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Integral Experiment Request 554 CED-2 Summary Report

Mathieu N. Dupont
David E. Ames
Gary A. Harms
William J. Marshall
Marco T. Pigni

December 2023

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Nuclear Energy and Fuel Cycle Division

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

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CED-2 SUMMARY REPORT

Mathieu N. Dupont
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For the Critical and Subcritical Experiment Design Team (C_EdT)

Mathieu N. Dupont (ORNL), C_EdT Lead
David E. Ames (SNL), Experiment Member
William J. Marshall (ORNL), Methods Member
Marco T. Pigni (ORNL), NDAG Member

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
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ABBREVIATIONS

7uPCX	Seven Percent Critical Experiments
ACRR	Annular Core Research Reactor
BUCCX	Burnup Credit Critical Experiment
CED	Critical Engineering Decision
C_EdT	Critical Subcritical Experiment Design Team
CT	computed tomography
DOE	US Department of Energy
EALF	energy corresponding to the average lethargy of neutrons causing fission
ENDF	Evaluated Nuclear Data File
HFIR	High Flux Isotope Reactor
ICSBEP	International Criticality Safety Benchmark Evaluation Project
IER	Integral Experiment Request
LLNL	Lawerence Livermore National Laboratory
MSC	Manufacturing Sciences Corporation
MSTD	Materials Science and Technology Division
NCSP	Nuclear Criticality Safety Program
NDAG	Nuclear Data Advisory Group
NNL	Naval Nuclear Laboratory
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
SNL	Sandia National Laboratories
SNS	Spallation Neutron Source
SPRF/CX	Sandia Pulsed Reactor Facility/Critical Experiments

ACKNOWLEDGMENTS

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Thanks to Michael Zerkle from the Naval Nuclear Laboratory (NNL) and Daniel Siefman from Lawrence Livermore National Laboratory (LLNL) for suggesting contacting Curtiss-Wright/NETCO to inquire about the neutron absorber plate characterization, and to Matt Harris and Ashleigh Quigley from Curtiss-Wright/NETCO for their help answering our questions and starting up the collaboration for this integral experiment request.

SUMMARY

This report summarizes the critical experiment design 2 (CED-2) or final design study for Integral Experiment Request 554 (IER-554). This experiment describes the effects and importance of adding a commercially available neutron absorber material to a known light-water low-enriched uranium assembly. The assembly in question is the Seven Percent Critical Experiments (7uPCX) at Sandia National Laboratories. The neutron absorber plates considered for the experiment are known as *Boralcan* and are made of boron carbide (B_4C) particles embedded in 1100 aluminum alloy. The concentrations of B_4C and 1100 aluminum were changed as well as the thickness and the positions of the plates, and the fuel rod configuration was adapted to ensure that the assembly would be critical in each case studied. A total of 6 critical configurations, each with a neutron absorber plate inserted, are described in this report. No results of high-quality integral experiments involving neutron absorbers made with B_4C and 1100 aluminum plates are currently publicly available. Sensitivity to the neutron absorber plate material definition, isotopes, and cross sections of specific regions and configurations are also analyzed. As part of the final design of the experiment, a safe plate holder made of 3003 aluminum was designed. The study results indicate that these experiments are achievable with sufficiently low uncertainties and minimal modification to the assembly, and the CED-3 phase can start when funding allows.

1. INTRODUCTION

The experiment designed as described in this report aims to produce additional critical benchmark data from the Sandia Pulsed Reactor Facility/Critical Experiments (SPRF/CX) apparatus at Sandia National Laboratories (SNL) using 7uPCX low-enriched uranium (LEU) fuel (6.90 wt % ^{235}U). This report describes the CED-2 step of the experiment request design process defined by the US Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP) [1], also called “Final design,” and is a direct continuation of the study performed during CED-1 “Preliminary design” [2]. Compared to the experiment described in CED-1, the different configurations of the experiment described in this report include more real-life considerations, such as minimizing the total experiment cost and providing a feasible solution for the absorber plate holder. The justification and benefits for this experiment were broadly detailed in the CED-1 report and in related publications [3, 4]. To summarize, these experiments aim (1) to add Boralcan, a commercially available neutron absorber material used in spent fuel storage and transportation, to the assembly and (2) to update the fuel rod configuration to reach criticality.

This experiment would benefit the community by providing industry members with the ability to judge the quality of the underlying nuclear data library specifically for B, C, and Al, as well as the interaction of these nuclei with fissile actinides such as uranium for a low-enriched configuration. These experiments involve predominantly thermal neutrons, so the measured data will provide an integral metric of the interplay between a slowly varying cross section typical of light nuclei in this neutron energy region and the thermal constants, together with first resonances typical of heavy fissile actinides. The nuclear data performance will be tested in terms of reactivity coefficients calculated by radiation transport codes simulating the experiment in its geometry and materials as LEU in water and neutron absorber plates made of B_4C and 1100 aluminum.

Another benefit is to verify the uniformity of B_4C particles among the metallic matrix plate in an integral experiment. Having more information about those plates could help industry members gain confidence in their modeling method and the use of this type of neutron absorber material. It would also help validate k_{eff} calculations and could justify relaxation of the boron loading credit limits in the US Nuclear Regulatory Commission (NRC) Standard Review Plan for dry cask storage [5].

As described in the CED-1 report, results from experiments involving B_4C neutron absorbers can be found in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP) Handbook [6], but none of the experiments involved Boralcan, the most recent product developed by Rio Tinto that has been used in nuclear installations since approximately 2010 [7]. Therefore, adding these newly designed Boralcan experiments to the ICSBEP Handbook would greatly benefit the community.

Ten critical configurations are described in the CED-1 report, each with a different neutron absorber plate inserted in its center or a different lattice configuration. The starting rod configuration of the assembly was based on the IER-304 CED-2 report [8], case 9 of which shows a critical configuration using the 7uPCX fuel rods with six central horizontal rows of fuel rods removed and replaced with water. In the CED-2 effort, an important decision was made in collaboration with Sandia National Laboratories (SNL) to facilitate the initiation and execution of the experiment. IER-441, currently in CED-3b (Integral Experiment Execution) at SNL, uses newly designed triangular grid plates for the 7uPCX LEU fuel rods. A central hole in the grid plates allows insertion of a central 6061 aluminum alloy test region filled with tantalum absorber rods [9], as seen in Figure 1. Because designing a new set of grid plates that would allow for insertion of the Boralcan plates in the assembly would involve excessive delay and cost, the grid plates from IER-441 will be used. This way, the Boralcan plates can be inserted into an aluminum holder that will be inserted from the top of the core in a manner similar to that used in the test region and tantalum rods in IER-441, as shown in Figure 2.

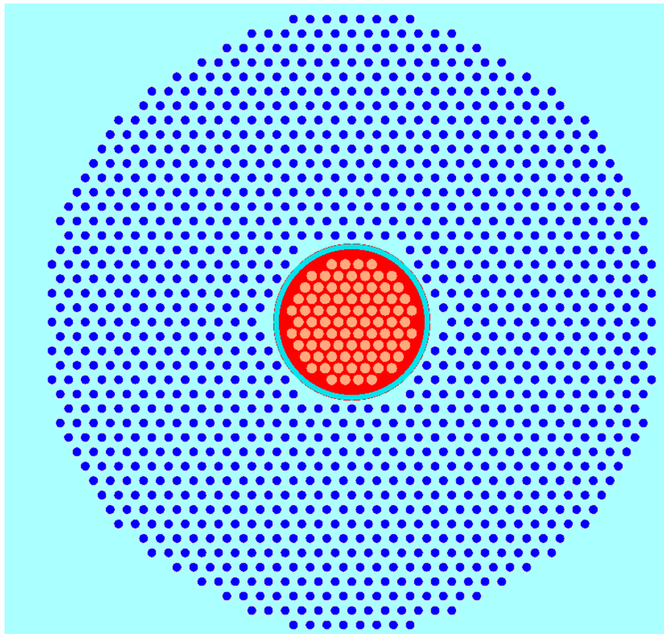

Figure 1. Fuel rod layout (1158 fuel rods and 85 tantalum rods) from upcoming IER-441 rendered with SCALE Fulcrum [9].

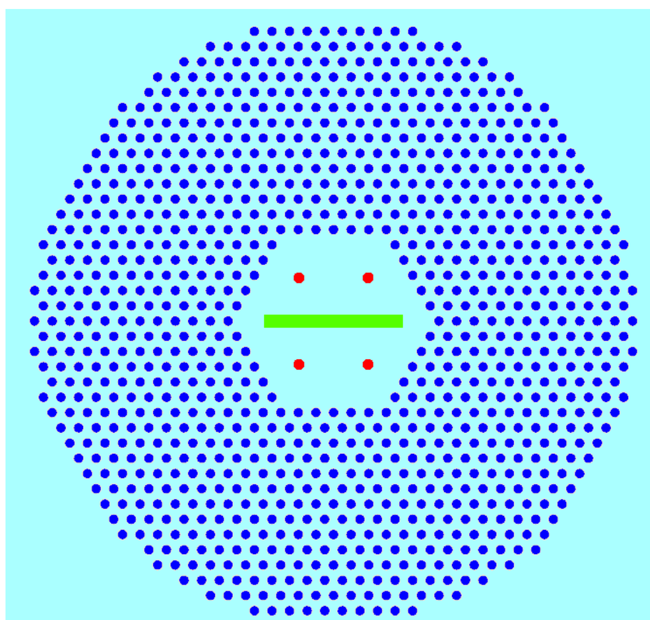

Figure 2. Fuel rod layout (979 fuel rods) of proposed Configuration 1. B_4C neutron absorber plate is shown in green, and aluminum holder parts are shown in red.

Six critical configurations are described in this report, each with a different neutron absorber plate inserted in its center or a different lattice configuration. The widths and lengths of the Boralcan plates used are constant at 8 × 30 cm, and the thickness and B_4C concentration is changing. In CED-1, the size of the plates differed between the configurations. In CED-2, it was decided to use only the largest Boralcan plate that could be inserted through the central grid plate holes (approximately 9 cm) to maximize the integral ^{10}B neutron absorption worth. In the first three configurations described in this report, the neutron absorber plates were inserted into the central hexagonal water channel. Additional fuel rods were added to the outer regions of the lattices to achieve criticality. In the fourth and fifth configurations, additional rods were removed to create a horizontal water channel, similar to the first nine configurations of CED-1 and a planned configuration in IER-304 CED-2 report [8]. The sixth configuration included an additional vertical channel. Rods were also added to achieve criticality. Using these six different configurations makes it possible to test a wide range of B_4C concentrations, neutron spectra, and energies corresponding to the average lethargy of neutrons causing fission (EALF).

This report includes several calculations required for the final design, or CED-2. All calculations were performed with SCALE 6.3.1/KENO-VI using the ENDF/B-VIII.0 continuous energy cross section library, and all results are given for a statistical calculation uncertainty of 10 pcm on the final calculated k_{eff} unless noted in the text. It is proposed that these experiments be performed with existing 7uPCX fuel rods at SNL. Nearly all physical components of the systems are kept the same as that documented in previously created benchmarks or in currently executed experiments at the SPRF/CX critical assembly as LCT-078 [10] and IER-441 [9], including the fuel rods, grids, detectors, assembly, dump tanks, and all other parts. Figure 3 presents an overview of the assembly from LCT-078 [10] loaded with the 7uPCX fuel rods.

