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EXPERIMENTS TO MEASURE THE EFFECT OF TANTALUM ON CRITICAL SYSYEMS

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ABSTRACT

Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL) collaborated to develop a capability to test the epithermal/intermediate cross sections of materials at the SNL critical experiment facility using the Seven Percent Critical Experiment (7uPCX) fuel. As a result, a new set of critical experiments has been designed to target the epithermal cross sections of tantalum (Ta) and is scheduled to be performed at SNL in 2023. These critical experiments will be evaluated for inclusion in the 2024 edition of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook.

The focus of these critical experiments is to measure the effects of Ta on the critical array size. The critical array size will be determined by an approach-to-critical experiment with the number of fuel rods in the array as a free parameter. The core configurations are designed to optimize the reactivity worth of Ta and the overall percentage of Ta absorption rates in the epithermal/intermediate energy range (0.625 eV – 100 keV). The baseline core configuration includes 7uPCX fuel rods set at a triangular pitch of 1.016 cm and a central dry test region that utilizes a cadmium liner for filtering out thermal neutrons. The central test region has locations for 85 Ta rods set at a triangular pitch of 0.813 cm. The Ta reactivity worth for the case with 85 Ta rods is approximately 2.55%, with the percentage of Ta absorption rates within the intermediate energy range at nearly 90%.

KEYWORDS

Tantalum, Critical Experiments, Epithermal/Intermediate

1. INTRODUCTION

The Sandia Critical Experiments (SCX) Program provides a specialized facility for performing water-moderated critical experiments for cores with fuel pin arrays. A history of safe assembly operations and flexibility in fuel type and assembly configurations has resulted in the completion of multiple sets of benchmark experiments that are documented in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [1]. The facility offers the ability to modify the core configuration and reactor tank to evaluate various reactor cores for pitch, moderator characteristics, and other criteria. Currently, there are two active SCX series, the Burnup Credit Critical Experiments (BUCCX) and the Seven Percent Critical Experiment (7uPCX). The 7uPCX was designed for validating reactor physics methods and models for fuel enrichments above the current 5% ^{235}U ceiling for US commercial pressurized water reactors [2]. The BUCCX was designed for inserting fission product materials to measure reactivity effects and uses 4.31% enriched UO_2 [3]. The two SCX series are both fueled by uranium oxide but differ in enrichment, material properties, geometry, and array configuration.

The set of experiments described here were designed using the 7uPCX fuel to determine the reactivity effects associated with introducing tantalum rods.

2. DESIGN OF THE CRITICAL ASSEMBLY FOR TANTALUM EXPERIMENTS

The overall concept of the critical assembly is shown in Fig. 1. The assembly core resides in an elevated assembly tank that is connected to a moderator dump tank located at a lower elevation. The moderator resides in the dump tank when not in operation. To begin operations, the moderator is pumped from the dump tank into the assembly tank. The moderator can be released by gravity to the dump tank through two large-diameter pneumatically operated dump values. The moderator is maintained at a constant temperature by a heater in the dump tank. During operation, the moderator is continually circulated between the dump tank and the assembly tank. The moderator level is maintained by overflow into a standpipe.

