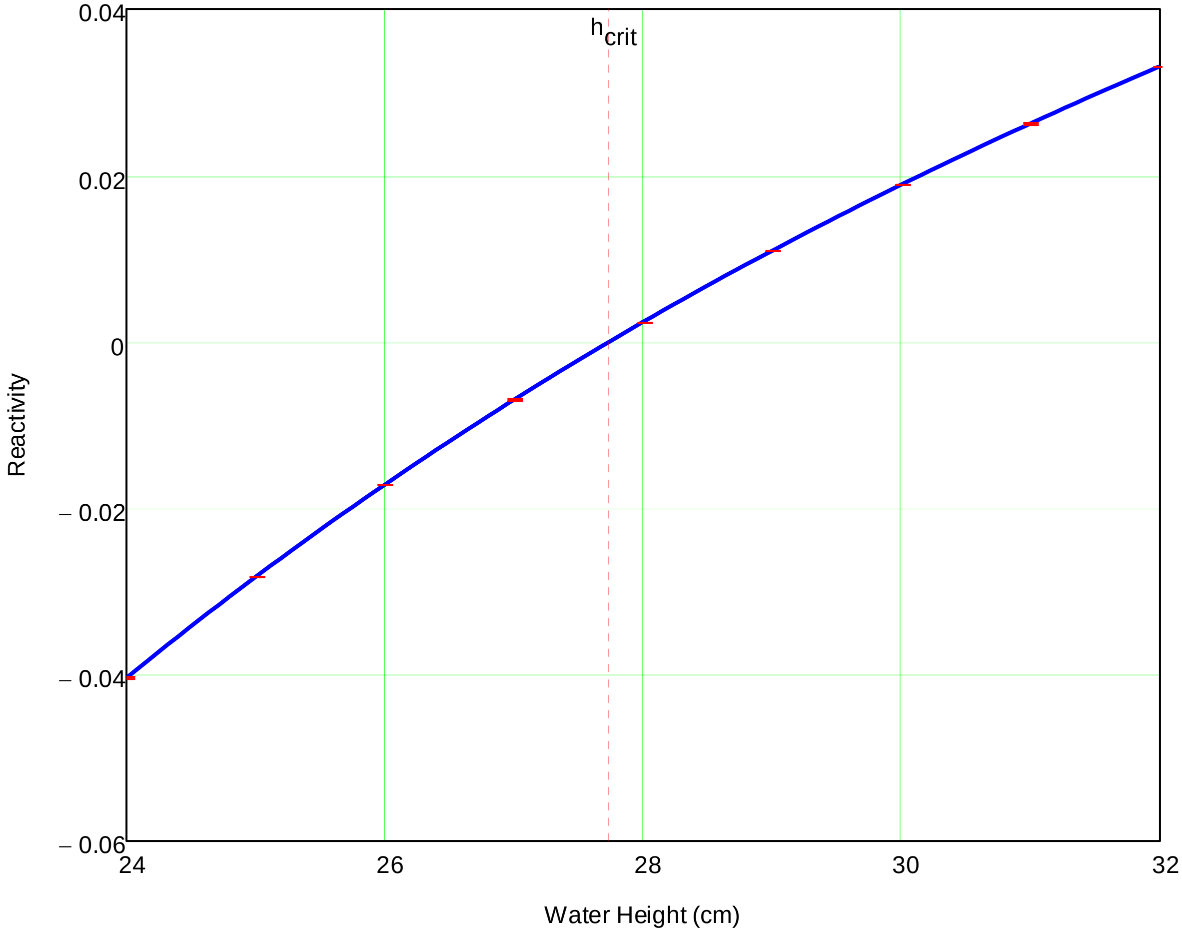


**Figure 7. Reactivity as a Function of Moderator Height for Configuration 2.**

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 0.00091 per mm of water height at the water height that gives a reactivity value of 0. Again, the sensitivity is higher than the value of 0.00052 per mm obtained for the equivalent configuration in IER-208.

Table 1 lists the calculated critical water heights and sensitivities of $k_{eff}$ to water height for Configurations 1 and 2 of IER-208 and IER-209.