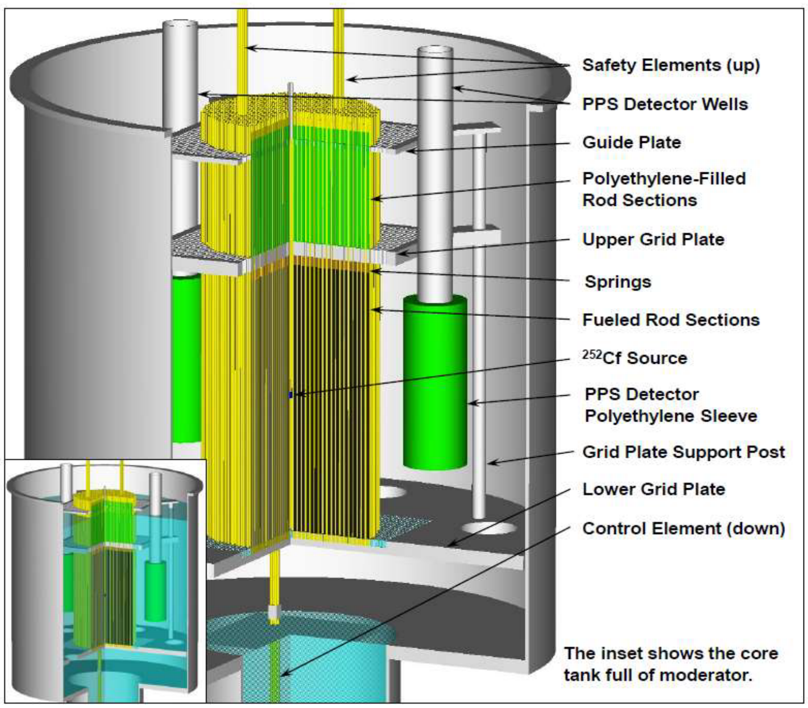

Figure 3. Experimental apparatus of the SPRF/CX from LEU-COMP-THERM-078 [10].

Figure 1 shows the fuel rod layout (1158 rods) in this assembly for an example preliminary configuration of IER-441 and 85 tantalum rods in an aluminum central region, rendered with SCALE Fulcrum, which is the starting point of this study. After removing the tantalum rods and central region, the neutron absorber plates were placed vertically in an aluminum holder in the central channel, thus decreasing the assembly reactivity compared to the version with only water in the center, and the fuel rod configuration is arranged to achieve criticality. A fuel layout of Configuration 1, one of the new configurations proposed, is shown in Figure 2. These lattice structures are both near delayed critical when fully moderated and fully reflected by pure water regulated at 25 °C (298 K). A 3D view of the neutron absorber plate inserted in the aluminum holder through the central grid holes is shown in Figure 4.

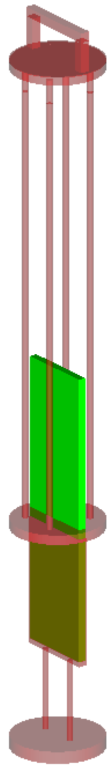

Figure 4. Example view of the neutron absorber plate (green) inserted in the aluminum holder (red) in the center of the assembly.

2. PROPOSED EXPERIMENT CONCEPT

The experiments described here as part of IER-554 are summarized in Table 1. The configurations all use the 7uPCX fuel rods with a pitch of 1.016 cm. The first three configurations include Boralcan plates of three different B_4C compositions and thicknesses and constant widths/lengths of 8 × 30 cm. The additional three configurations use the same plate as that used in Configuration 1 and a different rod arrangement. By changing the layout of fuel rods to reach delayed critical, the use of these different combinations of Boralcan plate characteristics allows a broader range of different parameters to be tested such as the EALF, neutron spectrum in the assembly, or k_{eff} material sensitivities. In all the configurations, the Boralcan plates are inserted in a 3003 aluminum alloy holder. The aluminum holder was designed to allow for safe insertion of the neutron absorber plates in the core from the top and through the central grid plate holes. Configurations 1 through 3 use neutron absorber plates measuring 8 × 30 cm and a central hexagonal water region corresponding to a circular region of about 10 cm diameter, as shown in Figure 5. Configuration 4 uses the same plate as that used in Configuration 1, with an additional horizontal water channel of 5 rod rows measuring approximately 4.6 cm wide. Configuration 5 is similar to Configuration 4, with the Boralcan plate turned 90 degrees. In Configuration 6, an additional vertical water channel approximately 4.6 cm wide is added. Configurations 4, 5 and 6 are shown in Figure 6. During the approach to critical, the central water region or water channels should not be modified, and the rods should only be added to the outer locations of the array. In the six critical configurations described, the neutron absorber plates are centralized in the assembly, and the thin face is perpendicular to the floor. For each of the six critical configurations, additional calculations were performed, adding more depth to the information provided. A first set of additional calculations was performed by replacing the Boralcan plate with a 1100 aluminum alloy plate of the same dimensions, and a second set of calculations was performed by simply removing the plate from the assembly. Those experiments help demonstrate the impact of the Boralcan plate separated from the water displacement effect, giving more information as a result. Additional critical configurations testing different parameters can be obtained by changing the plate's position, inducing analysis of different effects on the assembly's neutron spectrum. It would also be possible to change other parameters, such as the size of the water channel for a given plate width, fuel rod pitch, use of different fuel rods available at the SPRF, such as the Burnup Credit Critical Experiment (BUCCX), to obtain different UO_2 enrichments and neutron energy spectra.

Table 1. Configuration description

Configuration number	Boralcan sample characteristics			Configuration description	Number of fuel rods	EALF at 298 K (eV)
	B_4C concentration (vol %)	Width × length (cm)	Thickness (cm)			
1	16	8 × 30	0.75	Hexagonal central water region	979	0.179
2	23	8 × 30	0.30		965	0.178
3	17	8 × 30	0.17		948	0.176
4	16	8 × 30	0.75	5 rows central channel	1,020	0.161
5	16	8 × 30	0.75	5 rows central channel, plate turned	1,027	0.161
6	16	8 × 30	0.75	90 degrees cruciform central channel	1,092	0.143

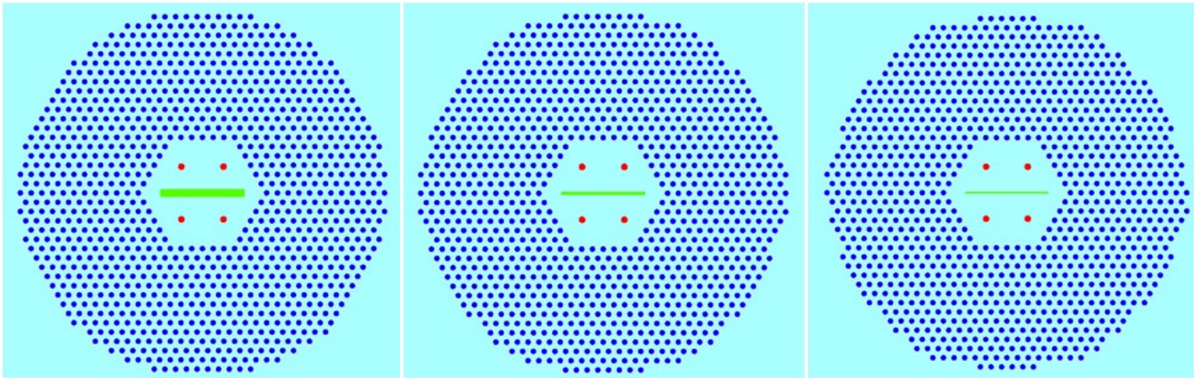

Figure 5. Configurations 1, 2, and 3. B_4C neutron absorber plate is shown in green, and aluminum holder parts are shown in red.

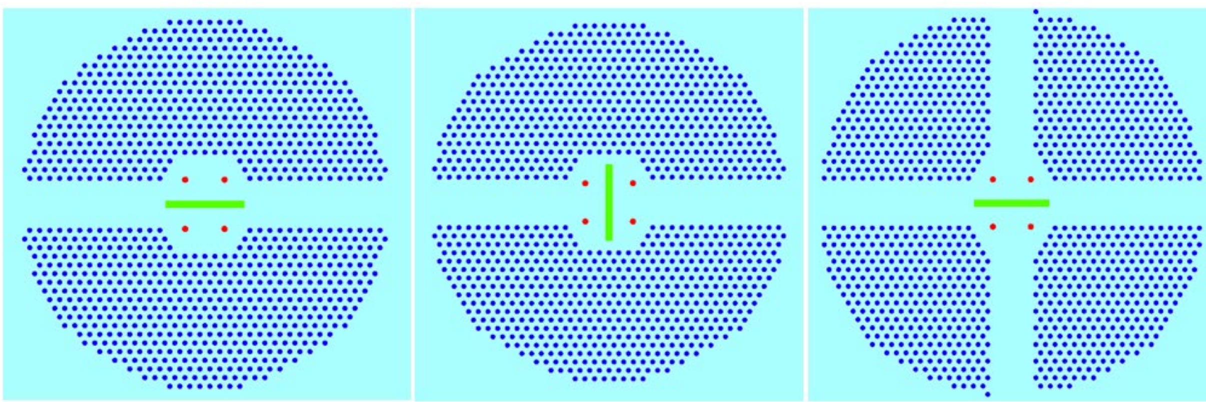

Figure 6. Configurations 4, 5, and 6. B_4C neutron absorber plate is shown in green, and aluminum holder parts are shown in red.

3. NEUTRON ABSORBER PLATES DESCRIPTION AND CHARACTERIZATION PLANS

3.1 PROCUREMENT AND INITIAL INFORMATION

The procurement and characteristics of the Boralcan plates were detailed in the CED-1 report [2]. Manufacturing Sciences Corporation (MSC) [11] agreed to sell samples of Boralcan plates manufactured by Rio Tinto [12]. The characteristics of the products selected from wider possibilities are shown in Table 2. Sample 1 was chosen for its maximum thickness, sample 3 for its maximum B_4C concentration, and sample 4 for its minimal thickness out of seven possibilities. These three samples can be cut to any desired width and length.

Table 2. Overview of chosen Boralcan sample products

Sample number	Designation	Thickness (cm)	B_4C concentration (vol %)
1	W1100N.16B	0.75	16
3	W1100N.23B	0.30	23
4	W1100N.17B	0.17	17

For CED-1, MSC provided an informative budgetary quote for procurement of several samples. Because the plate dimensions requirements changed, MSC is creating an updated budgetary quote for the plates. MSC also provided various example documents characterizing each batch of products they receive from UK Abrasive and Rio Tinto. The same documents will be obtained for each plate procured from MSC. Capital information was obtained from these documents:

- B_4C Certificate of Conformance: measured boron and ^{10}B concentration, average measured B_4C powder particles size
- Boralcan Chemical Analysis Certificate: 1100 aluminum material composition
- Boralcan metallographic report: overview of B_4C particle uniformity in the finished Al-B_4C metal matrix product

3.2 ^{10}B AREAL DENSITY

Regardless of the valuable information obtained by the manufacturers, the exact material composition of the plates and the uniformity of the B_4C powder concentration in each plate can still be questioned. For example, the uniformity of B_4C particles in the plate could be modified when MSC performs the rolling of the Boralcan products. Moreover, the US NRC standard review plan for dry storage of spent nuclear fuel, NUREG-2215 [5], suggests that neutron absorber materials be characterized by neutron transmission measurements to obtain the ^{10}B areal density at different locations of the plate. The expected result from these measurements is a uniform ^{10}B areal density, guaranteeing the uniform neutron absorbing effects of the plates to prove that they can be used for storage and transportation of spent nuclear fuel and/or other fissile materials. The neutron transmission measurements of the selected Boralcan samples will be performed by Curtiss-Wright/NETCO [13] at the Breazeale Reactor Facility at Penn State University (PSU) [14]. Curtiss-Wright is responsible for performing some of those required measurements for the industry. An informative budgetary quote for measurements performed by Curtiss-Wright/NETCO is being created. It should be noted that the B_4C included in the absorber plates contains natural boron, although the ^{10}B content is specified and confirmed via the proposed neutron transmission measurements.

