Space Nuclear Thermal Propulsion Critical Assembly Boron Worth Experiments

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INTRODUCTION

The Space Nuclear Thermal Propulsion (SNTP) project was an attempt to create a more powerful and more efficient rocket engine utilizing nuclear technologies. As part of this project a zero-power critical assembly referred to as SNTP-CX was designed and installed at Sandia National Laboratories. The SNTP-CX was a light water moderated particle bed reactor utilizing highly enriched uranium fuel in the form of UC particles. The SNTP-CX performed 142 runs covering numerous experiments from the year 1989 to 1992 [1].

The program was canceled in 1994 as the nation's priorities shifted [2]. Now these experiments are being evaluated for use as criticality safety benchmarks. Nineteen of the 142 reactor runs were dedicated to a series of experiments to calculate the worth of the boron used in the light water moderator. This series of experiments has been selected for further evaluation as a critical benchmark for the International Criticality Safety Benchmark Evaluation Project (ICSBEP) [3].

SNTP-CX DESIGN OVERVIEW

The active core lies inside of a cylindrical tank assembly. The assembly consists of the base plate and the upper tank that are connected by the lower grid plate. The base plate allows for 2.54 cm of moderator below the lower grid plate and also contains two holes connected to dump valves to allow for the moderator to be quickly drained from the assembly and stored in the dump tank residing below. The upper tank is 81.3 cm tall and allows for the attachment of the upper grid plate, control blade assembly, standpipe, and fission chambers. At a full moderator height of 55.0 cm above the lower grid plate it allows for 5.97 cm of moderator above the active core. The active core is defined as the top of the lower grid plate to the top of the upper polyethylene reflector. A standpipe sits at 55.5 cm with an overflow hole at 56.5 cm, both also measured from the top of the lower grid plate. The inner diameter of the upper tank is 71.0 cm allowing for a minimum of 12.0 cm of moderator surrounding the core radially.

The upper and lower grid plates allow for the positioning of 19 fuel stalks in a triangular array with a pitch of 9.40 cm. The lower grid plate is 2.54 cm thick and is located between the base plate and upper tank as described above. In addition to the holes for positioning the 19 fuel stalks, drain holes are also positioned to allow for the moderator to drain quickly. The bottom of the upper grid plate is located 56.1 cm above the top of the lower grid plate. In comparison to the lower grid plate the upper grid plate is only 0.635 cm thick. In addition to the holes for positioning the 19 fuel stalks the upper grid plate also contained three cut outs to allow for the passage of the two safety blades and one control blade. The control and safety blades are identical to one another and have a 'Y' shaped cross section with an angle of 120 degrees between each blade. The absorbing material used for the blades is cadmium which is clad in stainless steel. Figure 1 shows a drawing of the SNTP-CX with important components labeled. The assembly could also make use of an Ag-In-Cd shim element for small reactivity changes. The shim element was designed to be inserted into the central void of a modified fuel stalk when its use was desired.

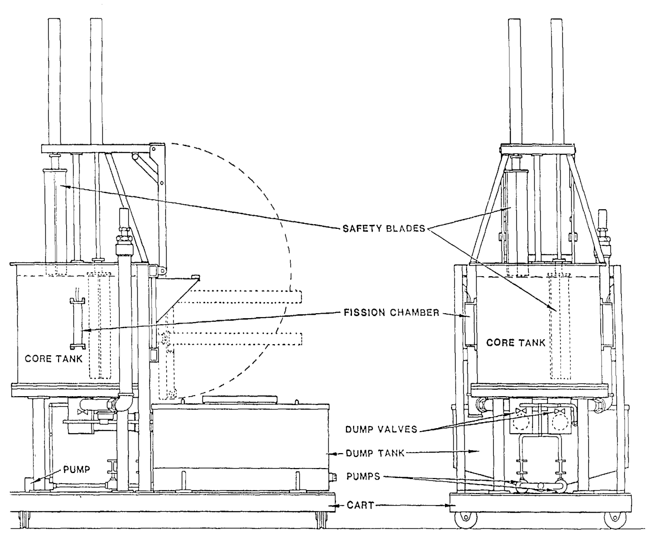

Figure 1: Labeled Drawing of the SNTP-CX [1].