**Table 1. Comparison of the Critical Water Height and the Sensitivity of $k_{eff}$ to the Water Height for IER-208 and IER-209.**

| Quantity | Configuration | IER-208 | IER-209 |
|---|---|---|---|
| Critical Water Height (mm) | Configuration 1 | 313.4 | 255.5 |
| | Configuration 2 | 364.1 | 277.4 |
| $k_{eff}$ Sensitivity to Water Height ($mm^{-1}$) at delayed critical (reactivity = 0) | Configuration 1 | 0.00072 | 0.00108 |
| | Configuration 2 | 0.00052 | 0.00091 |

## Configurations with Boron in the Moderator

Critical assembly configurations that were fully reflected, like the LCT078 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, the layout used for Configuration 1. Figure 8 shows the reactivity of the assembly as a function of the concentration of boron dissolved in the moderator/reflector as calculated by KENOV.a from SCALE6.1.1 using 238-group ENDF/B-VII.0 cross sections. The vertical dashed line labeled $B_c$ is shown at the boron concentration that has a reactivity of zero. The bias used was the same as that used in the analysis of Configuration 1. This is the critical boron concentration which occurs at 1121 ppm boron by mass in the moderator/reflector. This configuration with the critical boron concentration will be referred to below as B1121.

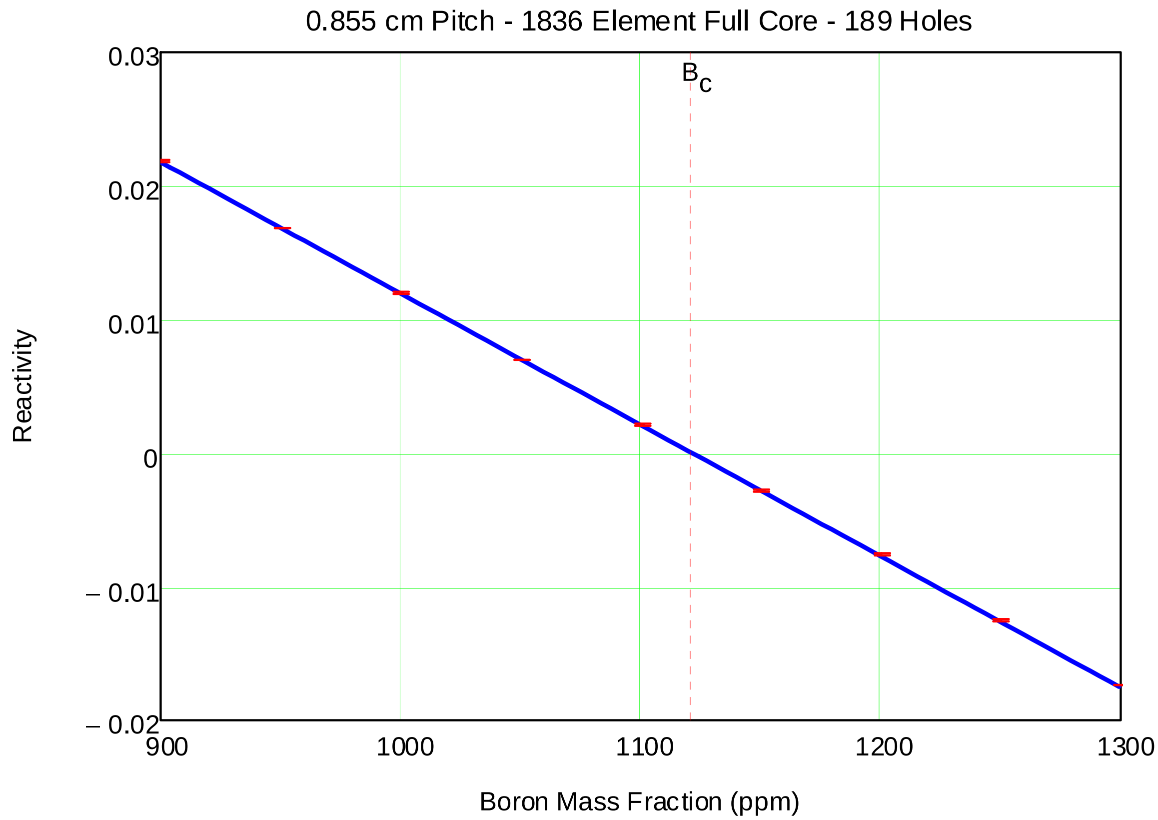


**Figure 8. Reactivity as a Function of Boron Concentration in the Moderator/Reflector for Configuration B1121.**

A similar configuration with all 2025 fuel rod positions filled was also investigated using the same methods and nuclear data. Figure 9 shows the reactivity as a function of boron concentration in the moderator/reflector with the critical concentration of 1055 ppm shown by the vertical dashed line. The bias used was the same as that used in the analysis of Configuration 2. This configuration will be referred to below as B1055.