3.3 X-RAY COMPUTED TOMOGRAPHY

Another way to check the B_4C particles uniformity is by performing x-ray computed tomography (CT) measurements of each Boralcan sample. According to the manufacturer's characterization documents, the B_4C particles to be resolved by the imaging system are estimated to range between 10 and 100 µm. After internal discussions with the Materials Science and Technology Division (MSTD) at ORNL, the B_4C particles should be observable using their Zeiss Versa 510 XCT machine. This system can achieve 700 nm spatial resolution in a 3D picture, and the maximum sample size is 30 cm, corresponding to the Boralcan sample plate chosen in the designed experiments. Figure 7 shows an example image obtained using this device [15] alongside a metallographic image of a Boralcan sample given by Rio Tinto [12]. The particle sizes appear to be similar, even if the B_4C and aluminum alloys have similar densities (approximately 2.52 g/cm^3 and 2.71 g/cm^3, respectively). The cross section with x-rays of 50 KV are different enough to have a contrast factor of two between B_4C and Al, which is considered sufficient for the present application.

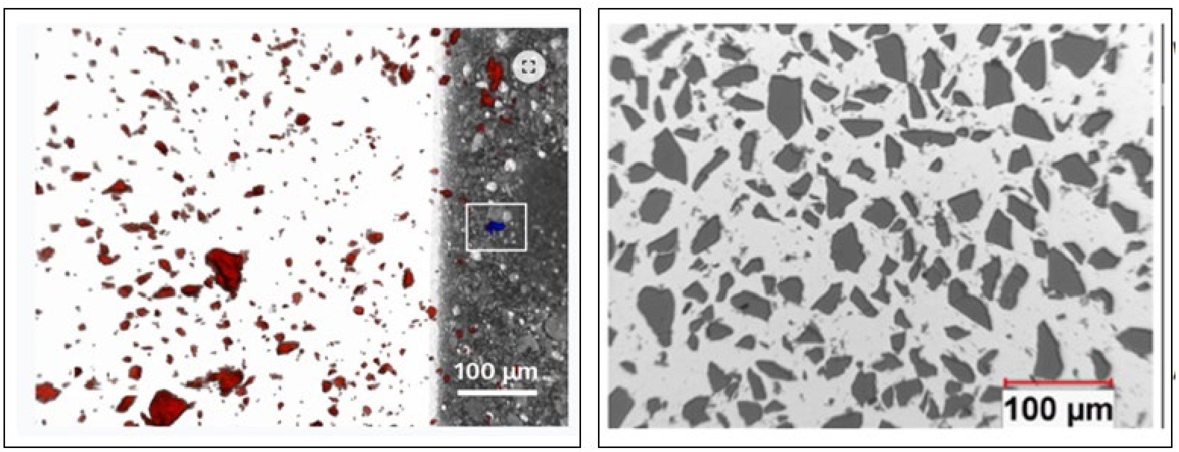

Figure 7. Example X-ray CT image obtained by Zeiss Xradia Versa device [15] (left); and excerpt of Boralcan metallographic report created by Rio Tinto [12] (right).

3.4 CHEMICAL ASSAY AND GEOMETRICAL CHARACTERIZATION

In another characterization step, coupons from the chosen Boralcan samples will be sent for chemical assay analysis to ensure that the concentration data given by the manufacturer are correct. When SNL receives the Boralcan plates, they will also perform a dimension and weight characterization of each plate to reduce experiment uncertainties.

3.5 PLATE MODELING METHODOLOGY

By using the different characterization results described above, particularly the 3D picture obtained by x-ray CT, approximation of the absorber plate modeling methodology being used can be checked. The neutron absorber plates are typically modeled as a single homogeneous mixture, an approach which neglects the fact that the boron carbide particles are in a powder state. Explicitly modeling of the B_4C powder particles has been shown to have little or no influence on k_{eff} in the CED-1 report [2]. The next step for this study will be to use a previously developed methodology in SCALE/Sampler to create random models. These models will contain randomly sampled B_4C ellipsoids with semi-major axes that cover a defined range. The B_4C particle positions will also be varied in the plate, all while maintaining the total B_4C mass. The sensitivity of k_{eff} to these different tests will be determined, and the accuracy of these hypotheses can be checked by comparing the results to the actual experimental results. For example, flipping the plates upside down in the experiments could reveal potential B_4C nonuniformity in the plate, and the assembly eigenvalue could be different. Furthermore, different plates of theoretically the same material composition can be interchanged. The final step of this work will be to create a Boralcan model replicating the concentration of B_4C particles derived in the actual x-ray CT measurement of the plate as closely as possible. Creating such a model and comparing the k_{eff} results with those of a homogeneous mixture will yield valuable results that can be used to evaluate the current modeling methodology.

3.6 SUMMARY OF CHARACTERIZATION STEPS

Performing these subsequent characterization steps on each plate that is inserted in the SPRF/CX facility will decrease the uncertainty of the experiment and will also provide very valuable information about the uniformity of the Boralcan product. Characterization plans for the plates are summarized in Figure 8. The results of all these tests and characterization will be used to develop evaluation models and ultimately benchmark models.

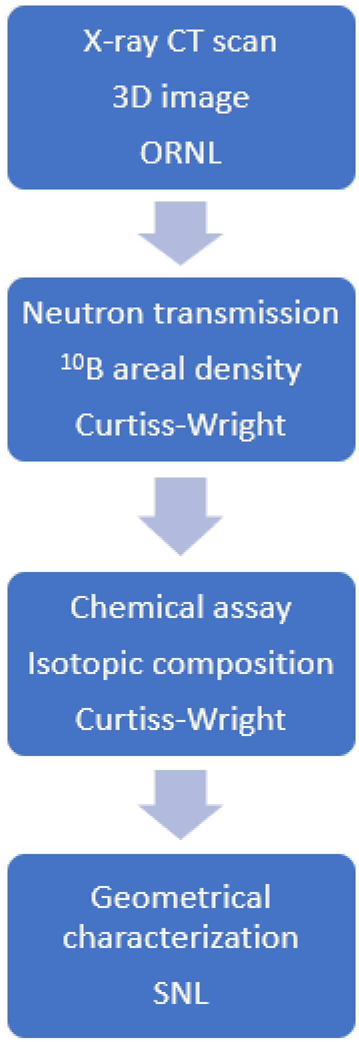

Figure 8. Characterization steps for each Boralcan plate, including the methodology, the results, and the location/organization performing the measurement.

4. ALUMINUM PLATE HOLDER DESIGN

The plates should be held and remain immovable in the assembly during the experiments. A preliminary design of a plate holder was developed in this effort; final design and manufacturing details will be established by SNL staff during CED-3a. To facilitate insertion of the plates in the system with a minimal effect on k_{eff}, a plate holder was modeled in KENO-VI as shown in Figure 9. The plate holder will be made of 3003 aluminum alloy to limit the influence on k_{eff}. As described above, the holder was designed to be inserted from the top of the assembly using the grid plates created for IER-441 with a central hole of approximately 9 cm in diameter. Dimensions of the designed plate holder and an example Boralcan plate are shown in Figure 10. The design goal was to make the item as sturdy as possible using as little material as possible. The overall length of the plate holder is 77 cm, approximately corresponding to the length of the fuel rods, so the handle will still be accessible from outside the assembly when inserted. The bottom part of the plate holder will be lodged in the bottom hole of the newly designed guide plate, and the top cylindrical part will be lodged in the newly designed guide plate, which is above the water level in the assembly tank. The 9.7 cm diameter lip will ensure that the plate holder fits securely; the lip is slightly bigger than the diameter of the central hole in the guide plate, as seen in the top right of Figure 10. The handle on top facilitates insertion into the core. In the current design, the slot for the Boralcan plate is 15 cm deep, which corresponds to half of the plate length and ensures that the plate does not move during operation. It should be noted that the addition or removal of aluminum parts from the current plate holder design has a minimal effect on the experiments' k_{eff} on the order of the calculation uncertainty of 10 pcm. To further increase the safety of the holder, a method to either encapsulate the top part of the Boralcan plate or to temporarily attach it to the holder could be implemented in the CED-3a phase of the integral experiment request. The thickness of the plate hole is 0.75 cm, which corresponds to the plate used in Configurations 1, 4, 5 and 6. Because the Boralcan plates used in the experiments are of three different thicknesses (0.75, 0.30 and 0.17 cm), three different plate holders are needed to safely accommodate plate insertion. Marco Steel and Aluminum Inc. [16] was contacted to provide an approximate budgetary quote for the three aluminum holders. As mentioned above, SNL will facilitate procurement during CED-3a.

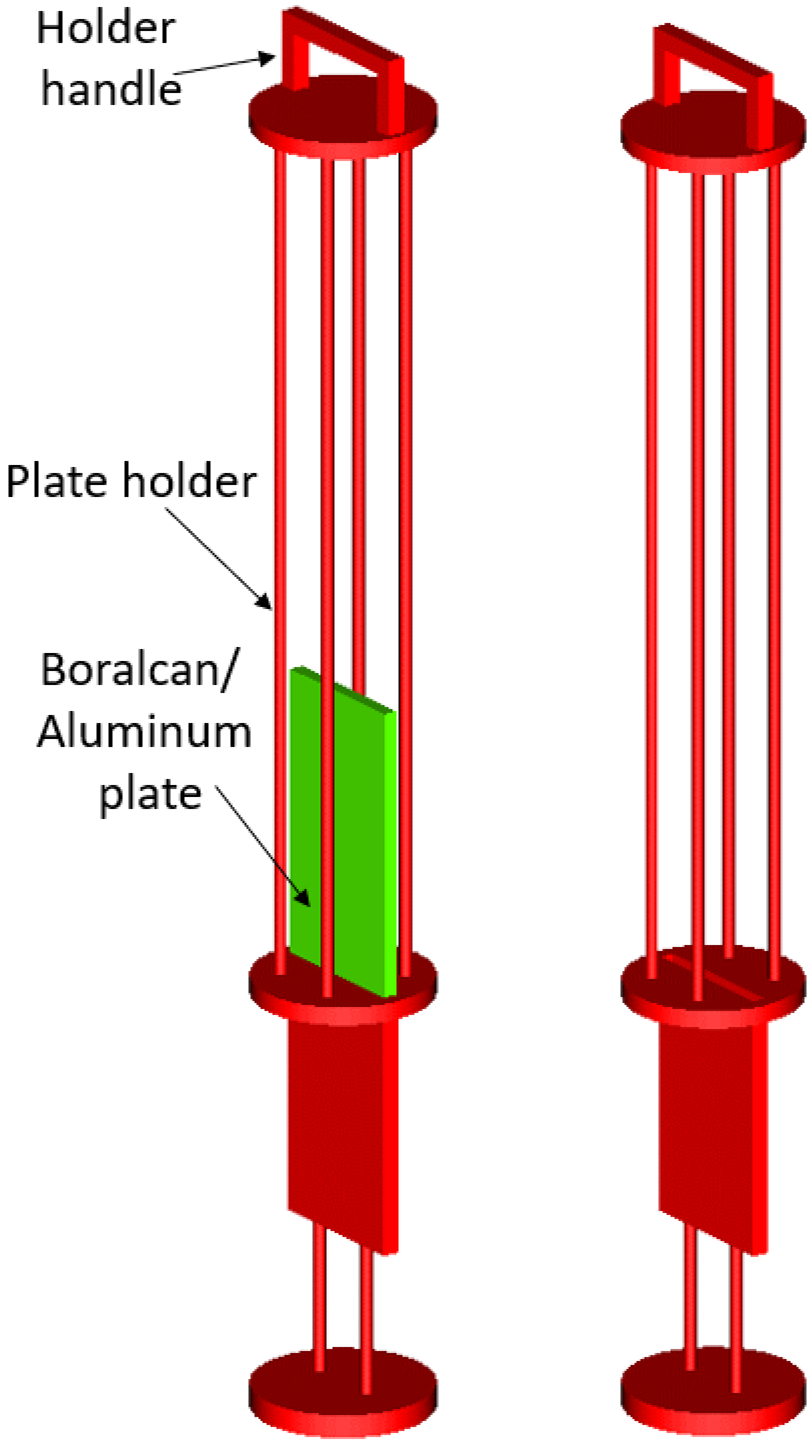

Figure 9. Aluminum plate holder with Boralcan plate inserted (left), and without Boralcan plate inserted (right).

