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Effects of Boron and Graphite Uncertainty in Fuel for TREAT Simulations

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INTRODUCTION

As a result of the accident at Fukushima, the United States has made a concerted effort to develop fuel with enhanced accident tolerance for the current fleet of reactors. In 2012 Congress laid out a schedule for the development of accident tolerant fuel (ATF), the goal of which is to test in a commercial reactor by 2022 [1]. Idaho National Lab's (INL) Transient Reactor Test Facility (TREAT) is one of the locations that will be performing ATF testing and is scheduled for restart in 2018. TREAT was built to subject fuel to conditions ranging from mild transients to severe reactor accidents. However, typically a number of pre-test calibrations are required before evaluation of fuel can begin, which is costly and time consuming [2].

Advanced modeling techniques and current computational capacity make full core TREAT simulations possible, with the goal of such simulations to understand the pre-test core and minimize the number of required calibrations. But, in order to simulate TREAT with a high degree of precision the reactor materials and geometry must also be modeled with a high degree of precision. This paper examines how uncertainty in the reported values of boron and graphite have an effect on simulations of TREAT.

GRAPHITE AND BORON UNCERTAINTY

TREAT is an air-cooled, graphite moderated reactor designed for large power bursts to simulate accident conditions leading to fuel damage, including melting or vaporization of test specimens, without damaging itself [3]. TREAT fuel elements are composed of highly enriched uranium (HEU) diffused in a graphite matrix. Elements used to initiate, sustain, and vary transient conditions within TREAT are referred to as control elements and are identical in size to the fuel elements. The major difference is that control elements contain a section of boron carbide powder (B_4C), a Zircaloy-clad follower, and a two-piece steel follower. The center of the core contains space for the insertion of an experimental vehicle (i.e. where test fuel will be placed). A two-dimension cutaway of the core is provided in Figure 1.

The graphite that surrounds TREAT fuel acts as a neutron moderator and is able to withstand large amounts of heat without damage. However, not all carbon in the fuel is graphite. Reference [3] suggests that graphite makes up only 59% of carbon in the fuel. Therefore, the carbon crystal structure in the fuel is a complex mixture of graphite particles in a non-graphitized elemental carbon matrix. This is significant because the scattering cross section of carbon changes depending on if it is graphitized or not [4]. This difference in

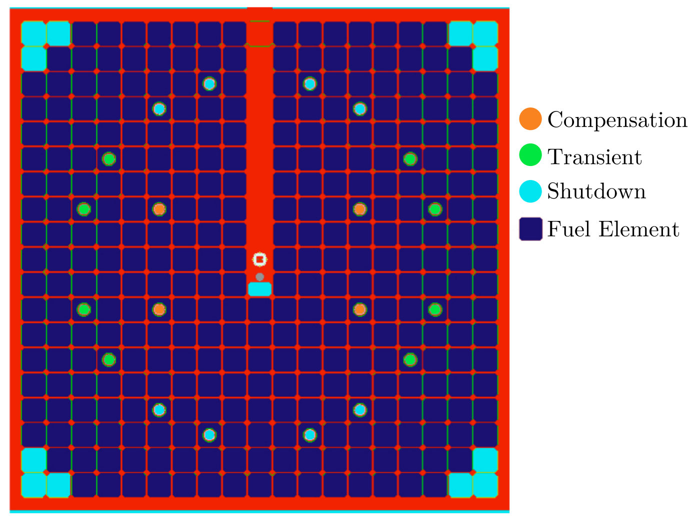

Fig. 1. Top down view of TREAT reactor core

scattering cross section means that graphitized carbon and non-graphitized carbon differ in performance as a moderator. Since TREAT's core is largely graphitized or non-graphitized carbon, the bounding error of graphite to total carbon ratio of 1% can mean a large effect on criticality of the system. Therefore one of the goals of this paper is to quantify how much of an effect the uncertainty in graphite to carbon ratio can have on the behavior of TREAT simulations.

There is also uncertainty in the boron impurity of the fuel. Although the material blocks used to construct the fuel only had a boron content very close to 1 ppm, later analyses of the fuel blocks showed varying quantities of boron with an average of 5.90 ± 0.35 ppm [3]. This increase in boron content was contributed to unexpected diffusion of boron from the borated steel divider plates used in the baking crucibles used in manufacturing the fuel [5, 6]. This uncertainty in boron impurity is important because boron is a strong neutron absorber and a small difference in boron impurities can have a noticeable effect on criticality.