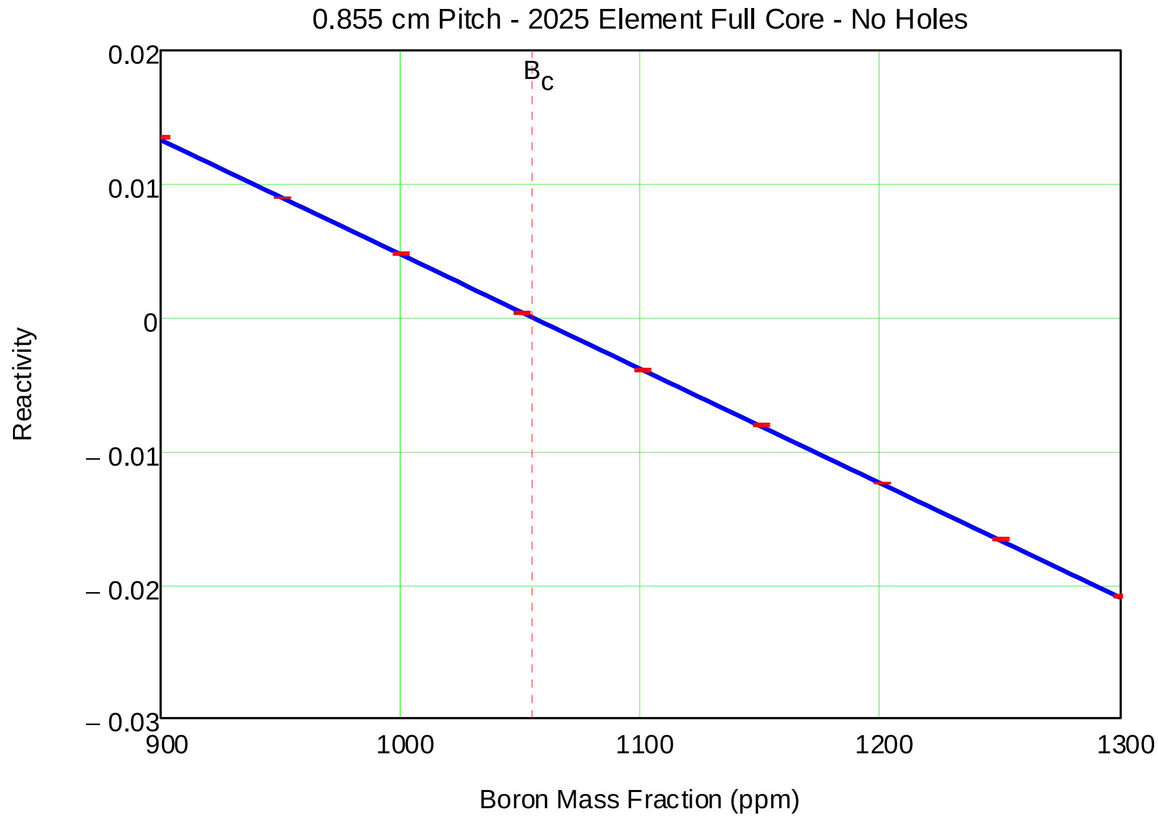


**Figure 9. Reactivity as a Function of Boron Concentration in the Moderator/Reflector for Configuration B1055.**

## 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 B1121. 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 B1055. Again, all spectra are similar with the spectra in the fuel being slightly harder than the corresponding spectra in the cell moderator.

Table 2 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 LCT078 Case 15, Configuration 1, and B1121 (corresponding configurations) and the set of LCT078 Case 1, Configuration 2, and B1055. The data show that the benchmark configurations from LCT078 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.