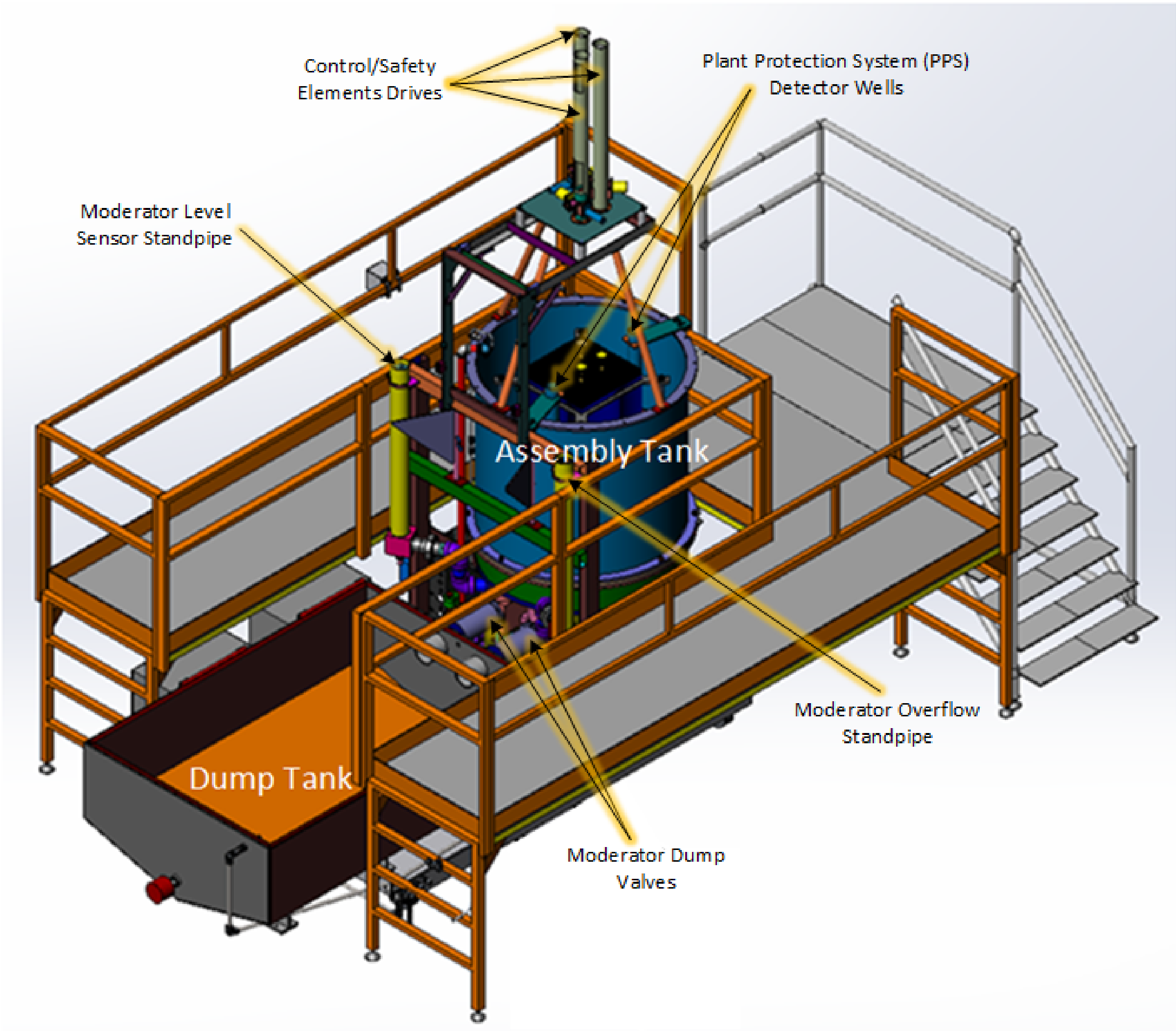

Figure 1. Overall Schematic of the Critical Assembly.

The 7uPCX is water-moderated and fueled with pins containing 6.90% enriched UO_2. The 7uPCX fuel rods were fabricated at SNL from fuel pellets that were removed from unirradiated fuel elements and placed into 3003 aluminum cladding tubes with welded end caps of the same alloy. A cutaway view of a 7uPCX fuel rod is shown in Fig. 2. The loading inside the fuel rod (listed right to left in the figure) consists of an aluminum bottom plug, the fuel pellet stack, a spring, an aluminum plug at the level of the upper grid plate, a polyethylene plug, and an aluminum top plug. The grid plates and fuel rods are designed so that the bottom of the fuel is at the same elevation as the top of the lower grid plate. The polyethylene in the fuel rod was designed to almost exactly replace the hydrogen in the water displaced by the upper part of the fuel rod. The fuel rod has a nominal diameter of 0.635 cm (0.25 in).