Overall, we want to see how variation of boron concentration and graphite to carbon ratio, within the given bounds, effects the criticality and power profile of simulated TREAT experiments.

MODELS AND RESULTS

To ascertain how variation in boron concentration and graphite to carbon ratio effects the criticality and power profile of TREAT simulations 9 different models of TREAT were generated. Each model is geometrically identical and only differs in boron, graphite, and carbon concentrations.

Three groups of models were created. One group with the lower bound of boron impurity given from reference [3], one group with the mean given boron impurity, and one group with the upper bound of boron impurity. Within each of these groups 3 additional models were created corresponding to the lower bound, given, and upper bound values of graphite to carbon ratio (GCR) given in [3], shown in Table I.

TABLE I. Overview of Model Materials

	Boron Concentration (ppm)		
GCR	5.55	5.90	6.25
0.58	Model 1	Model 2	Model 3
0.59	Model 4	Model 5	Model 6
0.60	Model 7	Model 8	Model 9

Each of the models were evaluated using KENO-VI from SCALE 6.2.1 and the 238 group ENDF/B-VII.1 cross section set. k_{eff} values, shown in Table II, were calculated using 5000 generations, 20000 particles per generation, and 500 skipped generations.

The variation of k_{eff} with respect to graphite and boron content are both as expected. With lower concentrations of boron there is less neutron absorption and therefore a higher k_{eff}. With higher concentrations of graphite there was a decrease in k_{eff}.

Each of the models were then evaluated with T-ReX (formerly TDKENO), a time-dependent neutron transport code, in order to determine how differences in boron concentration and graphite to carbon ratio may effect simulations [7]. A temperature-limited transient experiment from the M8 Power Calibration (M8CAL) series, referred to as transient #2855, was simulated for each of the 9 models [8]. Each of the temperature-limited transients in the M8CAL have the same core configuration but have different reactivity insertions. In transient #2855 a reactivity insertion of 1.8% is induced by the withdrawal of transient control rods by approximately 33.02 *cm* (13 *in.*) over 0.13 seconds. These simulations used 5000 generations, 20,000 particles per generation, and 500 skipped generations along with the 238 group ENDF/B-VII.1 cross section set.

From Figure 2 we see that increased boron impurity resulted in a smaller peak power. For the models with 59% graphite the difference in peak power between the 5.55 ppm

TABLE II. k_{eff} Values

Boron (ppm)	GCR	k_{eff}
5.55	0.58	0.998748±0.000086
5.55	0.59	0.998389±0.000089
5.55	0.60	0.998168±0.000086
5.90	0.58	0.9958145±0.000085
5.90	0.59	0.995317±0.000085
5.90	0.60	0.995224±0.000084
6.25	0.58	0.992791±0.000089
6.25	0.59	0.992341±0.000094
6.25	0.60	0.992209±0.000087

and 6.25 ppm cases was 108 MW. In Figure 3 we see that the difference in boron impurity also resulted in a large difference in the final yield for the 59% graphite models. In this case the difference in final yield between the 5.90 ppm and 6.25 ppm models was 12.18 MW-s.