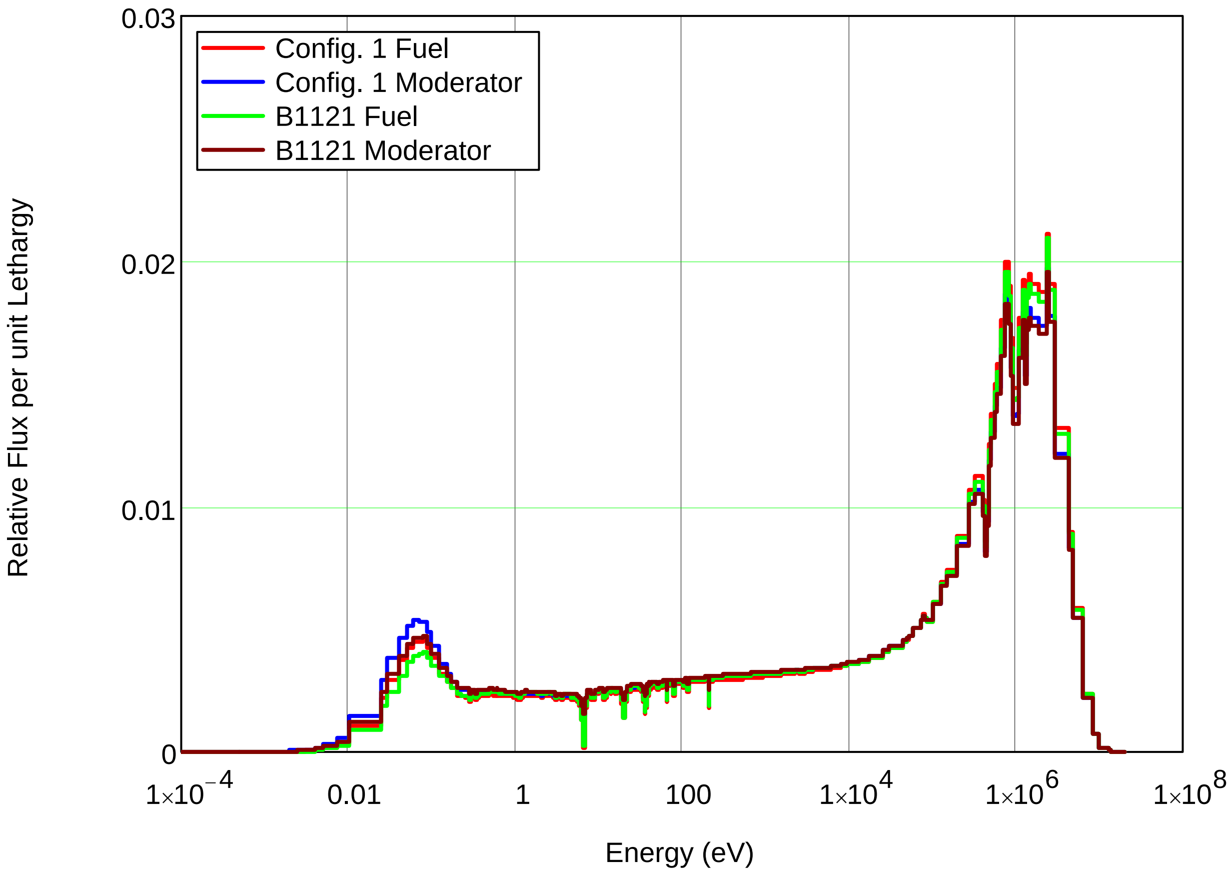


**Figure 10. Comparison of the Neutron Spectra in the Fuel and the Moderator in the Fuel Rod Cells in Configuration 1 and the Corresponding System with Boron-Poisoned Moderator (B1121).**