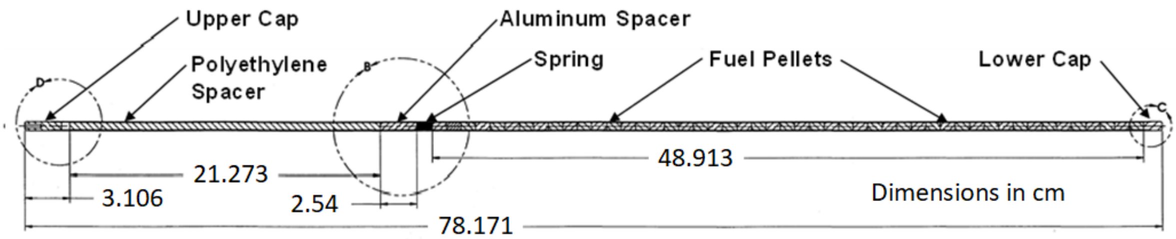

Figure 2. 7uPCX Fuel Rod.

The fuel rods are supported by two 2.54 cm (1.0 in) thick aluminum grid plates that maintain spacing of the fuel rods in the critical assembly. The grid plates are positioned in the assembly tank to provide a 16.51 cm (6.5 in) thick water reflector below the lower grid plate and a 15.24 cm (6.0 in) thick water reflector above the upper grid plate when the assembly tank is full. The diameter of the tank provides a radial water reflector around the assembly that is at least 15.24 cm (6.0 in) thick. The grid plates were fabricated with the holes on a 1.016 cm (0.40 in) triangular pitch and have 2016 available fuel rod positions. The grid plates have a 9.601 cm (3.78 in) diameter hole at the center to allow for a central test region.

The central test region provides a dry cavity for placement of the tantalum test rods. The dimensions for the tantalum test rods are provided in Fig. 3. As indicated, the diameter of the test rod is the same as the fuel rod, but the test rod has a slightly longer length. The central test region is composed of an outer cylindrical aluminum can, a thin cadmium liner, an inner aluminum tube, and an aluminum grid structure for supporting the tantalum test rods. The outer aluminum can has an outer diameter of 9.525 cm (3.75 in), length of 76.098 cm (29.96 in), and wall thickness of 0.3175 cm (0.125 in). The inner surface of the aluminum can is lined with cadmium sheeting that is 0.1016 cm (0.04 in) thick, which provides a thermal flux filter. Aluminum tubing with an outer diameter of 8.687 cm (3.42 in) and wall thickness of 0.127 cm (0.05 in) is used to hold the cadmium sheet in place. An upper and lower aluminum grid structure provides locations for 85 test rods set on a 0.8128 cm (0.32 in) triangular pitch. Fig. 4 shows the central test region with 85 tantalum test rods and a cut-away view detailing the placement of the cadmium liner.

The experiments were designed to target the epithermal/intermediate cross sections of tantalum. The fuel rod pitch and the design features of the central test region (e.g., materials, dimensions, and location) were optimized to produce the desired neutron spectrum and tantalum reactivity worths.