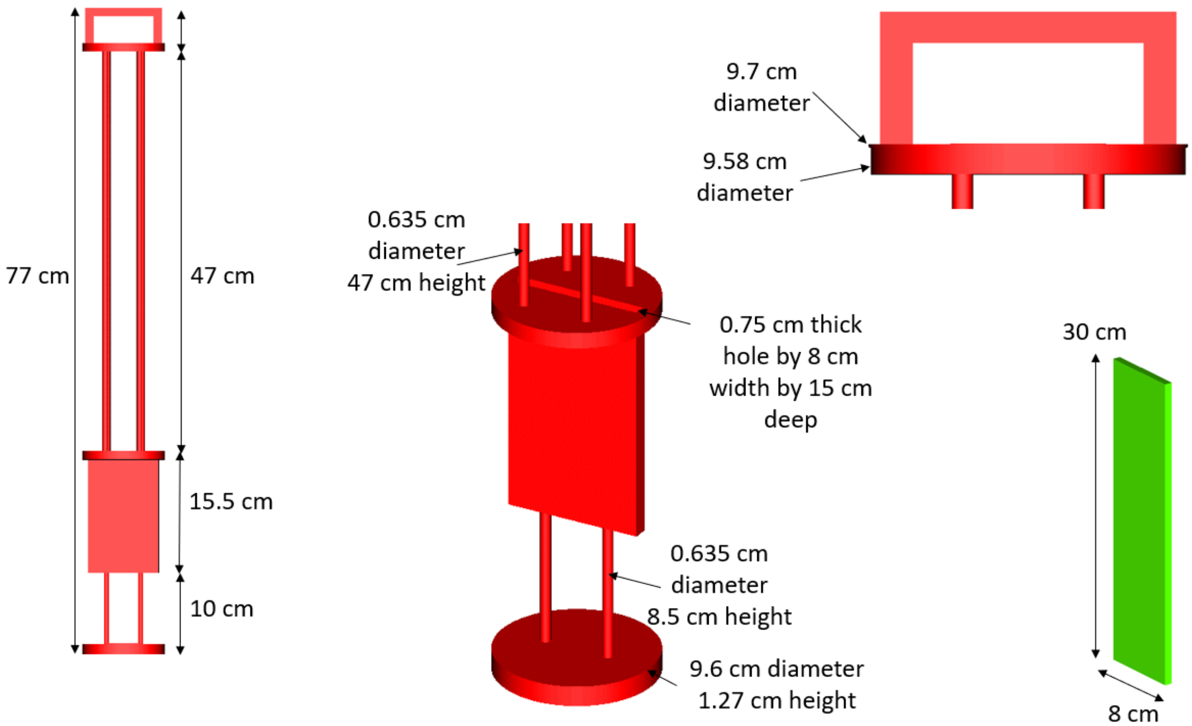

Figure 10. Dimensions of the 0.75 cm thick aluminum plate holder and a Boralcan plate.

5. DETAILED DESCRIPTION OF THE PROPOSED EXPERIMENTS

This section describes the six critical configurations in more detail. For each configuration, the following information is given:

- Table summarizing the primary information about the configuration (plate characteristics, k_{eff} with and without the neutron absorber plate, k_{eff} with the neutron absorber plate replaced by an aluminum plate)
- Rod layout with the array visible to facilitate rod placement
- Fission map

An overview of the six configurations' characteristics is given in Table 3. In addition to the type of information given in Table 1, this table includes k_{eff} calculation results and other parameters. The influence of the insertion of the Boralcan plates in the assembly is observed, with a loss of about 2,000–3,300 pcm with the insertion of the 8 × 30 cm plate, depending on the plate's thickness, B_4C concentration, and water region configuration. Replacing the neutron absorber plate with an aluminum plate significantly increases k_{eff} to be slightly above a configuration in which no plate is inserted.

Table 3. Overview of the six critical configurations characteristics with k_{eff} calculation results

Config. number	Boralcan sample characteristics			Fuel rods number	Water channel (cm)	EALF at 25 °C (298 K) (eV)	k_{eff} with Boralcan plate	k_{eff} without Boralcan plate	k_{eff} with Al plate
	B_4C concentration (vol %)	Width × length (cm)	Thickness (cm)						
1	16	8 × 30	0.75	979	Hexagonal 11.56 × 9.88	0.179	0.99996	1.03323	1.03563
2	23	8 × 30	0.30	965		0.178	0.99978	1.03096	1.03196
3	17	8 × 30	0.17	948		0.176	0.99962	1.02747	1.02825
4	16	8 × 30	0.75	1,020	Horizontal 4.6	0.161	1.00001	1.02659	1.02874
5	16	8 × 30	0.75	1,027		0.161	0.99980	1.02789	1.03004
6	16	8 × 30	0.75	1,092	Horizontal 4.6 And vertical 5	0.143	0.99950	1.01985	1.02153

5.1 CONFIGURATION 1

An overview of the Configuration 1 characteristics is given in Table 4. The rod layout is given in Figure 11, and the fission map is given in Figure 12.

Table 4. Overview of Configuration 1 characteristics

Configuration 1: hexagonal water channel and Plate 1 of 8 × 30 × 0.75 cm							
Boralcan sample characteristics			Fuel rods number	EALF at 25 °C (eV)	k_{eff} with Boralcan plate	k_{eff} without Boralcan plate	k_{eff} with Al plate
B_4C concentration (vol %)	Width × length (cm)	Thickness (cm)					
16	8 × 30	0.75	979	0.179	0.99996	1.03323	1.03563

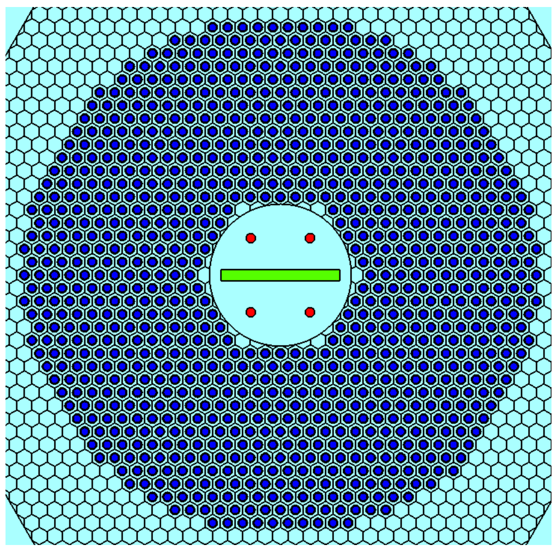

Figure 11. Configuration 1 rod layout.

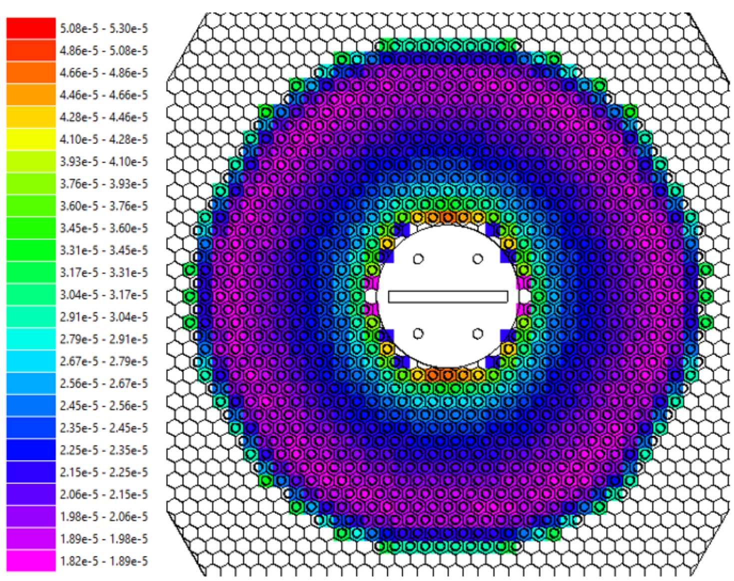

Figure 12. Configuration 1 fission map, fissions neutrons per cm^3 per source neutron.

5.2 CONFIGURATION 2

An overview of the Configuration 2 characteristics is given in Table 5. The rod layout is given in Figure 13, and the fission map is given in Figure 14.

Table 5. Overview of Configuration 2 characteristics

Configuration 2: hexagonal water channel and Plate 2 of 8 × 30 × 0.30 cm							
Boralcan sample characteristics			**Fuel rods number**	**EALF at 25 °C (eV)**	**k_{eff} with Boralcan plate**	**k_{eff} without Boralcan plate**	**k_{eff} with Al plate**
B_4C concentration (vol %)	**Width × length (cm)**	**Thickness (cm)**					
23	8 × 30	0.30	965	0.178	0.99978	1.03096	1.03196

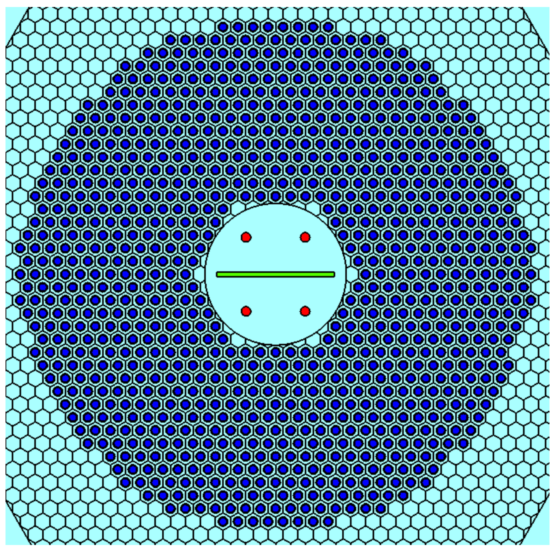

Figure 13. Configuration 2 rod layout.