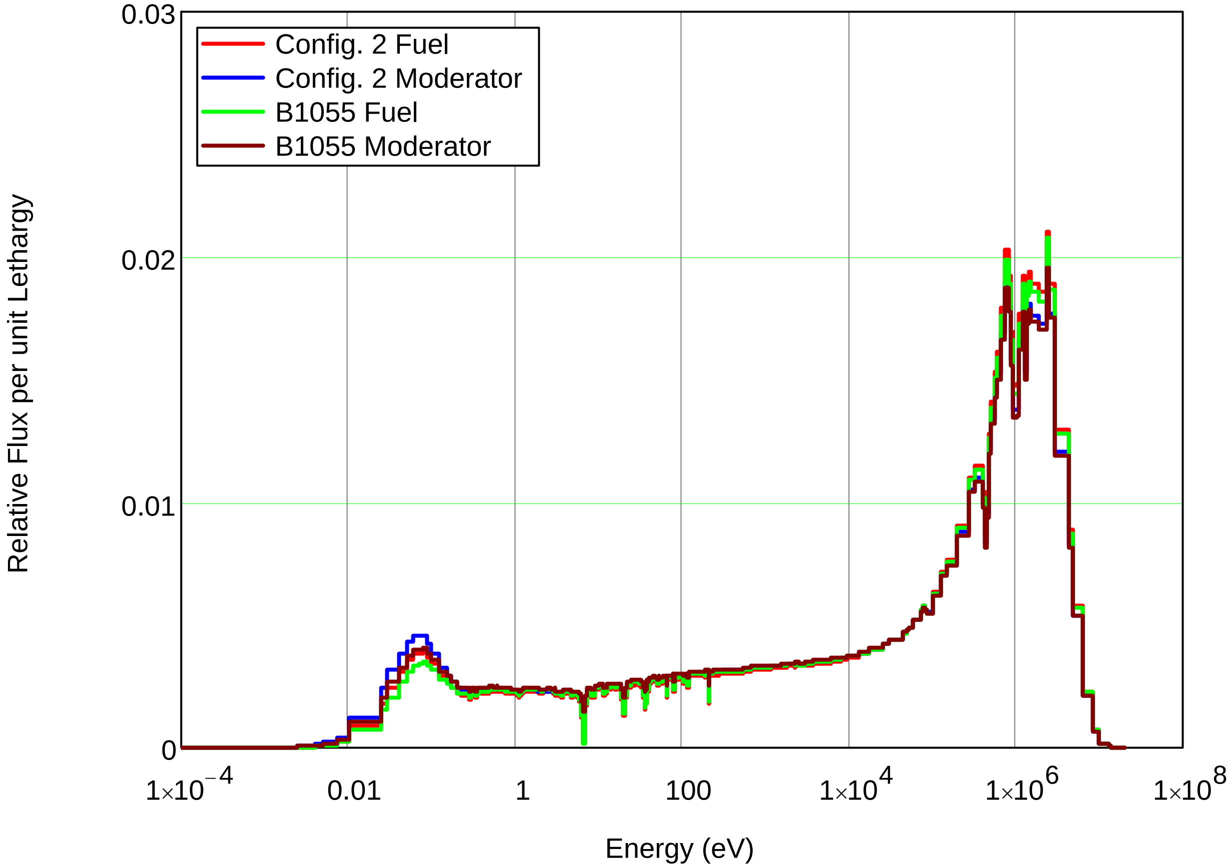


**Figure 11. Comparison of the Neutron Spectra in the Fuel and the Moderator in the Fuel Rod Cells in Configuration 2 and the Corresponding System with Boron-Poisoned Moderator (B1055).**

**Table 2. Breakdown by Neutron Energy of the Neutron Spectrum and the Assembly Fissions for LCT078 Case 15 and Case 1, Configurations 1 and 2, and for B1121 and B1055.**

| Quantity | Configuration | Thermal [1] | Intermediate [2] | Fast [3] |
|---|---|---|---|---|
| Flux | LCT078 Case 15 | 11.6 | 35.0 | 53.5 |
| | Configuration 1 | 11.0 | 35.5 | 53.5 |
| | B1121 | 10.2 | 36.8 | 53.1 |
| | LCT078 Case 1 | 10.3 | 35.8 | 53.9 |
| | Configuration 2 | 9.7 | 36.3 | 54.0 |
| | B1055 | 9.1 | 37.4 | 53.5 |
| Fissions | LCT078 Case 15 | 82.4 | 12.2 | 5.4 |
| | Configuration 1 | 79.9 | 13.6 | 6.5 |
| | B1121 | 78.9 | 14.9 | 6.2 |
| | LCT078 Case 1 | 80.1 | 13.8 | 6.1 |
| | Configuration 2 | 77.5 | 15.3 | 7.2 |
| | B1055 | 76.4 | 16.7 | 6.9 |