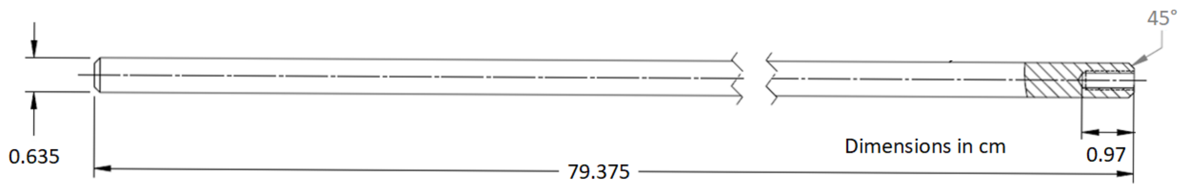

Figure 3. Tantalum Test Rod

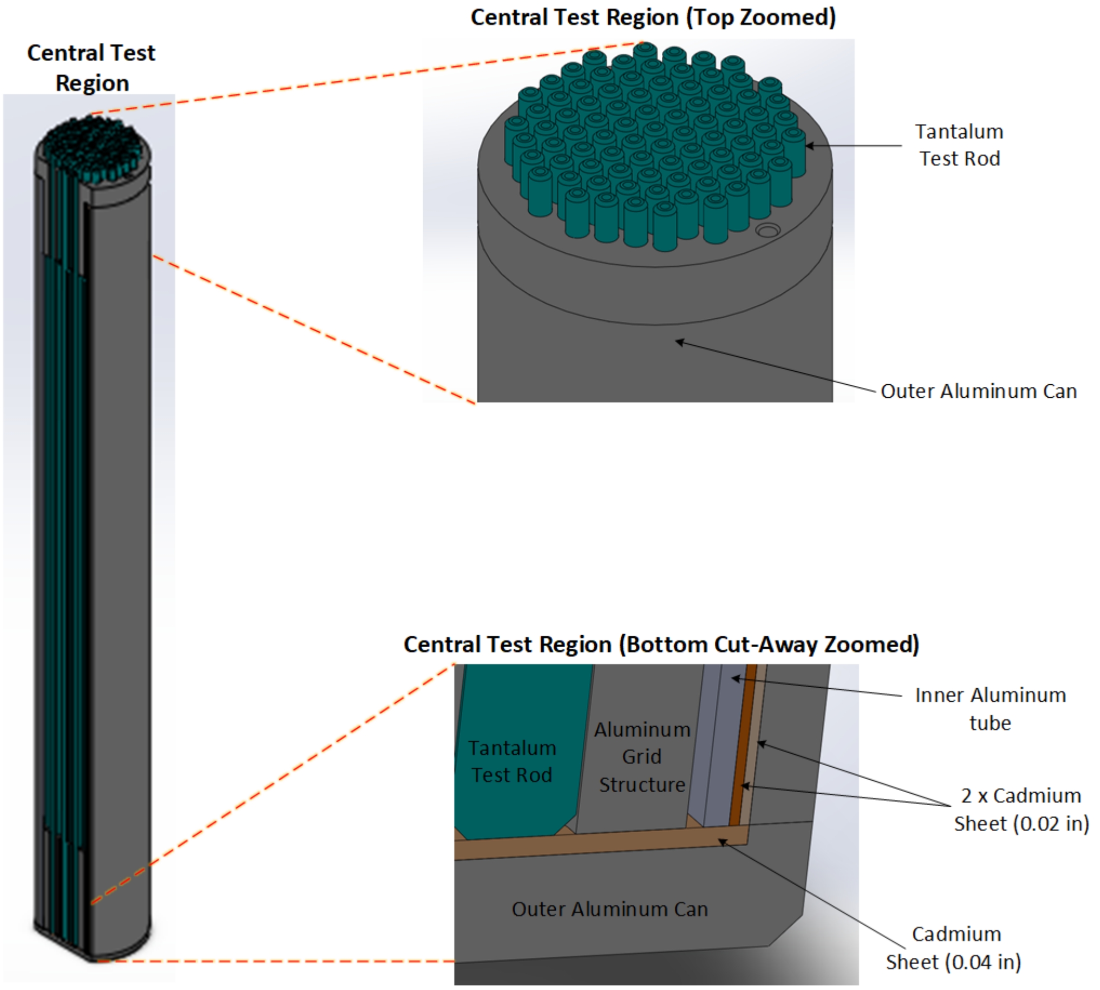

Figure 4. Central Test Region with 85 Tantalum Test Rods

The assembly has two safety elements and one control element, each a cluster of four rods that replaces four rods in the fuel array. The control and safety elements are identical and distinguished only by the way they are used. Each has a four-rod B_4C poison section followed by a four-rod fueled section. The poison and fueled sections are separated by a four-rod polyethylene-filled decoupler section 15 cm (5.906 in) long. When fully raised, the fuel follower is in the core, the poison sections are above the water level in the core tank, and the control and safety elements are neutronically identical to every other fueled position in the array.

During approach-to-critical experiments, the assembly is driven by a small stainless-steel-clad ^{252}Cf source that is designed to be placed in a grid plate hole or in one of the test rod locations in the central test region. The behavior of the neutron population in the assembly is monitored by several fission chambers located outside the fuel array either in dry wells or outside the assembly tank. Two of the detectors inside the tank are in dry wells surrounded by polyethylene and provide signals to the assembly plant protect system (PPS). Fig. 5 shows the positioning of the grid plates, the control and safety elements, and the central test region within the assembly tank.