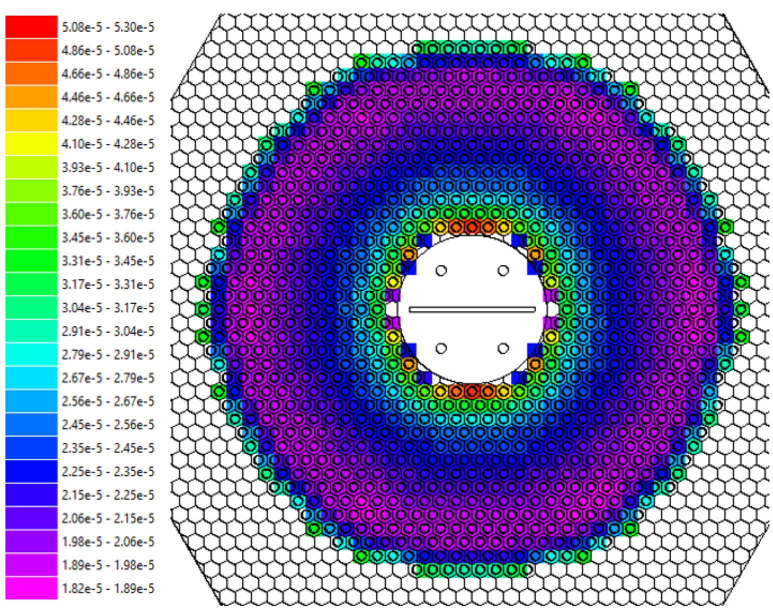

Figure 14. Configuration 2 fission map, fissions neutrons per cm^3 per source neutron.

5.3 CONFIGURATION 3

An overview of the Configuration 3 characteristics is given in Table 6. The rod layout is given in Figure 15, and the fission map is given in Figure 16.

Table 6. Overview of Configuration 3 characteristics

Configuration 3: hexagonal water channel and Plate 3 of 8 × 30 × 0.17 cm							
Boralcan sample characteristics			**Fuel rods number**	**EALF at 25 °C (eV)**	**k_{eff} with Boralcan plate**	**k_{eff} without plate**	**k_{eff} with Al plate**
B_4C concentration (vol %)	**Width × length (cm)**	**Thickness (cm)**					
17	8 × 30	0.17	948	0.176	0.99962	1.02747	1.02825

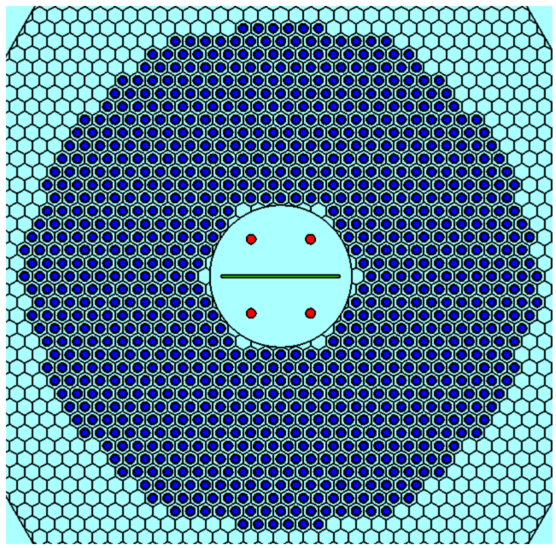

Figure 15. Configuration 3 rod layout.

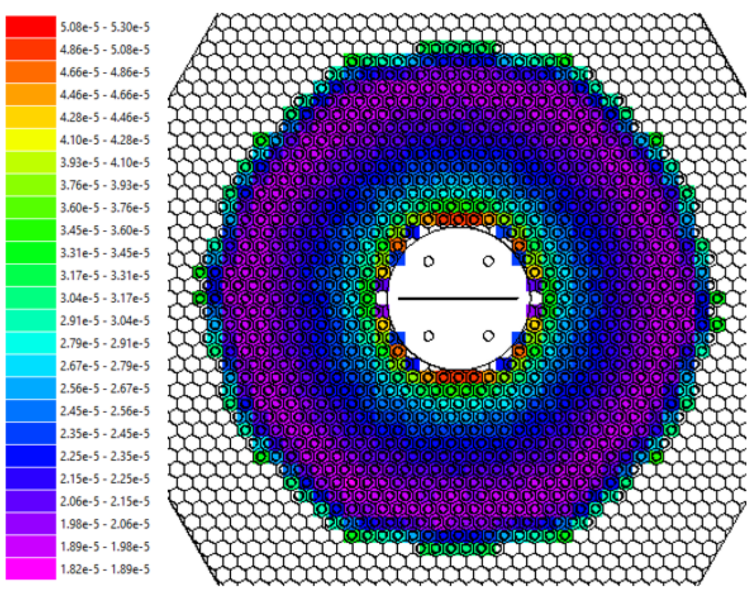

Figure 16. Configuration 3 fission map, fissions neutrons per cm^3 per source neutron.

5.4 CONFIGURATION 4

An overview of the Configuration 4 characteristics is given in Table 7. The rod layout is given in Figure 17, and the fission map is given in Figure 18.

Table 7. Overview of Configuration 4 characteristics

Configuration 4: 4.6 cm wide horizontal water channel and Plate 1 of 8 × 30 × 0.75 cm							
Boralcan sample characteristics			**Fuel rods number**	**EALF at 25 °C (eV)**	**k_{eff} with Boralcan plate**	**k_{eff} without plate**	**k_{eff} with Al plate**
B_4C concentration (vol %)	**Width × length (cm)**	**Thickness (cm)**					
16	8 × 30	0.75	1,020	0.161	1.00001	1.02659	1.02874

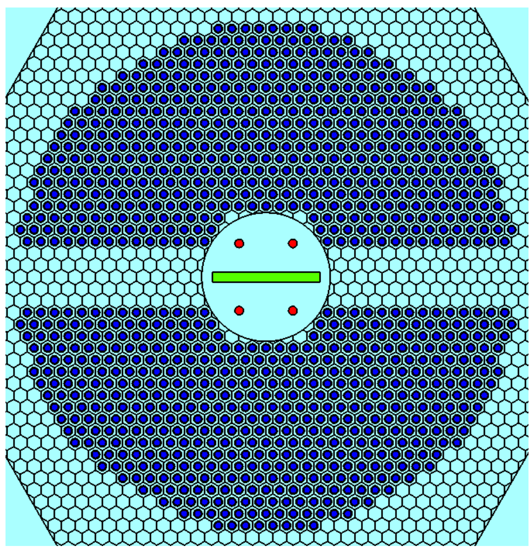

Figure 17. Configuration 4 rod layout.

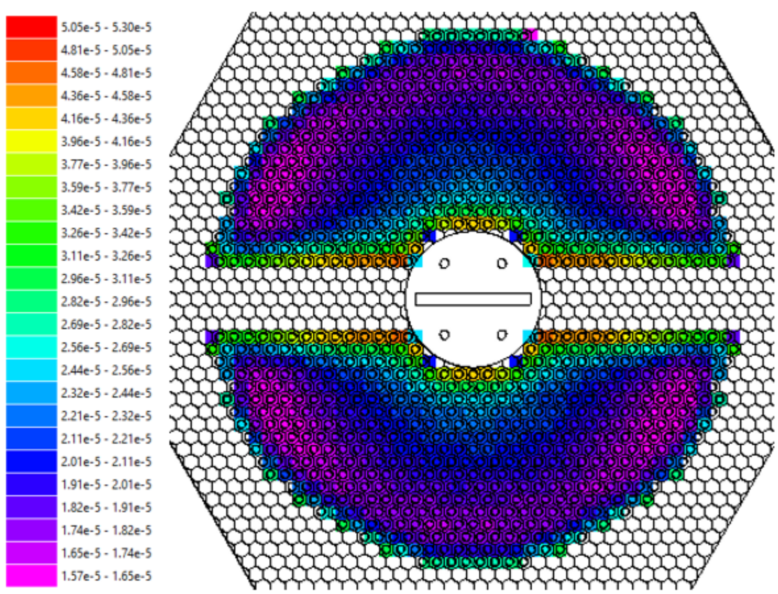

Figure 18. Configuration 4 fission map, fissions neutrons per cm^3 per source neutron.

5.5 CONFIGURATION 5

An overview of the Configuration 5 characteristics is given in Table 8. The rod layout is given in Figure 19, and the fission map is given in Figure 20.

Table 8. Overview of Configuration 5 characteristics

Configuration 5: 4.6 cm wide horizontal water channel and Plate 1 of 8 × 30 × 0.75 cm turned 90 degrees							
Boralcan sample characteristics			**Fuel rods number**	**EALF at 25 °C (eV)**	**k_{eff} with Boralcan plate**	**k_{eff} without Boralcan plate**	**k_{eff} with Al plate**
B_4C concentration (vol %)	**Width × length (cm)**	**Thickness (cm)**					
16	8 × 30	0.75	1,027	0.161	0.99980	1.02789	1.03004

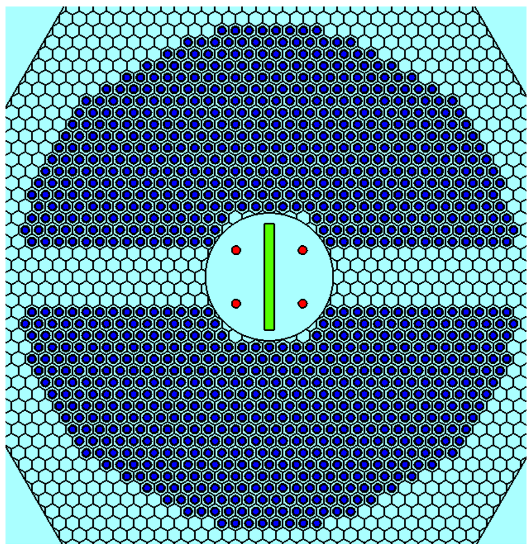

Figure 19. Configuration 5 rod layout.

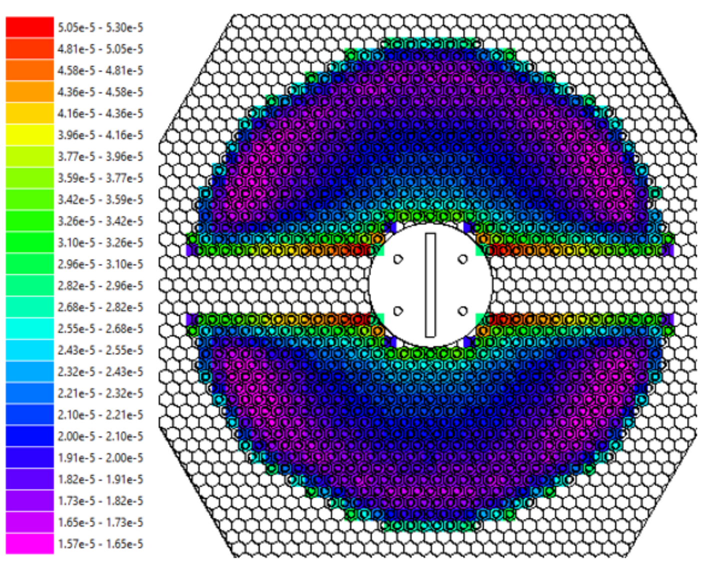

Figure 20. Configuration 5 fission map, fissions neutrons per cm^3 per source neutron.

5.6 CONFIGURATION 6

An overview of the Configuration 6 characteristics is given in Table 9. The rod layout is given in Figure 21, and the fission map is given in Figure 22.