The fuel stalks contain an annulus (referred to as the fuel annulus) nominally 43.0 cm high, an inner radius of 1.7740 cm, and outer radius of 3.3045 cm that is created from two cylinders. Below the fuel annulus is a 5.0 cm thick polyethylene cylinder with a radius of 3.4860 cm acting as the lower axial reflector. Above the annulus is a 5.0 cm thick polyethylene cored cylinder with an inner radius of 3.3300 cm and an outer radius of 3.4860 cm acting as the upper radial reflector. The axial reflectors and fuel canister are then placed into a cylindrical canister with a spring above the upper axial reflector to hold the interior components in place. Figure 2 shows a cross section of the fuel stalk and its components.

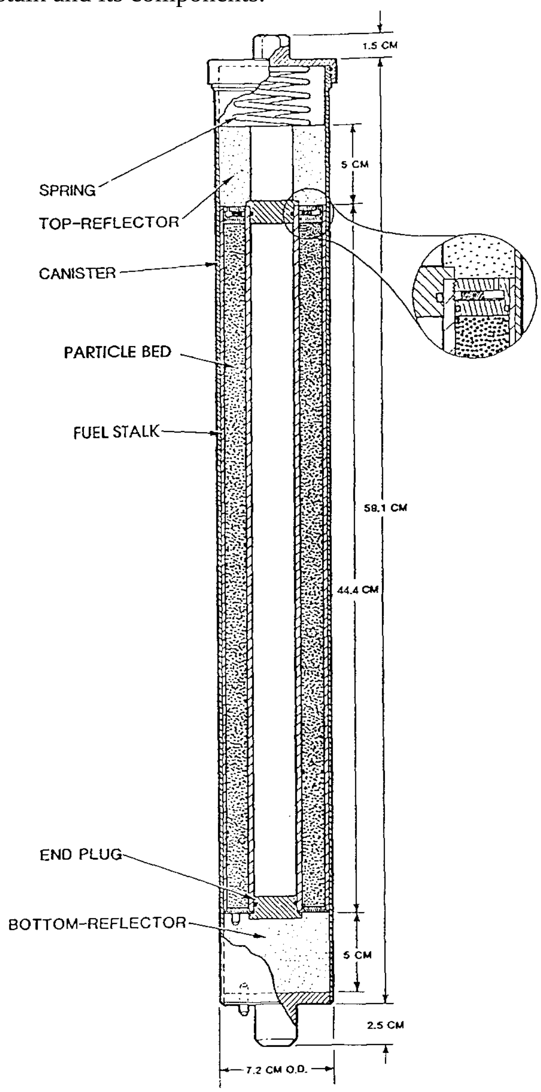

Figure 2: Cross Section of a Fuel Stalk [1].

The particle bed that fills the fuel annulus is composed of three different types of particles. The first being the fuel particle, which is a UC fuel kernel enriched nominally to 93% U-235 with a nominal diameter of 250 microns. The fuel kernel is coated in a carbon graphite shell with a nominal thickness of 15 microns. The second particle type is a carbon graphite filler particle, supplied by Versar, and referred to as CARBOSHPERE Type S220. The carbon particles have a sulfur impurity of 6.2 % by weight and are nominally 250 microns in diameter. The third particle type is was a Zircaloy-4 particle with a nominal diameter of 250 microns.

METHODS

The experiment series being evaluated was designed to determine the reactivity of the boron used in the light water moderator. Nineteen runs were performed with 10 different boron concentration. Water height was used as the approach to critical parameter. For all 19 runs the control and safety blades along with the shim element were fully withdrawn from the core and had no effect on the reactivity of the system.

Table 1 shows the boron concentration and corresponding moderator temperature. Boron concentration values were corrected to 20 °C. The source for the data in Table 1 is the report “As-Built Description and Excess Reactivity of Reference CX Core 94WS100” [1]. For each boron concentration two reactivity values were recorded except for case 1. One at delayed critical corresponding to the critical water height, and the second at the previous boron concentrations critical water height. This allowed for the differential boron worth to be calculated at various water heights and boron concentrations. Case 1 only requires a value to be recorded at delayed critical as there was no case preceding it with a critical water height at a different boron concentration.