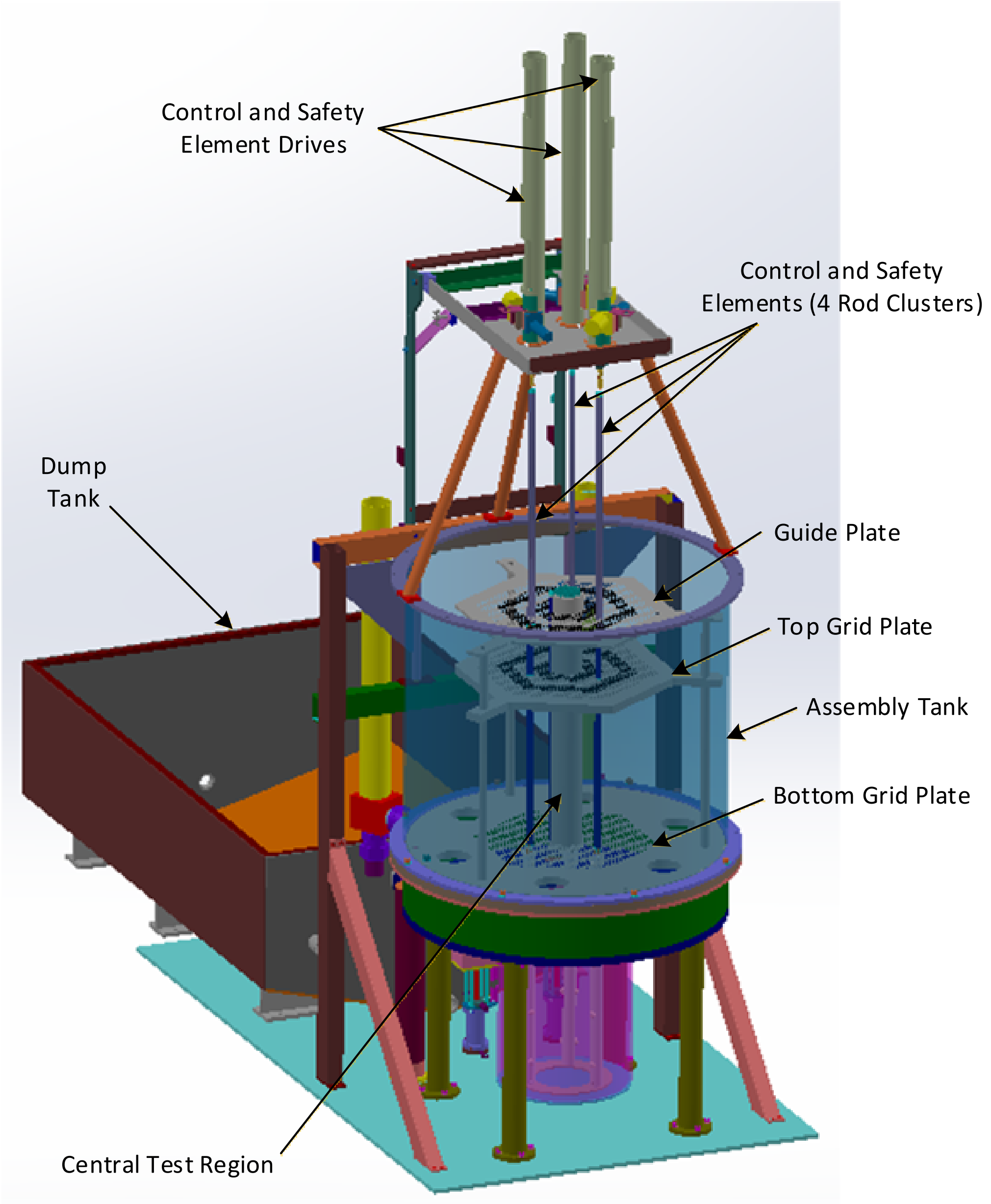

Figure 5. 7uPCX Critical Assembly Showing Grid Plates and Central Test Region.

3. EXPERIMENT METHOD

The focus of these critical experiments is to measure the effects of tantalum test rods on the critical array size. The critical array size for each configuration will be determined in an approach-to-critical experiment with the number of fuel elements in the array as a free parameter. The inverse count rate at successive fuel configurations as a function of the number of fuel rods will be extrapolated to zero to obtain an estimate of the critical array size. The control and safety elements will be in their fully withdrawn or most reactive positions during all measurements. The triangular-pitched arrays will be loaded from the center toward the outside while maintaining a roughly cylindrical cross section of the array. At conditions near delayed critical, the fuel rods will be added a few at a time on the periphery of the array in a pattern that maintains symmetry as best as possible.

