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Abstract

Analyses of the Advanced Fuels Campaign Fission Accelerated Steady-state Test in the Advanced Test Reactor are presented. A detailed methodology was employed to better account for uncertainties in the planned power and duration of sequential reactor loading cycles. By performing coupled depletion analyses at multiple power levels and durations, the differences in experiment heating outputs can be found. The effects of these uncertainties upon multiple experiment configurations were assessed in an effort to streamline the process of planning for and documenting future irradiations. The data generated from this work has been used to help inform assumptions on subsequent projections to only perform a nominal case depletion.

Keywords — Advanced Test Reactor, Fuel Irradiation, Irradiation Experiments

I. INTRODUCTION

The Advanced Test Reactor (ATR) provides a testing platform for a wide range of reactor experiments spanning from testing of structural materials to development and qualification of new fuel types [1]. While the ATR operates using a thermal neutron spectrum, it has been shown that it is possible to perform testing of fuels intended for fast spectrum reactors within the ATR by modifying the spectrum incident upon samples with a cadmium shroud [2]. The Advanced Fuels Campaign (AFC) utilizes such techniques to perform irradiations within ATR. This paper will discuss the Fission Accelerated Steady-state Test (FAST), an AFC testing campaign which began irradiation in 2020. Specifically, the modeling efforts performed to support the irradiation experiment's continued insertion in the ATR across multiple core loadings, ATR Cycles 171A and 171B, will be discussed. Figure 1 shows the ATR core geometry and labels several core positions used for irradiation of AFC-FAST and similar experiments.

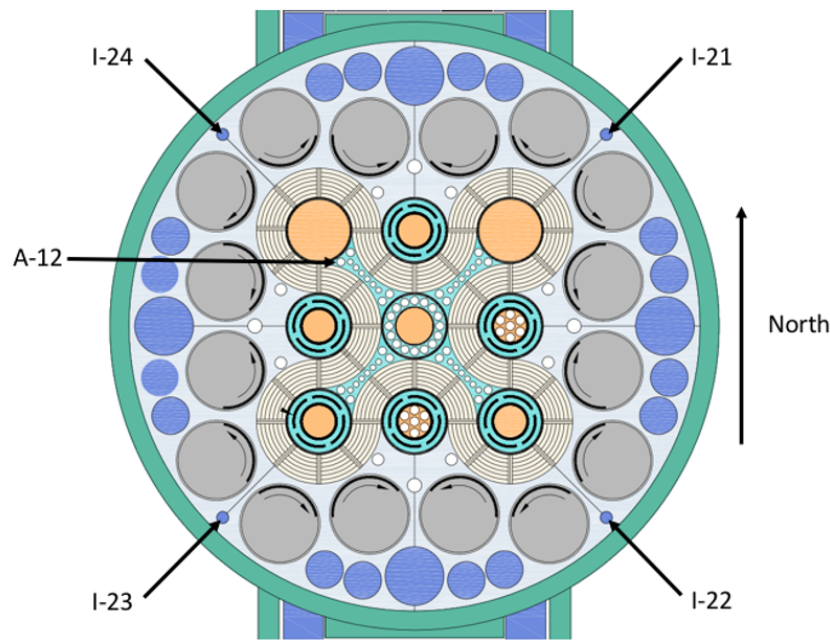


Fig. 1. ATR core region showing irradiation positions utilized for AFC-FAST experiments.

A unique feature of the ATR is the arrangement of the fuel into a serpentine pattern. Nine large irradiation fixtures (flux traps) are evenly spaced in a 3 by 3 grid. The 8 fuel elements surrounding each corner of this grid are referred to as the corner lobes of the reactor and identified

by their compass direction (NW,NE,SE,SW). The remaining 8 fuel elements make up the center lobe. The power of each of the corner lobes can be controlled independently using 4 control drums located outside of the core. The center lobe power is not directly manipulated by reactivity control mechanisms but instead is a function of the corner lobe powers. The relative independence of the corner lobe powers greatly simplifies analysis of irradiation experiments. The amplitude of the neutron flux incident upon irradiation positions can generally be approximated as a function of the power of the nearest lobe as opposed to the total core power. This allows the ATR to maintain a flexible operating plan in support of a wide range of experiment while limiting the need for individual experiments to adjust to power changes in distant lobes of the reactor [3].

