Design of Temperature-Dependent Critical Experiments with SPRF/CX

Justin B. Clarity, Ryan C. Gallagher, Mathieu N. Dupont, Christopher W. Chapman

Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN 37831
PO Box 2008, MS-6170, Oak Ridge, TN 37831, clarityjb@ornl.gov

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INTRODUCTION

This paper describes the investigation of temperature-dependent critical experiments using the Seven Percent Critical Experiments (7uPCX) and Burnup Credit Critical Experiments (BUCCX) fuel types within the Sandia Pulsed Reactor Facility/Critical Experiments (SPRF/CX) apparatus at Sandia National Laboratories (Sandia). The goal of these experiments is to test the effect of varying system temperature on the k_{eff} bias of water-moderated systems. Temperatures of 5–95°C were considered in this work. Eighteen representative lattice configurations were analyzed that had variations in the number of fuel rods and water holes, as well as in the array configuration, to achieve a variety of moderation regimes. The configurations were based on those detailed in the LEU-COMP-THERM-078 [1] and LEU-COMP-THERM-079 [2] experiments, both of which were published in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [3].

The proposed integral experiments will be performed using the 7uPCX or BUCCX fuel, or potentially both. The 7uPCX fuel is 6.90 wt % enriched UO_2 fuel, and the BUCCX fuel is 4.31 wt % enriched UO_2 fuel. Both fuels have been used in previous critical experiments and are available for use [1, 2]. This paper discusses the nuclear and thermal analysis performed to support this experiment, and it also briefly discusses potential facility modifications for SPRF/CX.

NUCLEAR ANALYSIS

This work examines a series of critical configurations performed at the SPRF/CX, as well as some additional arrays developed with the help of Sandia staff [4] in an effort to examine a broad range of moderation regimes and provide flexibility in the performance of the final experiments. The goal of this work is to allow Sandia staff to select final configurations with which to perform experiments instead of prescribing the arrays to be used. The arrays considered herein used both 7uPCX and BUCCX fuel. If a fuel array was used in a previous experiment that is documented in an ICSBEP Handbook evaluation or pending evaluation, then the array is referred to by its ICSBEP designation. A fuel array that has not been in a documented experiment is referred to by the grid plate pitch and some descriptive term. All the arrays presented herein calculate within 700 pcm of criticality at 25°C, and most are substantially closer, indicating that these are obtainable critical configurations. The 7uPCX fueled arrays considered are described in Table I, and the BUCCX fueled arrays considered are described in Table II. Tables I and II contain the grid plate pitch used the number of rods in the critical array, and the fuel-to-water volume ratio. The fuel-to-water volume ratio is not included for the channeled arrays because it is not directly comparable to the other arrays.

TABLE I. 7uPCX Fueled Arrays Considered in the Analysis

Fuel array	Grid plate pitch (cm)	Number of rods	Fuel-to-water-volume ratio
LCT-102-001	0.8001	1,449	0.671
LCT-102-007	0.8550	1,045	0.524
LCT-102-012	0.8001	928	0.225
LCT-102-016	0.8550	413	0.189
LCT-102-020	0.8001	338	0.097
LCT-102-024	0.8550	346	0.083
LCT-102-027	0.8550	367	0.077
0.855 cm pitch: 4 row channel	0.8550	948	N/A
0.855 cm pitch: 6 row channel	0.8550	1,128	N/A

TABLE II. BUCCX Fueled Arrays Considered in the Analysis

Fuel array	Grid plate pitch (cm)	Number of rods	Fuel-to-water-volume ratio
LCT-079-001	2.0	258	0.641
LCT-079-006	2.8	132	0.238
2.8 cm pitch 3 holes	2.8	136	0.231
2.8 cm pitch 6 holes	2.8	139	0.225
2.8 cm pitch 18 holes	2.8	145	0.205
2.8 cm pitch 42 holes	2.8	145	0.173
2.8 cm pitch 81 holes	2.8	190	0.154
2.8 cm pitch channel: 1 row	2.8	150	N/A
2.8 cm pitch channel: 2 rows	2.8	194	N/A