Table 9. Overview of Configuration 6 characteristics

Configuration 6: 4.6 cm wide horizontal and 5 cm wide vertical water channels and Plate 1 of 8 × 30 × 0.75 cm							
Boralcan sample characteristics			**Fuel rods number**	**EALF at 25 °C (eV)**	**k_{eff} with Boralcan plate**	**k_{eff} without Boralcan plate**	**k_{eff} with Al plate**
B_4C concentration (vol %)	**Width × length (cm)**	**Thickness (cm)**					
16	8 × 30	0.75	1,092	0.143	0.99950	1.01985	1.02153

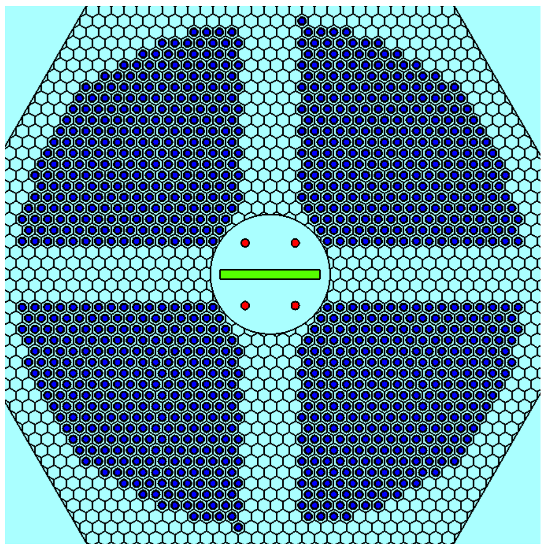

Figure 21. Configuration 6 rod layout.

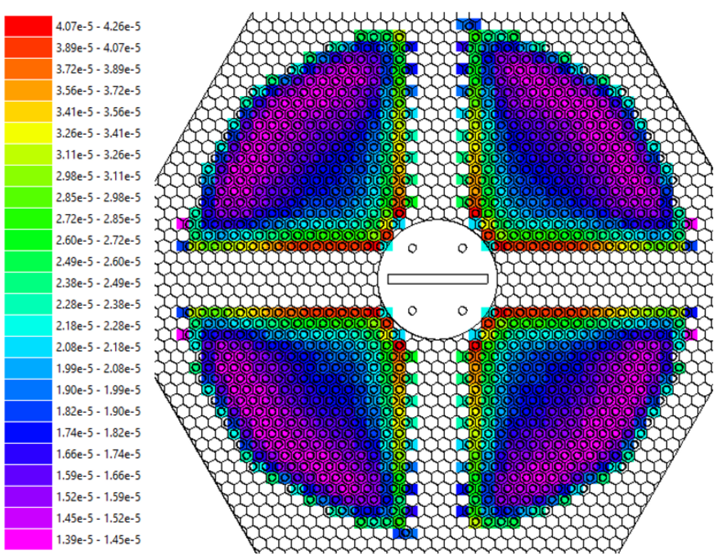

Figure 22. Configuration 6 fission map, fissions neutrons per cm^3 per source neutron.

6. SPECTRAL COMPARISONS

The spectra of neutron absorption reaction rates by ^{10}B in the Boralcan plates calculated by KENO-VI are shown in Figure 23 for the six critical configurations. Table 10 compares the neutron absorption reaction rates converted to a three-group energy structure (i.e., thermal, intermediate, and fast). Overall, the reaction rates are similar across all configurations, with absorptions mainly occurring in the thermal region. Configuration 3, which includes the thinnest Boralcan plate, appears to have a slightly higher peak of absorption at 0.0253 eV than the other configurations, and it has a lower absorption rate compared to the other configurations at higher energies, such as the visible peak at 550 eV. The graphical observations are confirmed by the results shown in Table 10. The thinner the Boralcan plate is, the higher the thermal neutron absorption proportion. The energy breakdown differences seen when comparing Configurations 4, 5 and 6 are small, because the same plate is used. Configurations 4 and 5 have a higher thermal proportion than Configuration 1 because of the horizontal channel added, and Configuration 6 has an even higher thermal proportion because of the vertical water channel added. These results show that the B_4C concentration has less influence than the thickness of the Boralcan plate on the absorption events by ^{10}B.

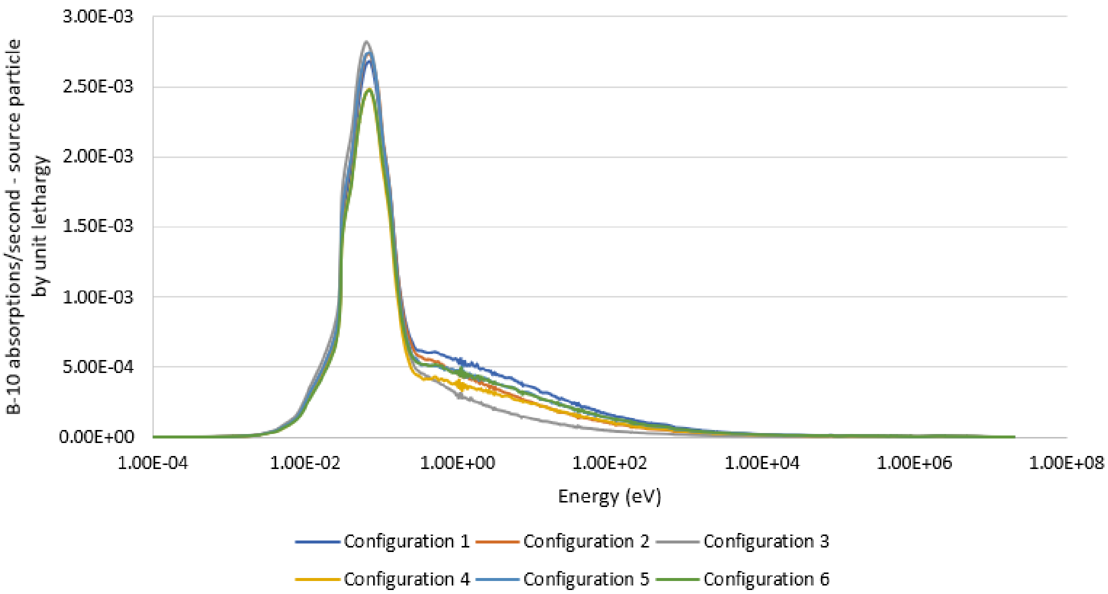

Figure 23. Comparison of neutron absorption rate spectra for the six configurations.

Table 10. Energy breakdown of ^{10}B absorption events for all six configurations

Configuration	B_4C concentration (vol %)	Width × length × thickness (cm)	Thermal (%)[1]	Intermediate (%)[2]	Fast (%)[3]
1	16	8 × 30 × 0.75	71.2	28.5	0.3
2	23	8 × 30 × 0.30	77.6	22.2	0.2
3	17	8 × 30 × 0.17	86.0	13.9	0.1
4	16	8 × 30 × 0.75	74.6	25.1	0.3
5	16	8 × 30 × 0.75	72.8	26.9	0.3
6	16	8 × 30 × 0.75	76.5	23.3	0.3

[1] Thermal: E < 0.625 eV
[2] Intermediate: 0.625 eV < E < 100 keV
[3] Fast: 100 keV < E

7. SENSITIVITY STUDY

As in the CED-1 report effort, CE-TSUNAMI 3D is used in this study to calculate k_{eff} sensitivities for various mixtures, elements, and isotopes in different critical configurations. Instead of calculating the sensitivities of the six configurations, only the most different configurations are being studied. Focusing on Configurations 1, 3, 4, and 6 will address the different system sensitivities because the thickness and B_4C concentration of the Boralcan plates changes between Configurations 1 and 3, and the water region shapes and volumes are changed between Configurations 1, 4, and 6. The following tables show the most sensitive results, always with neutron absorber–related sensitivities (Boralcan and ^{10}B). All TSUNAMI sensitivity results in this section were checked with direct perturbations calculations.

The calculated sensitivities of k_{eff} to the fuel, water, and Boralcan are shown in Table 11. Overall, the mixture sensitivities are similar across all the configurations. The most notable observations are as follows:

- In all configurations, the most sensitive mixture is water, followed by UO_2 fuel.
- The sensitivity to Boralcan is low, indicating that a small relative difference in the plate density has a minimal relative influence on k_{eff}.
- Configurations 1 and 3 sensitivity results are similar but are higher in absolute values for all three mixtures in Configuration 3, indicating that this configuration is more sensitive overall.
- The Boralcan sensitivity has a higher magnitude in Configurations 1 and 3 compared to Configurations 4 and 6. This is because there is less water in the system in Configurations 1 and 3, so the Boralcan plates have a greater influence on k_{eff}.
- Similarly, the water sensitivity is higher in Configurations 1 and 3 compared to 4 and 6 because there is less water in the system in Configurations 1 and 3. These results are addressed in the next paragraph by separating the water regions into different categories: moderator, reflector, and central region.

Table 11. TSUNAMI sensitivity results by mixture for Configurations 1, 3, 4, and 6

Mixture	Configuration 1		Configuration 3		Configuration 4		Configuration 6	
	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Sensitivity	Uncertainty
UO_2 fuel	9.61E-02	1.2%	9.84E-02	1.2%	1.01E-01	1.1%	1.12E-01	1.0%
Water	3.77E-01	1.5%	3.85E-01	1.6%	3.26E-01	1.9%	2.07E-01	3.3%
Boralcan	-4.02E-03	2.3%	-4.41E-03	1.3%	-2.95E-03	2.8%	-2.03E-03	3.4%

In the following calculation, the focus is on water. As in previous studies [8, 17], the water has been separated into three different regions in the model, as shown in Figure 24. The moderator region is defined as the water between the fuel rods, the central water corresponds to the water channel or central region where the Boralcan plate is located, and the reflector is the water region outside the array of fuel rods. The calculated sensitivity of k_{eff} to water is shown in Table 12. Overall, the mixture sensitivities are mostly similar between configurations. The most notable observations are as follows:

- In all configurations, the most sensitive water region is the moderator region.
- Sensitivity results for Configurations 1 and 3 are similar but are higher in absolute values for all three regions in Configuration 3, indicating that this configuration is more sensitive overall.
- The moderator region sensitivity decreases with increasing water channel regions.

- The central water region's absolute sensitivity increases with increasing water channel region volume. It is always negative.
- The reflector region sensitivity decreases with increasing central water region volume.

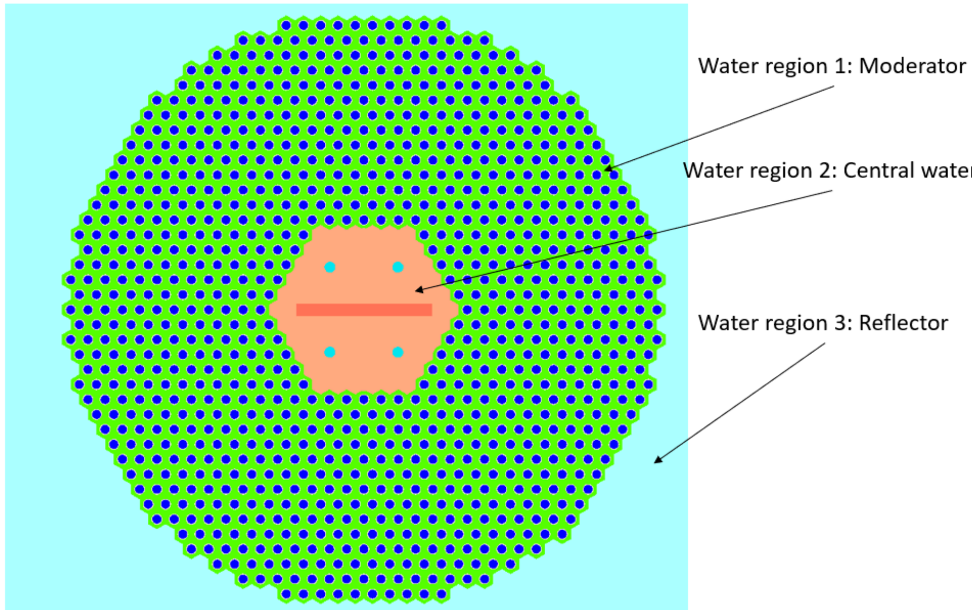

Figure 24. Water region separation for sensitivity study.