4. ANTICIPATED CRITICAL CONFIGURATIONS

Critical configurations were developed for eight cases. Case 1 contains no tantalum test rods. Cases 2 through 8 include various numbers and arrangements of tantalum test rods. Fig. 6 shows a cross sectional view of the central test region for each experiment case. The tantalum test rods (grey) are within the dry central test region (blue) surrounded by fuel rods (red) and moderated by water (green). Shown in Fig. 7 is the critical configuration for Case 8, with 1158 Fuel rods and 85 tantalum rods.

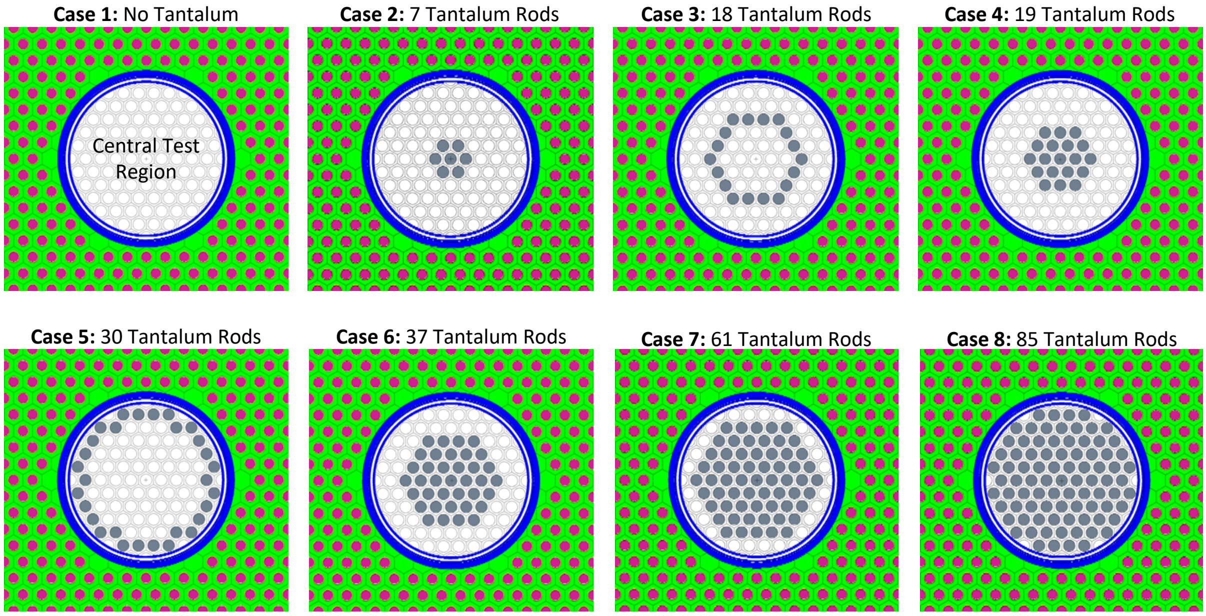

Figure 6. Tantalum Test Rod Configurations for Each Experiment Case.