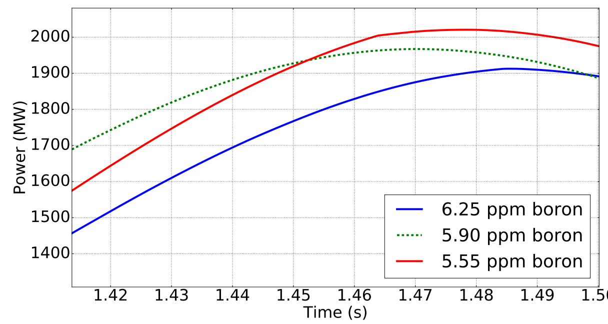

Fig. 2. Power vs Time - 59% Graphite

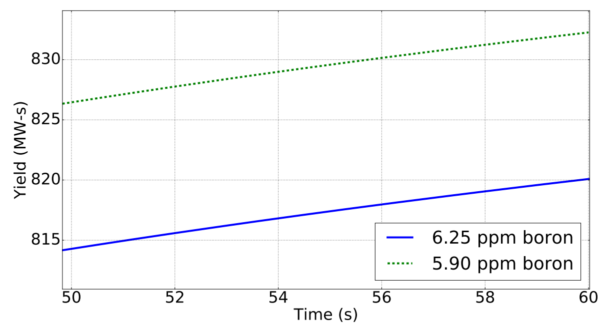

Fig. 3. Yield vs Time - 59% Graphite

However, the results from varying graphite to carbon ratio were less conclusive. Although we see a clear trend in the k_{eff} values of the pre-transient core with varied GCR, results from the T-ReX simulations do not show a clear trend for peak power and final yield as seen in Figures 4 , 5, and 6.

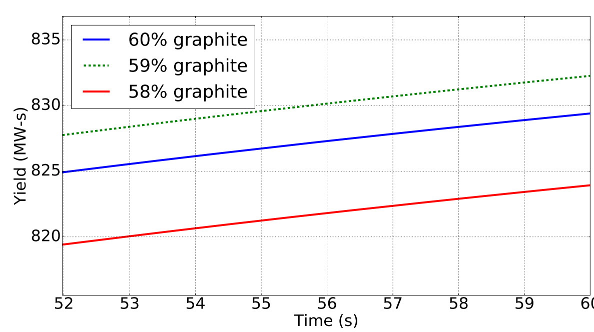

Fig. 4. Yield vs Time - 5.90 ppm Boron

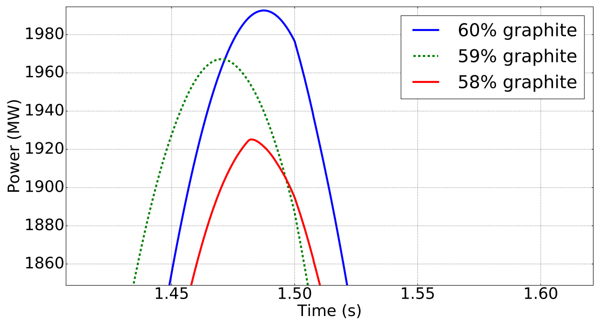

Fig. 5. Power vs Time - 5.90 ppm Boron

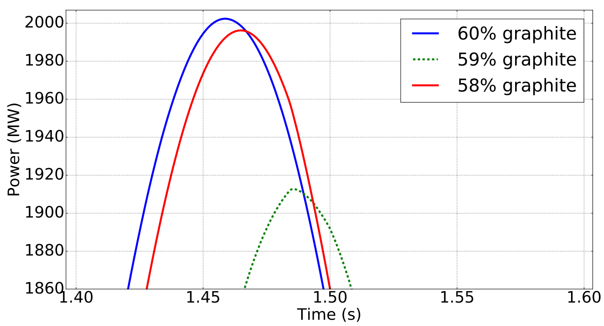

Fig. 6. Power vs Time - 6.25 ppm Boron

CONCLUSIONS

There are substantial differences in peak power and final yield in simulations of the TREAT reactor where the fuel is defined to have boron and graphite concentrations within the bounds of uncertainty given by reference [3]. The peak power and final yield of the transient #2855 simulations showed a decreasing trend with increased boron impurity, but there was no apparent trend for the variation of GCR. This lack of a clear trend appears to be due to the variation of GCR causing changes in k_{eff} value of the system small enough that the results are statistically the same. This is the case with the k_{eff} values in Table II. Total yield for the simulated transient #2855 experiment was on average about 830 MW-s and the difference in yield of cases was as much as 25 MW-s. A 3% difference in final yield is large enough to be investigated further by reevaluating the given models with a higher number of particles per generation in order to reduce the calculational uncertainties. Reference [9] found that a minimum of 100K particles per generation with at least 2000 active generations and 500 inactive generations is needed to properly analyze the TREAT core. This reduction in uncertainty also has the potential to show a more clear trend on how GCR effects peak power and yield. Further work will be done with simulation of different experiments in order to establish a confidence interval for the accuracy of TREAT simulation results given the uncertainty in material compositions.

ACKNOWLEDGMENTS

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