[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 15 and 1 of LCT078, Configurations 1 and 2 described above, and the two boron-poisoned fully-reflected configurations B1121 and B1055. A comparison of the material sensitivities for Configuration 1 and B1121 is shown in Table 3. The last column shows the ratio of the sensitivity of each material in Configuration 1 to the sensitivity of the same material in B1121. Table 4 shows a similar comparison for Configuration 1 and LCT078 Case 15. Table 5 shows the comparison for Configuration 2 and B1055 and Table 6 shows the comparison for Configuration 2 and Case 1 of LCT078.

**Table 3. Comparison of the Material Sensitivities of Configuration 1 and B1121.**

| Material | Configuration 1 | | B1121 | | Ratio |
|---|---|---|---|---|---|
| | Sensitivity | Uncertainty | Sensitivity | Uncertainty | Config 1/B1121 |
| $UO_2$ Fuel | 1.120E-01 | 0.4% | 1.545E-01 | 0.1% | 0.73 |
| Clad | 9.035E-03 | 0.8% | 6.571E-03 | 1.1% | 1.38 |
| Moderator | 4.418E-01 | 0.5% | 2.952E-01 | 0.3% | 1.50 |
| Grid Plates | 7.009E-03 | 1.0% | 3.431E-03 | 0.5% | 2.04 |
| Fuel Springs | 5.355E-06 | 4.0% | -2.429E-05 | -13.8% | -0.22 |
| Reflector | 2.618E-02 | 23.1% | 7.488E-03 | 3.5% | 3.50 |

**Table 4. Comparison of the Material Sensitivities of Configuration 1 and Case 15 of LCT078.**

| Material | Configuration 1 | | LCT078 Case 15 | | Ratio |
|---|---|---|---|---|---|
| | Sensitivity | Uncertainty | Sensitivity | Uncertainty | Config 1/Case 15 |
| $UO_2$ Fuel | 1.120E-01 | 0.4% | 9.022E-02 | 0.5% | 1.24 |
| Clad | 9.035E-03 | 0.8% | 4.994E-03 | 1.4% | 1.81 |
| Moderator | 4.418E-01 | 0.5% | 4.120E-01 | 0.6% | 1.07 |
| Grid Plates | 7.009E-03 | 1.0% | 2.355E-03 | 1.2% | 2.98 |
| Fuel Springs | 5.355E-06 | 4.0% | -1.060E-04 | -2.5% | -0.05 |
| Reflector | 2.618E-02 | 23.1% | 3.973E-02 | 19.5% | 0.66 |

**Table 5. Comparison of the Material Sensitivities of Configuration 2 and B1055.**

| Material | Configuration 2 | | B1055 | | Ratio |
|---|---|---|---|---|---|
| | Sensitivity | Uncertainty | Sensitivity | Uncertainty | Config 2/B1055 |
| $UO_2$ Fuel | 9.987E-02 | 0.4% | 1.349E-01 | 0.3% | 0.74 |
| Clad | 9.667E-03 | 0.8% | 7.176E-03 | 1.0% | 1.35 |
| Moderator | 4.395E-01 | 0.5% | 3.390E-01 | 0.6% | 1.30 |
| Grid Plates | 6.359E-03 | 1.1% | 3.808E-03 | 0.8% | 1.67 |
| Fuel Springs | 6.262E-06 | 4.2% | -2.475E-05 | -8.3% | -0.25 |
| Reflector | 2.454E-02 | 26.5% | 8.263E-03 | 14.4% | 2.97 |

**Table 6. Comparison of the Material Sensitivities of Configuration 2 and Case 1 of LCT078.**

| Material | Configuration 2 | | LCT078 Case 1 | | Ratio |
|---|---|---|---|---|---|
| | Sensitivity | Uncertainty | Sensitivity | Uncertainty | Config 2/Case 1 |
| $UO_2$ Fuel | 9.987E-02 | 0.4% | 8.129E-02 | 0.5% | 1.23 |
| Clad | 9.667E-03 | 0.8% | 5.818E-03 | 1.2% | 1.66 |
| Moderator | 4.395E-01 | 0.5% | 4.129E-01 | 0.5% | 1.06 |
| Grid Plates | 6.359E-03 | 1.1% | 2.593E-03 | 1.3% | 2.45 |
| Fuel Springs | 6.262E-06 | 4.2% | -1.173E-04 | -2.5% | -0.05 |
| Reflector | 2.454E-02 | 26.5% | 3.932E-02 | 20.4% | 0.62 |