Table 12. TSUNAMI sensitivity results in different water regions for Configurations 1, 3, 4, and 6

Material	Configuration 1 Central water hexagonal 11.56 × 9.88 cm		Configuration 3 Central water hexagonal 11.56 × 9.88 cm		Configuration 4 Addition of horizontal channel of 4.6 cm width		Configuration 6 Addition of vertical channel of 5 cm width	
	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Sensitivity	Uncertainty	Sensitivity	Uncertainty
Moderator	3.59E-01	1.0%	3.74E-01	1.0%	3.18E-01	1.1%	2.76E-01	1.2%
Central water	-2.31E-02	9.0%	-3.50E-02	6.8%	-2.16E-02	17.6%	-8.90E-02	5.4%
Reflector	4.04E-02	9.6%	4.61E-02	8.9%	2.93E-02	12.6%	1.97E-02	18.0%

The sensitivities of isotopes to k_{eff} calculation results are shown in Table 13. Overall, the isotope sensitivities are mostly similar across configurations. The sensitivity results obtained for hydrogen in the reflector region and oxygen in the central water region are removed because of their very low values. The most notable observations are as follows:

- In all configurations, the most sensitive isotope is hydrogen in water, followed by ^{235}U in fuel.
- In all configurations, the greatest negative sensitivity is ^{238}U in fuel, except for Configuration 6, in which the greatest negative sensitivity is hydrogen in the central region. In that configuration, there is so much water that it becomes a strong neutron absorber and significantly reduces k_{eff}.
- The ^{10}B sensitivity is low.

Table 13. TSUNAMI sensitivity results of the most sensitive isotopes for Configurations 1, 3, 4, and 6

Material	Configuration 1		Configuration 3		Configuration 4		Configuration 6	
	Sensitivity	**Uncertainty**	**Sensitivity**	**Uncertainty**	**Sensitivity**	**Uncertainty**	**Sensitivity**	**Uncertainty**
^{16}O in fuel	1.19E-02	5.1%	1.36E-02	4.5%	1.14E-02	5.1%	1.13E-02	4.9%
^{235}U in fuel	1.33E-01	0.5%	1.34E-01	0.5%	1.40E-01	0.5%	1.49E-01	0.5%
^{238}U in fuel	-4.65E-02	1.5%	-4.73E-02	1.5%	-4.83E-02	1.4%	-4.65E-02	1.4%
H in central region	-2.47E-02	8.3%	-3.59E-02	6.6%	-2.69E-02	13.9%	-9.39E-02	5.1%
H in moderator	3.27E-01	1.1%	3.41E-01	1.0%	2.89E-01	1.2%	2.51E-01	1.3%
^{16}O in moderator	3.20E-02	2.7%	3.29E-02	2.6%	2.92E-02	2.9%	2.57E-02	3.1%
^{16}O in reflector	4.11E-02	1.0%	3.98E-02	1.0%	3.53E-02	1.1%	3.18E-02	1.1%
^{10}B in Boralcan	-4.04E-03	0.8%	-4.44E-03	0.8%	-3.02E-03	0.9%	-2.12E-03	1.1%

8. EXPERIMENT UNCERTAINTIES

This section presents an evaluation of the experimental uncertainties of the designed experiments. A new set of grid plates will be used to perform the experiments, along with other core structural components. Those components are manufactured for IER-441 [9] using a 1.016 cm triangular pitch that had not been used in any of the previously published ICSBEP benchmarks from the SPRF/CX. Because these components have not yet been used in a published experiment, their uncertainty could not be evaluated. The other important parameter to consider is the uncertainty in the dimensions and composition of the Boralcan plates and their potential impact on k_{eff}.

Despite those differences, the designed experiments are still quite similar to those previously published in the ICSBEP handbook: the same fuel rods and facility are used, and the same characterization methodology is expected to be used for the new components manufactured, thus leading to an expected similar uncertainty. After analyzing published and currently designed experiments at the SPRF/CX, the most similar configurations to the designed experiments in this IER are from LCT-102 case 12 [18], in which a square pitch of 1.1315 cm is used, and CED-2 of IER-304 case 9 at 25 ºC [8], in which a central water channel is used. All experiments use the 7uPCX fuel rods. The parameters leading to the highest k_{eff} uncertainty were identified from these two experiments, and their k_{eff} uncertainty was evaluated again for the experiments described in this report following the methodology described in LCT-102. The five identified parameters having the biggest influence on k_{eff} uncertainty are fuel enrichment, fuel stoichiometry, pitch, cladding outer diameter, and temperature. Regarding the other parameters, which usually lead to less than 20 pcm k_{eff} uncertainty, the values from LCT-102 case 12 are used. Additionally, the experimental uncertainties related to the neutron absorber plates were also explicitly evaluated in this work and added in quadrature to the total experimental uncertainty. The experimental uncertainties are only evaluated for Configurations 1, 3, 4, and 6, representing the parameter bounds of the six configurations.

The experimental uncertainties explicitly evaluated in this work—including the parameters related to the neutron absorber plate and the main k_{eff} uncertainty contributors from previously published ICSBEP benchmarks from the SPRF/CX—are derived by multiplying the sensitivity values obtained by KENO-VI perturbation calculations by their individual uncertainty. The original values, uncertainty values, and source for uncertainty derivation of each parameter and configuration of interest are shown in Table 14. Additional explanations for the choice of uncertainty value for each parameter and configuration are given as follows:

- **Boralcan density.** The uncertainty values correspond to half of the last significant digit of the expected density of the plates. This is the methodology recommended if no information about the density is available. The density of the plate is expected to be measured with an even lower uncertainty during the CED-3 phase.
- **Boralcan width/length/thickness.** In LCT-111 [21], a previous experiment performed at the SPRF/CX, tubes were used and their length was measured with a digital caliper with a specific accuracy, resolution, and repeatability to provide a measurement uncertainty. When the CED-3 phase of this IER begins, staff members from SNL should use a similar measuring device to characterize the Boralcan plates so that the same dimension uncertainty of 0.0.00704 cm will be used for the Boralcan dimensions. It is important to note that the sensitivity of k_{eff} to those dimension parameters is relatively high, so a poor dimension characterization could lead to an increased k_{eff} uncertainty compared to that shown in the following tables.
- **Boralcan ^{10}B content (atoms/b-cm).** The manufacturer of the B_4C powder, UK Abrasives, states that uncertainty in the boron and ^{10}B contents is 0.3%, corresponding to about 3.5E-03 atoms/b-

cm. This uncertainty is expected to be reduced through the chemical assay measurements planned in the CED-3 phase.

- **Fuel enrichment (wt %).** The methodology detailed in Section 2.4.8 of LCT-102 is followed to derive the sensitivity of k_{eff} to the enrichment of the fuel based on (1) the derivation of the sensitivities of the system k_{eff} to the fuel's ^{235}U and ^{238}U atom densities, and (2) the fuel's enrichment uncertainty of 0.0071 %.
- **Fuel stoichiometry:** The methodology detailed in Section 2.4.11 of LCT-102 is followed to derive the sensitivity of k_{eff} to the stoichiometry of the fuel based on (1) the derivation of the sensitivities of the system k_{eff} to the fuel's total uranium and oxygen atom densities, and (2) the fuel's stoichiometry uncertainty of 0.1.
- **Pitch (cm).** The methodology detailed in Section 2.4.1 of LCT-102 is followed to derive the fuel rod pitch uncertainty based on (1) the different grid plate assumed uncertainty factors, and (2) the number of fuel rods on a chord. For this derivation, it is assumed that the water regions are filled with fuel rods.
- **Temperature (°C).** The methodology detailed in Section 2.4.16 of LCT-102 is followed to derive the sensitivity of k_{eff} to the system temperature considering a base value of 25°C and a temperature of uncertainty of 1°C.
- **Clad outer diameter (cm).** The uncertainty value of 0.0000954 cm of the cladding outer diameter is used as explained in Section 2.4.2 of LCT-102. This uncertainty can be used because the same fuel rods are used in both experiments.

Table 14. Uncertainty values for the different parameters used in the uncertainty study

Uncertainty source	Original value	Uncertainty value	Derivation method
Boralcan density (g/cm^3)	2.718 for Configurations 1, 4, and 6; 2.716 for Configuration 3	4.00E-03 for Configurations 1, 4, and 6; 3.00E-03 for Configuration 3	ICSBEP guide to the expression of uncertainties [19]
Boralcan width (cm)	8	0.00714	LCT-111 Section 2.4.20 [21]
Boralcan length (cm)	30	0.00714	LCT-111 Section 2.4.20 [21]
Boralcan thickness (cm)	0.75	0.00714	LCT-111 Section 2.4.20 [21]
Boralcan ^{10}B content (atoms/b-cm)	3.50E-03 for Configurations 1, 4, and 6; 3.73E-03 for Configuration 3	1.05E-05 for Configurations 1, 4, and 6, 1.12E-05 for Configuration 3	UK Abrasives [X]
Fuel enrichment (wt %)	6.90	0.0071	LCT-102 Section 2.4.8 [18]
Fuel stoichiometry	2	1.00E-01	LCT-102 Section 2.4.11 [18]
Pitch (cm)	1.016	7.03E-04 for Configurations 1 and 3; 1.33E-03 for Configuration 4; and 1.20E-03 for Configuration 6	LCT-102 Section 2.4.1 [18]
Temperature (K)	298.15	1	LCT-102 Section 2.4.16 [18]
Clad outer diameter (cm)	0.635	9.54E-05	LCT-102 section 2.4.2 [18]

The expected k_{eff} experimental uncertainties are shown in Table 15 for Configuration 1, in Table 16 for Configuration 3, in Table 17 for Configuration 4, and in Table 18 for Configuration 6, combining the five factors related to the addition of the Boralcan plates and the five factors judged to have the most influence on k_{eff} for their individual uncertainties. In all configurations, the parameters resulting in the highest k_{eff} experimental uncertainties are fuel enrichment and the pitch.