Table 1: Case 1-10 Boron Concentration and Moderator Temperature [1].

Case	Experiment Run	Natural Boron (PPM*)	Recorded Moderator Temperature (°C)
1	1	68.90	19.9
2	2-3	61.70	19.0
3	4-5	55.10	17.9
4	6-7	47.70	17.5
5	8-9	39.90	17.4
6	10-11	32.70	17.5
7	12-13	24.20	16.5
8	14-15	16.47	16.5
9	16-17	8.69	17.5
10	18-19	0.27	19.2

*Parts Per Million Corrected to 20 °C

A detailed model was created using MCNP6.2 [4] to represent each of the 19 runs as accurately as possible. This included a detailed model of the particle bed using a face centered cubic lattice structure. Figure 3 shows a 3D model of the fuel lattice created to represent the fuel bed in the model. Light grey represents a fuel particle with carbon shell, silver represents a zircaloy-4 particle, and dark grey represents a carbon particle. For reference the fuel particle is modeled with a diameter of 280 µm (250 kernel µm + 2 x 15 µm thick carbon shell). To create the lattice for the MCNP model a script was created in Python. The script used inputs of total fuel stalk particle masses, material densities of the carbon and zircaloy-4 particles, dimensions of the fuel particle, and desired packing fraction. The script then iteratively calculated for the dimensions of the carbon and zircaloy-4 particles, the material densities of the UC kernel and carbon shell, and the side length of the lattice element. This ensured that the correct mass of each of the materials was in the fuel stalk and the particle bed was at the correct packing fraction. The parameters chosen to be iteratively calculated were based on what information was available about the model. For instance, material densities for the carbon and zircaloy-4 particles were able to be calculated with the information available, while the densities for the UC kernel and carbon shell could not.

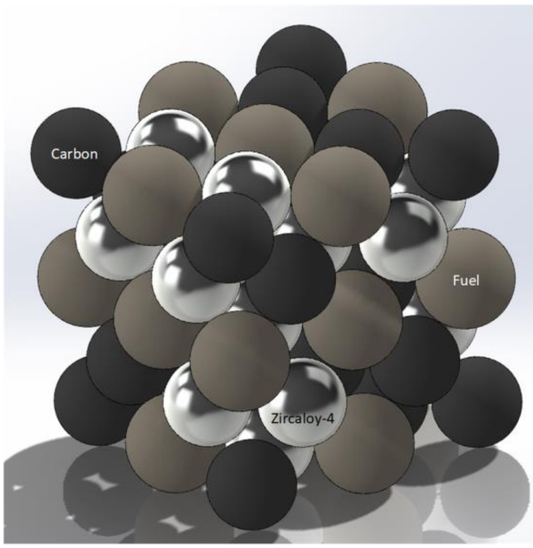

Figure 3: Lattice Representation of the Particle Bed.

Figure 4 shows a simplified 3D representation of the model. Each model was run with approximately 400 million particle histories producing an estimated multiplication factor standard deviation of at most 0.00005 pcm. The ENDF/B-VII.1 cross section library set was used for the MCNP calculations.

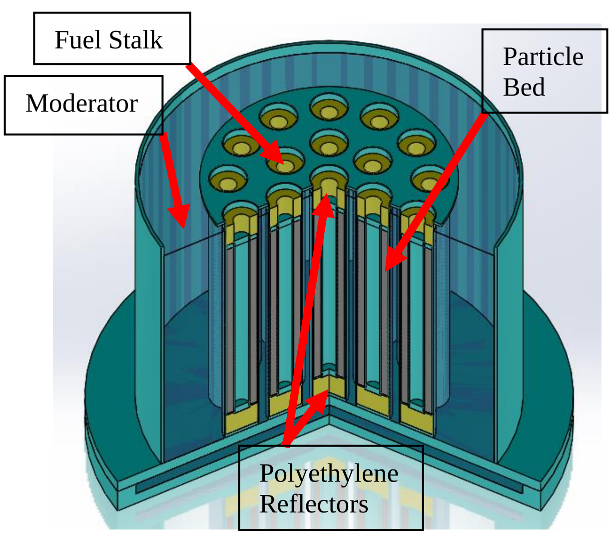

Figure 4: 3D representation of the MCNP model.