A ranking of the $k_{eff}$ sensitivities listed in Tables 3 through 6 from highest to lowest is moderator, $UO_2$ fuel, reflector, clad, grid plates, and fuel springs. Table 7 repeats the sensitivity ratios for the two configurations compared with Configuration 1 taken from the last columns of Tables 3 and 4. Table 8 repeats the sensitivity ratios for the two configurations compared with Configuration 2 taken from the last columns of Tables 5 and 6.

**Table 7. Ratio of the Material Sensitivities of Configuration 1 to B1121 and LCT078 Case 15.**

| Material | B1121 Sensitivity Ratio | LCT078 Case 15 Sensitivity Ratio |
|---|---|---|
| $UO_2$ Fuel | 0.73 | 1.24 |
| Clad | 1.38 | 1.81 |
| Moderator | 1.50 | 1.07 |
| Grid Plates | 2.04 | 2.98 |
| Fuel Springs | -0.22 | -0.05 |
| Reflector | 3.50 | 0.66 |

**Table 8. Ratio of the Material Sensitivities of Configuration 2 to B1055 and LCT078 Case 1.**

| Material | B1055 Sensitivity Ratio | LCT078 Case 1 Sensitivity Ratio |
|---|---|---|
| $UO_2$ Fuel | 0.74 | 1.23 |
| Clad | 1.35 | 1.66 |
| Moderator | 1.30 | 1.06 |
| Grid Plates | 1.67 | 2.45 |
| Fuel Springs | -0.25 | -0.05 |
| Reflector | 2.97 | 0.62 |

The material $k_{eff}$ sensitivities of Configurations 1 and 2 to the moderator are somewhat higher than for the boron-poisoned configurations B1121 and B1055 and nearly the same as for the LCT078 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 LCT078 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 LCT078 configurations. Configurations 1 and 2 are slightly more sensitive to the clad material than either of the corresponding boron-poisoned and LCT078 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 LCT078 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 upper reflector in the other configurations.

The sensitivity comparisons shown above indicate that the proposed configurations are not radically different from the corresponding boron-poisoned and LCT078 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 sensitivities in the poisoned experiments.

## Experiment Uncertainties

Table 9 gives a comparison of the expected benchmark $k_{eff}$ uncertainties in Configuration 1 with the benchmark $k_{eff}$ uncertainties determined for LCT078 Case 15. 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 LCT078 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 similar the value given for LCT078 Case 15.

**Table 9. Comparison of the Expected Benchmark $k_{eff}$ Uncertainties for Configuration 1 With Those for LCT078 Case 15.**

| **Uncertainty Source** | **Configuration 1 $\Delta k_{eff}$** | **LCT078 Case 15 $\Delta k_{eff}$** |
|---|---|---|
| Pitch of Fuel Rods | 0.00044 | 0.00069 |
| $UO_2$ Stoichiometry | -0.00068 | -0.00055 |
| Clad Composition | -0.00022 | -0.00026 |
| Moderator height (0.5 mm uncertainty) | 0.00054 | 0.00000 |
| Clad OD | -0.00005 | -0.00008 |
| Clad ID | -0.00002 | -0.00001 |
| Fuel Pellet OD | 0.00000 | 0.00000 |
| Rod Fuel Mass | 0.00003 | 0.00002 |
| Rod Fuel Length | -0.00011 | 0.00003 |
| Enrichment | 0.00013 | 0.00013 |
| 234U | -0.00001 | -0.00001 |
| 236U | -0.00001 | -0.00001 |
| Measured Fuel Impurities | -0.00010 | -0.00011 |
| Undetected Fuel Impurities | -0.00002 | -0.00007 |
| Grid Plate Composition | -0.00028 | -0.00012 |
| Water Composition | -0.00003 | -0.00024 |
| Temperature | -0.00009 | -0.00004 |
| **Sum in Quadrature** | **0.00106** | **0.00098** |

Table 10 provides a similar $k_{eff}$ uncertainty comparison between Configuration 2 and LCT078 Case 1. Again, the estimated benchmark $k_{eff}$ uncertainty for the proposed Configuration 2 is similar to the value given for LCT078 Case 1.