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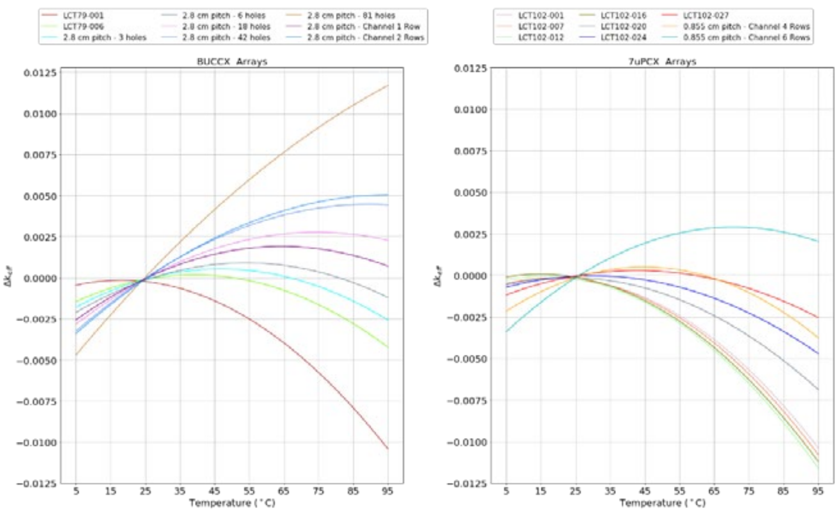
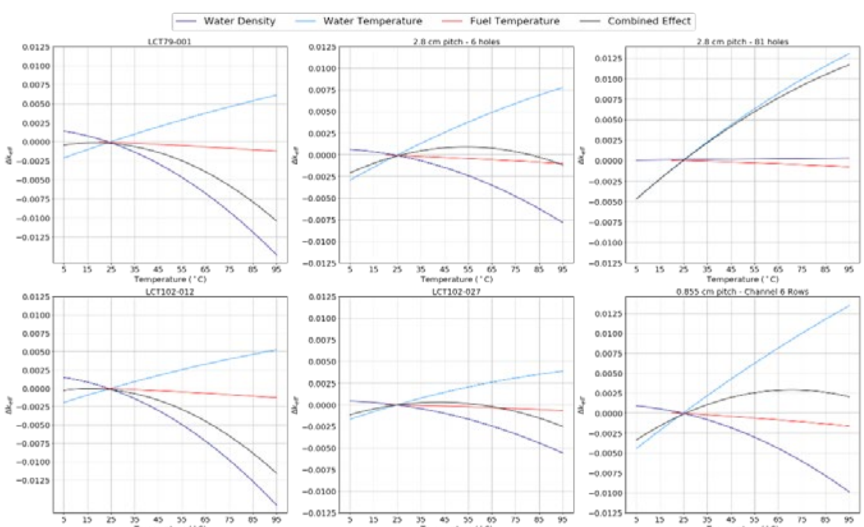
All the calculations were performed with KENO using a specialized version of the Evaluated Nuclear Data File (ENDF)/B-VII.1 library with expanded thermal scattering data. The thermal neutron scattering cross sections for light water were generated using the LEAPR module of NJOY21 version 1.0.5 and AMPX 6.3.pre-beta6 for SCALE. For the LEAPR inputs, the continuous phonon density of states, translational weight, continuous normalization, and oscillator weights were linearly interpolated from the values provided in Appendix 10.2.1 of Mattes and Keinert [5].

To understand which physical effects are most important to the evolution of k_{eff} for each array, a series of calculations was performed. The first set of calculations considered the combined effects of water density, water thermal scattering data, and fuel Doppler broadening for each of the 18 arrays in Tables I and II to identify arrays that had the most positive response of k_{eff} to system temperature (PTR), the most negative response of k_{eff} to system temperature (NTR), and the minimum response of k_{eff} to system temperature (MTR). The results of those calculations are shown in Fig. 1. Separate effects calculations were performed with the NTR, PTR, and MTR arrays in which the water density, water thermal scattering data, and fuel temperature were varied independently. The results of the separate effects calculations are shown in Fig. 2. The results showed that in all arrays the increased temperature resulted in positive contributions from the thermal scattering effect, negative contributions from the water density effect, and small but negative contributions from the fuel temperature effect. The relative magnitudes of these effects in each array were responsible for the overall temperature response.





THERMAL ANALYSIS

The existing SPRF/CX apparatus does not provide the capability to control the water moderator temperatures in the 5–90°C range because it was designed to operate closer to room temperature. Currently, one immersion heater is installed in the dump tank to maintain the moderator at a constant temperature (typically 25°C). To facilitate the larger range of temperature-controlled experiments described herein, several facility upgrades will be required. The following thermal calculations were completed to analyze the capability gaps of the existing apparatus and to advise upgrade decisions.

- Heat loss through the sides and tops of the tanks was calculated to inform insulation and heating requirements for high-temperature operation.
- The thermal equilibrium time was calculated for two different fuel assemblies.
- The impact of water evaporation on heat and mass losses was analyzed.
- Cooling requirements were calculated to inform chiller sizing.

Heat Losses

The steady-state heat losses for an uncovered, uninsulated assembly tank are shown in Fig. 3. The analysis shows that the system could require more than 16 kW of heating if it remained uninsulated and uncovered at 90°C. Even with well-insulated surfaces, evaporation can contribute more than 7.5 kW of heat loss at 90°C.

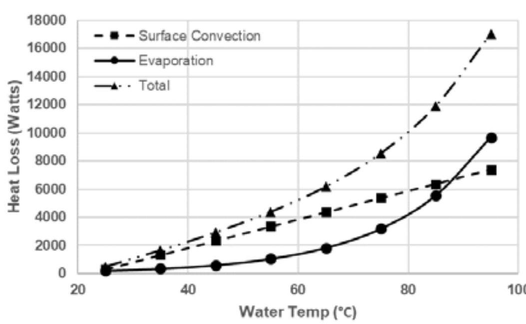


Fig. 3. Calculated evaporative and convective heat loss for the current assembly and dump tanks.