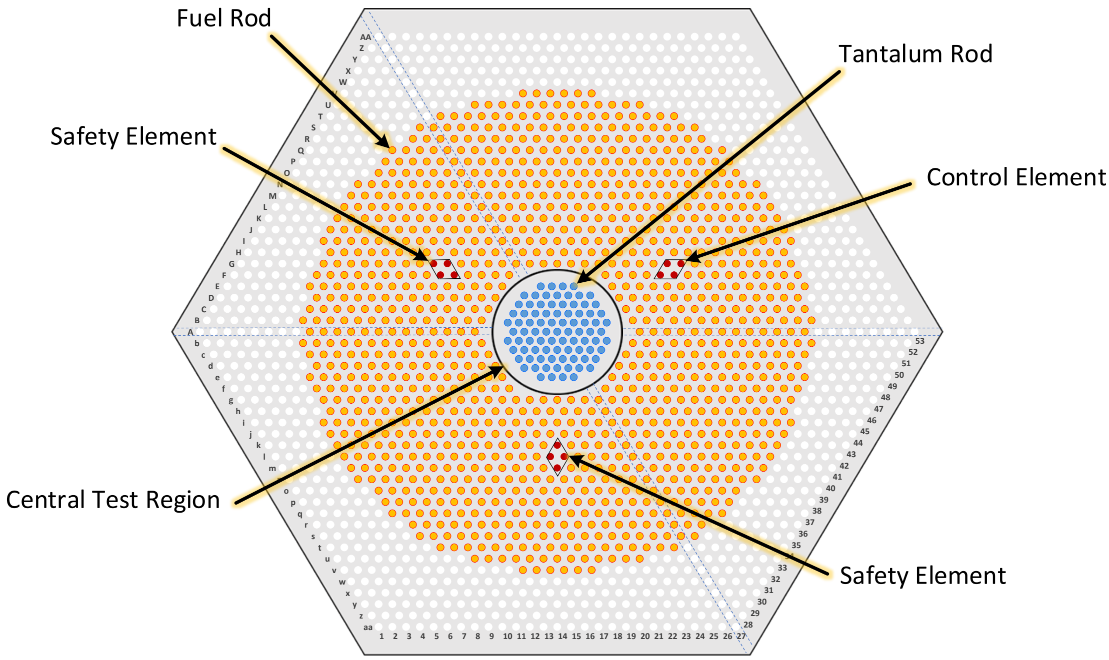

Figure 7. Critical Configuration for Case 8 (1158 Fuel Rods and 85 Tantalum Rods).

Critical configurations were evaluated using the MCNP 6.2 code [3] with the ENDF/B-VII.1 cross-section library. As discussed previously, the experiments were designed to target the epithermal/intermediate (0.625 eV – 100 keV) cross sections of tantalum. Considering the 7uPCX fuel rods require moderation to achieve criticality, shifting the thermal neutron spectrum of the fueled region to a harder neutron spectrum in the central test region, while also producing meaningful tantalum reactivity worths, can be challenging.

Fig. 8 shows the tantalum energy-dependent absorption reaction rates (with and without the cadmium filter), the neutron spectra in the fuel, and the capture cross sections for tantalum (Ta-181) and cadmium (Cd-113). As indicated, the neutron flux in the fuel displays a thermal peak, which is also prevalent in the tantalum absorption reaction rates when there is no cadmium filter. However, without moderator in the central test region and with a cadmium filter in place, the tantalum absorption peak in the thermal energy range can effectively be removed.

Table I provides the calculated number of fuel rods at critical, the tantalum reactivity worth, and the tantalum absorption rates within the three listed energy groups as a percentage of the total absorptions for each case. An additional case, with 85 tantalum rods but without the cadmium filter is provided for comparison.