RESULTS

Table 2 shows the experimental results of the 19 runs performed for measuring the boron worth at various water heights. The source for the data in Table 2 is the report " As-Built Description and Excess Reactivity of Reference CX Core 94WS100" which contains a list of each reactor run and its parameters (water height, boron concentration, recorded reactivity etc.) [1]. The differential Boron worth for each case is also show in cents/PPM boron. The average measured boron concentration from the experiments is -2.936 cents/PPM boron. Equation 1 was used for calculating the differential boron worth from the given data.

$$Differential\ Boron\ Worth = \frac{\rho_2 - \rho_1}{B_2 - B_1} \quad (1)$$

Table 3 shows results from the 19 models corresponding to the 19 runs performed above. Reactivity is reported in cents using a β_{eff} of 0.00783 ± 0.00005 which was calculated using MCNP6.2 KOPTS card. The model results show an overall higher reactivity in the core. Results modeled after the critical configurations show reactivities ranging from 19.256 cents to 32.484 cents. The average calculated boron worth is -3.353 ± 0.76 cents/PPM boron. In each case the boron worth of the model agrees with the experimental results within one standard deviation. Equation 2 was used to convert the calculated k_{eff} from MCNP into reactivity in the form of cents.

$$\rho = \frac{k_{eff} - 1}{k_{eff} * \beta_{eff}} * 100 \quad (2)$$

The cause of the consistently high reactivity in the model compared to the experiments might be attributed to limitations in modeling accuracy. As example, due to the available experimental data, some of the modeled components rely on best estimates. However, by evaluating a series of experiments that consider changes in reactivity rather than total reactivity the computational model can be tested for correct or expected behavior.

Table 2: Experimental Conditions and Boron Worth [1]

Case	B (PPM)	Water Height (mm)	Reactivity (Cents)	B Worth (Cents/PPM)
1	68.89	-	-	-
		542.5	0	
2	61.66	542.5	18.26	-2.526
		534.6	0	
3	55.12	534.5	17.70	-2.706
		528.4	0	
4	47.71	528.4	20.16	-2.721
		522.2	0	
5	39.86	522.2	22.63	-2.883
		516.2	0	
6	32.7	516.2	22.56	-3.151
		510.7	0	
7	24.21	510.7	22.76	-2.681
		505.2	0	
8	16.54	505.2	21.98	-2.866
		500.1	0	
9	8.69	500.1	26.10	-3.325
		494.5	0	
10	0.27	494.5	30.00	-3.563
		488.4	0	
			Average	-2.936

Table 3: MCNP6.2 Model Results for Boron Worth.

Case	B (PPM)	Water Height (mm)	Reactivity (Cents)	B Worth (Cents/ PPM)	Std. Dev. (Cents)
1	68.89	NA	NA	NA	NA
		542.5	19.256		
2	61.66	542.5	43.149	-3.305	0.814
		534.6	23.583		
3	55.12	534.5	44.544	-3.205	0.898
		528.4	26.128		
4	47.71	528.4	51.389	-3.409	0.718
		522.2	28.925		
5	39.86	522.2	55.188	-3.346	0.718
		516.2	31.086		
6	32.7	516.2	53.922	-3.189	0.718
		510.7	29.307		
7	24.21	510.7	57.973	-3.376	0.718
		505.2	31.595		
8	16.54	505.2	57.594	-3.390	0.717
		500.1	32.484		
9	8.69	500.1	58.732	-3.344	0.717
		494.5	29.942		
10	0.27	494.5	60.377	-3.615	0.812
		488.4	26.509		
			Average	-3.353	0.759

CONCLUSION

The boron worth experiments performed on SNTP-CX were originally intended as a reference for future experiments. They are now being evaluated as potential criticality safety benchmarks for ICSBEP. Initial results are promising as current models agree with the experimentally measured boron worth within one standard deviation. Further work to confirm the accuracy of the results will be done by closer consideration of the uncertainties and associated sensitives of both the experiments and the models.

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