A transient finite element model was used to determine the time required for the fuel rods to reach thermal equilibrium. Both the BUCCX and 7uPCX fuel rod geometries were analyzed to verify that the system could be heated to the desired temperature within 10 min. This was done to verify that fuel heating would not prolong the experiment time. If the moderator temperature remains within a few degrees of the desired temperature, then it should not significantly impact the fuel heating. Thus, isothermal water could be assumed in the fuel heating model. A diagram of the ANSYS models is shown in Fig. 4; BUCCX fuel is shown on the left, and the 7uPCX fuel is shown on the right.

The temperature of the fuel centerline as a function of time is shown in Fig. 5. For this simple analysis, the maximum time required to heat a fuel rod centerline within 0.5°C of the water temperature would be less than five min. This initial analysis shows that the time required for heating should not be a major issue in performing experiments. However, current analysis only considers one rod with an isothermal temperature boundary; it does not consider the potential impact of neighboring rods or the assembly restricting mixing of the water, which might reduce the heat transfer rate. The initial time required to heat the water will likely be greater than the time required to establish equilibrium.

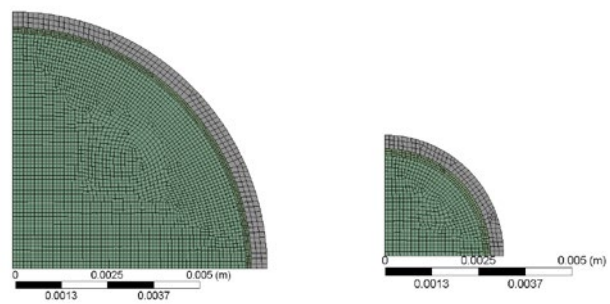


Fig. 4. Mesh used in the two fuel rod geometries: BUCCX (left) and 7uPCX (right).

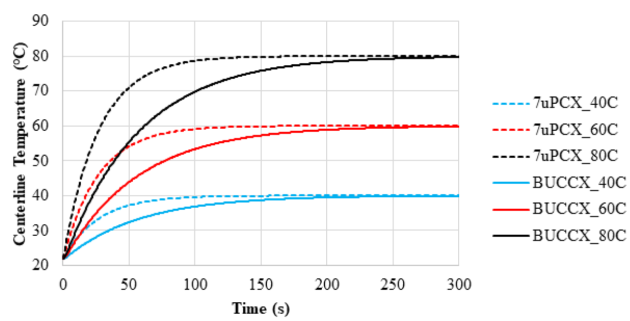


Fig. 5. Fuel centerline temperature over time for the two fuel types.

POTENTIAL FACILITY MODIFICATIONS

To accommodate operation at temperatures other than room temperature, upgrades to the existing SPRF/CX facility were suggested. The potential facility modifications are shown in Fig. 6. The dump tank could be replaced with a larger capacity tank to increase the available thermal mass of water supplied to the assembly tank during an experiment. Elevated temperatures would be enabled using immersion heaters and a proportional–integral–derivative controller. The dump tank should also be insulated to limit thermal losses. Alternatively, a heated, insulated jacket would provide secondary temperature regulation in the assembly tank. The assembly tank could also feature immersion heaters, provided that they do not cause thermal gradients in the water and/or fuel. Significant evaporative mass and health loss would be expected when operating at the upper temperature range. Therefore, an insulated cover should be installed that would reduce evaporative losses while still allowing for instrumentation and ease of fuel loading.

Upgrades should also consider reduced temperatures in the experiment facility. A chilling system could be coupled to the dump tank to control its water temperature. Because the temperature difference between the environment and the chilled water will be relatively low compared with high-temperature measurements, the insulation and water recirculation from the dump to the assembly tank are expected to be adequate for controlling temperatures below room temperature.

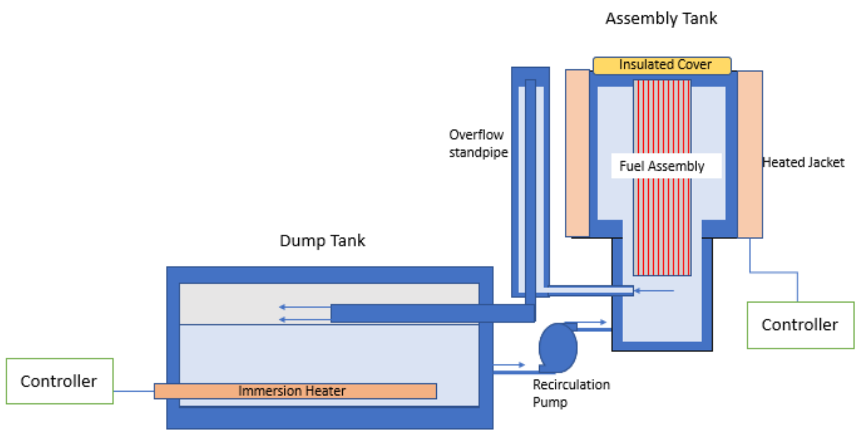


Fig. 6. Schematic of SPRFCX apparatus during operation with a heated moderator.

ACKNOWLEDGMENTS

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