I.A. The AFC-FAST Experiment

The AFC-FAST experiment aims to test fast spectrum reactor fuel within the ATR utilizing a reduced fuel geometry to accelerate burnup. By reducing the diameter of the fuel sample while increasing fuel enrichment to maintain a prototypical linear heat generation rate (LHGR), the fission density can be increased. Under these conditions, target burnups can be achieved with a shorter duration irradiation than previous fast spectrum fuel tests in the ATR [4]. At the same time, reducing the radius of the fuel helps to mitigate radial peaking factor within the rodlet caused by the high thermal flux in ATR [5]. The decrease in peaking factor has allowed the FAST series of tests to be performed without the need to modify the flux spectrum and intensity with a cadmium shroud while maintaining power profiles similar to fast spectrum fuels.

Two distinct capsule designs are utilized by the AFC-FAST experiments. The first is the FAST-OA capsule, shown in Figure 2, which contains a single rodlet and is irradiated within ATR Outboard A (OA) positions such as A-12 (Figure 1). A cadmium lined basket is utilized in these positions to reduce thermal flux. In previous AFC experiments, this was necessary to minimize radial peaking factors and better simulate power profiles in a fast reactor spectrum. Though not needed for this purpose with the reduced diameter FAST fuel samples, the cadmium basket was utilized to allow more direct comparisons with earlier irradiations. This allows the FAST-OA specimens to serve as control samples. The A-12 position utilized for this irradiation has a diameter of 0.625 inches which accommodates both the capsule and the cadmium lined basket. Axially, space is available for 5 FAST-OA capsules within the basket.

The second capsule design is the FAST-SI capsule, shown in Figure 3. Each FAST-SI capsule contains two rodlets arranged axially. FAST-SI capsules can be irradiated within ATR Small I (SI) positions such as I-24 and I-23. In addition to accommodating multiple rodlets per capsule, the SI positions offer the benefit of significantly more space to arrange capsules. Each ATR SI position has a diameter of 1.5 inches. An aluminum basket containing three flow channels, shown in Figure 4, is used to position up to 21 SI capsules simultaneously. The larger space available radially allows the diameter of the SI capsules to be increased and the length to be decreased relative to the OA capsules while maintaining the same plenum volume. The shorter length increases the number of capsules in an axial stack from five to seven. This allows for both greater flexibility than the OA positions as well as higher throughput. By aligning channels one and three to face toward the center of the core, the conditions of capsules at the same axial position are nearly identical.

For each reactor cycle in which an AFC-FAST capsule is to be irradiated, analysis must be performed to demonstrate compliance with multiple safety limits established during the initial design process:

- LHGR of each rodlet is less than 500 W/cm
- Burnup of each rodlet is less than 35% Fissions of Initial Metal Atoms (FIMA)
- Adjacent lobe exposure is less than 2500 MWD for cadmium baskets (FAST-OA only).

The requirement for a new analysis specific to each cycle has historically been beneficial to similar experiments in that it allows for the reconfiguration of capsules within the irradiation position. This allows samples to be removed as soon as they achieve burnup targets and for remaining samples to be relocated to more ideal positions if they become available. At the same time, the requirement has resulted in such experiments being forced to perform projections for the next cycle on very short timelines between cycles or risk delaying reactor startup. Over time the outage times between cycles have trended towards being shorter, increasing the risk that analysis for the experiment in the next cycle is not yet complete.

I.B. ATR Cycles 171A and 171B

ATR Cycles 171A and 171B were planned to operate for a nominal length of 60 days each. A range of +/- 5 days is generally included in analyses to account for early shutdowns or extended

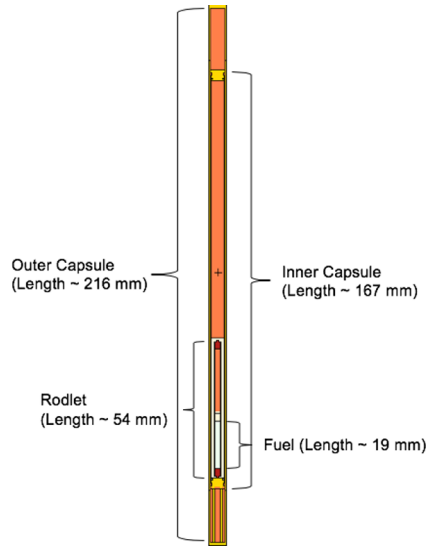


Fig. 2. Axial rendition of a FAST-OA capsule.