Table 15. Derived sensitivity values and experimental uncertainties for the main uncertainty parameters of Configuration 1

Uncertainty source	Uncertainty value	Sensitivity value	Δk_{eff}
Boralcan density (g/cm^3)	4.00E-03	-2.99E-03	-0.00001
Boralcan width (cm)	7.14E-03	-2.52E-02	-0.00018
Boralcan length (cm)	7.14E-03	-1.98E-02	-0.00014
Boralcan thickness (cm)	7.14E-03	-5.93E-03	-0.00004
Boralcan ^{10}B content (atoms/b-cm)	1.05E-05	-5.07E-03	0.00000
Fuel enrichment (wt %)	7.10E-05	9.05E+00	0.00064
Fuel stoichiometry	1.00E-01	-2.48E-03	-0.00025
Pitch (cm)	7.03E-04	-5.92E-01	-0.00042
Temperature (°C)	1.00E+00	1.17E-04	0.00012
Clad outer diameter (cm)	9.54E-05	-3.68E-01	-0.00004

Table 16. Derived sensitivity values and experimental uncertainties for the main uncertainty parameters of Configuration 3

Uncertainty source	Uncertainty value	Sensitivity value	Δk_{eff}
Boralcan density (g/cm^3)	3.00E-03	-1.26E-03	0.00000
Boralcan width (cm)	7.14E-03	-2.52E-02	-0.00018
Boralcan length (cm)	7.14E-03	-1.51E-02	-0.00011
Boralcan thickness (cm)	7.14E-03	-4.38E-03	-0.00003
Boralcan ^{10}B content (atoms/b-cm)	1.12E-05	-5.81E-03	0.00000
Fuel enrichment (wt %)	7.10E-05	9.89E+00	0.00070
Fuel stoichiometry	1.00E-01	-1.36E-03	-0.00014
Pitch (cm)	7.03E-04	-5.68E-01	-0.00040
Temperature (°C)	1.00E+00	1.04E-04	0.00010
Clad outer diameter (cm)	9.54E-05	-3.61E-01	-0.00003

Table 17. Derived sensitivity values and experimental uncertainties for the main uncertainty parameters of Configuration 4

Uncertainty source	Uncertainty value	Sensitivity value	Δk_{eff}
Boralcan density (g/cm^3)	4.00E-03	-2.07E-03	-0.00001
Boralcan width (cm)	7.14E-03	-2.03E-02	-0.00014
Boralcan length (cm)	7.14E-03	-1.51E-02	-0.00011
Boralcan thickness (cm)	7.14E-03	-5.18E-03	-0.00004
Boralcan ^{10}B content (atoms/b-cm)	1.05E-05	-4.90E-03	0.00000
Fuel enrichment (wt %)	7.10E-05	9.54E+00	0.00068
Fuel stoichiometry	1.00E-01	-1.20E-03	-0.00012
Pitch (cm)	1.33E-03	-4.59E-01	-0.00061
Temperature (°C)	1.00E+00	1.60E-04	0.00016
Clad outer diameter (cm)	9.54E-05	-3.28E-01	-0.00003

Table 18. Derived sensitivity values and experimental uncertainties for the main uncertainty parameters of Configuration 6

Uncertainty source	Uncertainty value	Sensitivity value	Δk_{eff}
Boralcan density (g/cm^3)	4.00E-03	-1.58E-03	-0.00001
Boralcan width (cm)	7.14E-03	-1.70E-02	-0.00012
Boralcan length (cm)	7.14E-03	-1.40E-02	-0.00010
Boralcan thickness (cm)	7.14E-03	-2.85E-03	-0.00002
Boralcan ^{10}B content (atoms/b-cm)	1.05E-05	-4.00E-03	0.00000
Fuel enrichment (wt %)	7.10E-05	1.02E+01	0.00072
Fuel stoichiometry	1.00E-01	-5.08E-03	-0.00051
Pitch (cm)	1.20E-03	-3.03E-01	-0.00036
Temperature (°C)	1.00E+00	2.06E-04	0.00021
Clad outer diameter (cm)	9.54E-05	-2.78E-01	-0.00003

Table 19 gives the expected benchmark k_{eff} uncertainties for Configurations 1, 3 ,4, and 6 using the previously derived uncertainties from the addition of the Boralcan plate and the most influential uncertainty factors from previous evaluations, with the additional experimental uncertainties from LCT-102, Case 12. In the four critical configurations analyzed, the experimental uncertainties are estimated to be between 88 pcm and 102 pcm. The experimental uncertainties for the two remaining Configurations 2 and 5 are expected to be within this range. Using the Boralcan dimension and composition uncertainty values explained above, it is estimated that the addition of the neutron absorber plate will not add any uncertainty to the system. Based on these results, the uncertainty of the designed experiments described in this report are considered low enough to be pursued as long as the Boralcan plates are characterized well enough to reach uncertainties on the order of that detailed previously.

Table 19. Estimated experimental uncertainties for Configurations 1, 3, 4, and 6

Uncertainty source	**Δk_{eff}**			
	Config. 1	Config. 3	Config. 4	Config. 6
Boralcan density (g/cm^3)	-0.00001	0.00000	-0.00001	-0.00001
Boralcan width (cm)	-0.00018	-0.00018	-0.00014	-0.00012
Boralcan length (cm)	-0.00014	-0.00011	-0.00011	-0.00010
Boralcan thickness (cm)	-0.00004	-0.00003	-0.00004	-0.00002
Boralcan ^{10}B content (atoms/b-cm)	0.00000	0.00000	0.00000	0.00000
Fuel enrichment (wt %)	0.00064	0.00070	0.00068	0.00072
Fuel stoichiometry	-0.00025	-0.00014	-0.00012	-0.00051
Pitch (cm)	-0.00042	-0.00040	-0.00061	-0.00036
Temperature (°C)	0.00012	0.00010	0.00016	0.00021
Clad outer diameter (cm)	-0.00004	-0.00003	-0.00003	-0.00003
Clad inner diameter (cm)	0.00000	0.00000	0.00000	0.00000
Fuel outer diameter (cm)	0.00000	0.00000	0.00000	0.00000
Upper reflector thickness (cm)	0.00000	0.00000	0.00000	0.00000
Fuel rod UO_2 mass (g)	0.00003	0.00003	0.00003	0.00003
Fuel rod pellet stack height (cm)	0.00002	0.00002	0.00002	0.00002
^{234}U fuel contents	0.00000	0.00000	0.00000	0.00000
^{236}U fuel contents	0.00001	0.00001	0.00001	0.00001
Impurities of the UO_2 fuel	0.00008	0.00008	0.00008	0.00008
Fuel clad composition	0.00015	0.00015	0.00015	0.00015
Aluminum grid plate composition	0.00001	0.00001	0.00001	0.00001
Water composition	0.00018	0.00018	0.00018	0.00018
Sum in quadrature	**0.00088**	**0.00089**	**0.00098**	**0.00102**

9. EXPECTED COST OF THE EXPERIMENTS

As explained above, this experiment was designed with the intention of using the set of grid plates and core components manufactured for IER-441. Based on this choice, the only additional efforts required to conduct the designed experiments with a neutron absorber plate placed in the assembly are (1) to obtain the plates and (2) to manufacture the aluminum plate holders as previously detailed. The Boralcan plates and aluminum plate holders will also likely require a storage location in the SPRF/CX building, but no specific storage is needed because the plates are not a sensitive, hazardous, or radioactive material. The neutron absorber plates used in the 6 configurations described in this report are small and do not require much work from MSC before being procured. MSC is in the process of creating a budgetary quote for 18 plates, 6 for each dimension/composition combination. Having six plates for each configuration allows for more characterization options and will be helpful if any issue or damage appears on the plates. The other cost of this experiment is the characterization of the plates. According to internal communication with MSTD at Oak Ridge National Laboratory (ORNL), the use of an x-ray CT system will be free of charge. Curtiss-Wright is in the process of creating a budgetary quote for the ^{10}B areal density and chemical assays measurements. The total cost of those measurements is expected to be below $50,000. Marco Steel and Aluminum Inc. in Albuquerque, New Mexico, was contacted to provide a budgetary quote to manufacture the three aluminum plate holders needed. The cost of the holders is expected to be less than $20,000 total. Besides these items, the remaining costs are for shipping/delivery of the plates to SNL and a potential additional specific cost to allow for entry of the plates on site and the labor to perform the experiments. The experiments are expected to have a significant duration because of the time that may be needed to change the plates from the assembly between each configuration.

A list of all the potential additional equipment with the associated cost estimates needed for this experiment is shown in Table 20. Currently, the only equipment required is the plates and the plate holder, and there will also be cost for storage. Additional work and consultation with the experiment team are needed to determine if other equipment is required. The cost estimates include acquiring the materials, manufacturing, installation labor, and other considerations.

Table 20. Potential additional equipment and experiment cost

Equipment (provider)	**Total cost estimate (material, manufacturing, labor, etc.)**
18 neutron absorber plates (MSC)	< $5,000, quote pending
3 Aluminum plate holders (Marco Steel and Aluminum Inc. or other company)	< $20,000, quote pending
Plates and plates support storage	$material + $manufacture, no estimate obtained
X-ray CT analysis (ORNL)	$0
^{10}B areal density, elemental/isotopic characterization (Curtiss-Wright / NETCO)	< $50,000, quote pending
Shipping/delivery/entry on site	$labor

10. BIASES

The proposed experiments are expected to occur in a manner similar to those documented in LCT-078, LCT-079, and some future experiments designed in IER-304. A potential bias may appear if the plates do not have a uniform B_4C particle distribution, so experimenters should track each plate and its orientation in the assembly, even those that theoretically have the same dimensions and B_4C concentrations.

11. COMPLIANCE WITH C$_E$dT MANUAL REQUIREMENTS

Table 5.1 in the C$_E$dT manual [1] provides an example of required input and calculated values for the design, execution, and documentation of criticality (k_{eff}) measurement experiments. Table 21 replicates the table's columns from the C$_E$dT manual applicable to the current CED-1 status. Brief explanations related to this IER are also included.

Table 21. C$_E$dT manual example requirements for CED-1 of a criticality measurement experiment.

Input parameters	**Preliminary design CED-2**[d]	**Notes**
Masses (m, σ_m)	✓ ✓	Most values and uncertainties are included in the LCT-078 and LCT-102 evaluations, and estimations are given for the neutron absorber plates.
Compositions (N, σ_N)	✓ ✓	Most values and uncertainties are included in the LCT-078 and LCT-102 evaluations, and estimations are given for the neutron absorber plates.
Dimensions (x, σ_x)	✓ ✓	Most values and uncertainties are included in the LCT-078 and LCT-102 evaluations, and estimations are given for the neutron absorber plates.
Positions (y, σ_y)	✓ ✓	Most values and uncertainties are included in the LCT-078 and LCT-102 evaluations, and estimations are given for the neutron absorber plates.
Calculated parameters	**Preliminary design CED-2**[d]	**Notes**
Eigenvalue (k_{eff}, σ_k)	✓ ✓	Experiment k_{eff} and uncertainties are provided in Section 5.
Material worth (Δk_{eff}, $\sigma_{\Delta k}$)[a]	✓ ✓[a]	Material sensitivities are provided in Section 7.
Neutron energy spectrum	✓	Energy-dependent ^{10}B neutron absorption profiles are provided in Section 6.
Neutron balance (by isotope, region)[b, c]	✓[c]	Not needed.
Isotope sensitivities (by reaction)[c]	✓[c]	Isotope sensitivities are provided in Section 7.

Note: Columns 1 and 2 and footnotes a–c are from [1, Table 5.1].

[a] If relevant.

[b] Production, absorption, and leakage fractions.

[c] Perhaps not required, but desirable.

[d] One check mark indicates that the value is required. A second check mark means that the uncertainties in the parameter are required.

12. CONCLUSION

IER-554 considers critical experiments based on assemblies using the 7uPCX fuel rods with the insertion of neutron absorber plates in their centers. Six different array configurations associated with three neutron absorber plates of different dimensions and B_4C concentrations are proposed, providing opportunities to analyze different sensitivities to k_{eff}. The analysis shows that such experiments can be performed with acceptably low k_{eff} uncertainties considering an adequate characterization of the neutron absorber plates. The sensitivity results obtained using TSUNAMI calculations show that the experiments have a low differential k_{eff} sensitivity to the neutron absorber plates, but the integral sensitivity is high. The information required to satisfy CED-2 is provided, so the experiment can move forward to phase CED-3.

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