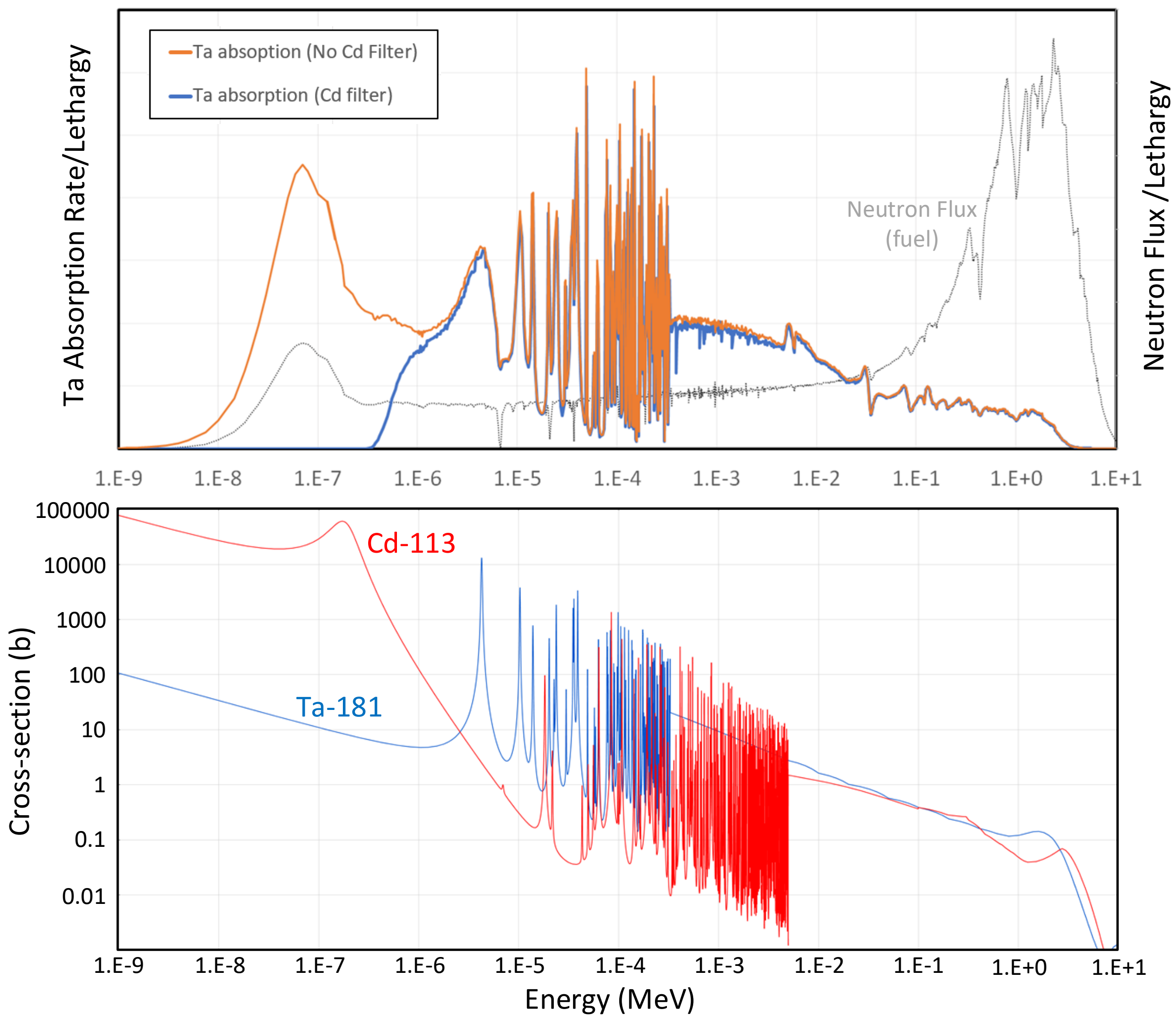

Figure 8. Tantalum Absorption Rates and Neutron Spectra in the Fuel (Top) and Capture Cross Sections for Cadmium and Tantalum (Bottom).

Table I. Critical Configurations with Tantalum Reactivity Worth and Absorption Rates.

Case	Ta-rods	Fuel Rods	Ta Worth ($\Delta k/k \pm \sigma$)	Three group energy-dependent Ta absorption rates		
				<0.625 eV	0.625 eV–100 keV	>100 keV
1	0	1044	-	-	-	-
2	7	1068	0.460 ± 0.006 %	1.40 %	93.89 %	4.72 %
3	18	1086	1.078 ± 0.006 %	1.30 %	93.75 %	4.95 %
4	19	1084	0.944 ± 0.006 %	1.52 %	92.52 %	5.97 %
5	30	1110	1.656 ± 0.006 %	1.11 %	93.55 %	5.34 %
6	37	1108	1.499 ± 0.006 %	1.47 %	91.46 %	7.07 %
7	61	1136	2.081 ± 0.006 %	1.38 %	90.43 %	8.19 %
8	85	1158	2.546 ± 0.004 %	1.27 %	89.59 %	9.15 %
No Cd	85	1134	5.725 ± 0.004 %	30.96 %	62.87 %	6.17 %

5. CONCLUSIONS

The set of experiments reported here were designed to use the 7uPCX fuel to measure the effects of tantalum material on the critical array size. The calculational results provide confidence that the critical experiments will produce significant material reactivity worths while targeting tantalum absorption reaction rates in the epithermal/intermediate energy range.

ACKNOWLEDGMENTS

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