**Table 10. Comparison of the Expected Benchmark $k_{eff}$ Uncertainties for Configuration 2 With Those for LCT078 Case 1.**

| Uncertainty Source | Configuration 2 $\Delta k_{eff}$ | LCT078 Case 1 $\Delta k_{eff}$ |
|---|---|---|
| Pitch of Fuel Rods | 0.00053 | 0.00073 |
| $UO_2$ Stoichiometry | -0.00062 | -0.00049 |
| Clad Composition | -0.00021 | -0.00027 |
| Moderator height (0.5 mm uncertainty) | 0.00046 | 0.00000 |
| Clad OD | -0.00006 | -0.00010 |
| Clad ID | -0.00002 | -0.00001 |
| Fuel Pellet OD | 0.00000 | 0.00000 |
| Rod Fuel Mass | 0.00002 | 0.00002 |
| Rod Fuel Length | -0.00010 | 0.00004 |
| Enrichment | 0.00012 | 0.00012 |
| $^{234}U$ | -0.00001 | -0.00001 |
| $^{236}U$ | -0.00001 | -0.00001 |
| Measured Fuel Impurities | -0.00010 | -0.00012 |
| Undetected Fuel Impurities | -0.00001 | -0.00010 |
| Grid Plate Composition | -0.00025 | -0.00011 |
| Water Composition | -0.00001 | -0.00021 |
| Temperature | -0.00009 | -0.00005 |
| **Sum in Quadrature** | **0.00102** | **0.00098** |

## Assembly Modifications for the Proposed Experiments.

As part of the work associated with IER-208, the remotely-adjustable standpipe (RASP) that sets the moderator level in the assembly was modified to accommodate the lower moderator levels needed for the IER-208 experiments. The modified RASP was installed during the IER-208 experiments and has been in use.

Similarly, the water level measurement system was modified under IER-208. A set of four acoustic level sensors mounted in still tubes in the assembly core tank was installed. Based on measurements made to date, the acoustic level measurement system appears to be capable of meeting the accuracy goals (<0.5 mm uncertainty) set during its design.

## Biases

The proposed experiments are expected to behave similarly to the experiments documented in LCT078. 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 the draft of LCT078 will be required.

### Critical Assembly Surroundings

The LCT078 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 $k_{eff}$ of 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 is shown in Table 11. The reactivity difference is small 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 LCT078 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 11. 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 11. $k_{eff}$ Bias From Two Major Model Simplifications**

| Simplification | Configuration 1 | | Configuration 2 | |
|---|---|---|---|---|
| | $\Delta k_{eff}$ | Uncertainty | $\Delta k_{eff}$ | Uncertainty |
| Remove Reactor Room | -0.00013 | 0.00004 | -0.00014 | 0.00004 |
| Use LCT078 Benchmark Model Simplifications | 0.00039 | 0.00004 | 0.00028 | 0.00004 |

## Conclusion

Integral Experiment Request 209 considers critical experiments in the 7uPCX assembly with fuel arrays larger than the fully-reflected arrays considered in LCT078 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.

## References

1. International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)3, December, 2012.

2. Areva Federal Services, LLC, *Reactor Physics and Criticality Benchmark Evaluations for Advanced Nuclear Fuel – Final Technical Report*, TDR-3000849-000 (September 10, 2008).
3. B. T. Rearden (ORNL), W. J. Anderson (Framatome ANP), and G. A. Harms (SNL), "Use of Sensitivity and Uncertainty Analysis in the Design of Reactor Physics and Criticality Benchmarks for Advanced Nuclear Fuel," Nuclear Technology, **151**, August, 2005.
4. *Scale: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design*, ORNL/TM-2005/39, Version 6.1, Oak Ridge National Laboratory, June, 2011.
5. *MCNP – A Monte Carlo N-Particle Transport Code*, Version 5, LA-UR-03-1987, Los Alamos National Laboratory, Revised February, 2008.