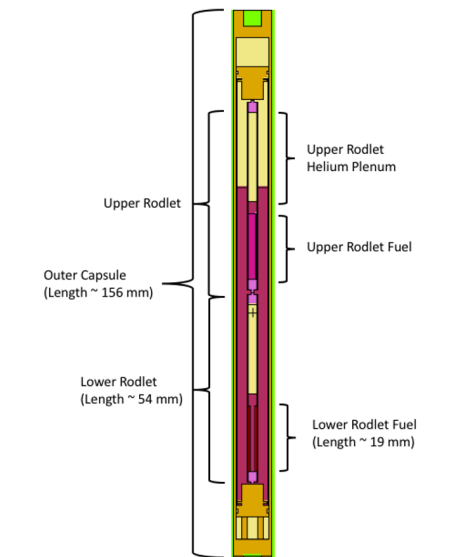


Fig. 3. Axial rendition of a FAST-SI capsule.

runs, both of which are possible to support facility schedule or experiment requirements. Table I shows the planned powers for ATR lobes adjacent to AFC-FAST experiment capsules. Nominal, Low, and High power columns indicate the ranges provided by ATR staff for each cycle. These powers represent a range in which the reactor is expected to operate, not an uncertainty in the power, and provide a degree of flexibility to increase or decrease power to support lead out experiments with actively monitored temperatures or pressures. The Minimum and Maximum columns

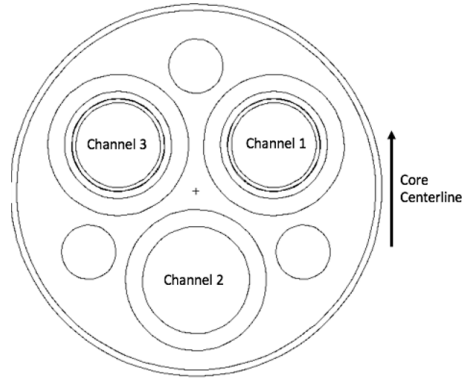


Fig. 4. Arrangement of FAST-SI capsule channels and orientation to core center-line.

account for an 8.5% uncertainty in measurement of individual lobe powers in the direction away from nominal.

TABLE I
ATR planned cycle power ranges.

Cycle	Lobe	Minimum Power MW	Low Power MW	Nominal Power MW	High Power MW	Maximum Power MW
171A	NW	15.67	17.0	20.0	23.0	24.96
	SW	18.43	20.0	24.0	26.0	28.25
171B	NW	15.67	17.0	20.0	23.0	24.96
	SW	18.43	20.0	25.0	26.0	28.25

II. METHODOLOGY

Projection analyses are performed for each reactor experiment using a coupled neutronics and depletion model. Neutron flux intensity and spectrum are calculated using an MCNP [6] model of the experiment within the ATR core. The ORIGEN module of the SCALE code package [7] is then used to calculate updated material properties for the experiment. The MCNP and SCALE models are coupled using an in-house coupling code which is able to account for ATR's unique lobe power scaling [8]. The condition of the reactor itself is modeled as a fixed source with power distribution and fuel compositions taken directly from the safety analysis performed on the core loading. When modeling experiments in core loadings for which this data is not yet available, it is necessary to make an assumption that the data from an existing core loading is an acceptable substitute. Formal guidance as to what constitutes an 'acceptable substitute' does not yet exist and is a desired outcome of this and subsequent works. Until such guidance exists, engineering

judgement and conservative safety margins will continue to play a significant role in experiment analysis for new ATR core loadings. In the case of Cycle 171B, the preceding cycle (171A) was selected on the basis that the identical minimum and maximum powers (Table I).

To account for the uncertainty that exists in the planned reactor power and cycle length when demonstrating compliance with the AFC-FAST safety limits listed above, a single projection at the nominal planned power can not be definitively considered to be bounding. Operation at the high end of the power band would result in higher burnup than the nominal case. Higher power would also initially result in higher linear heat generation rates. This would seem to suggest that performing the depletion analysis at the maximum power as opposed to nominal will allow a single calculation to bound both the LHGR and burnup. For an irradiation in which the sample is subjected to a constant flux, this would be correct. For a real experiment however, this neglects the fact that the incident flux upon the experiment may change either as a result of a change in reactor power or reconfiguration of the experiment between irradiation cycles.

To address the need to document compliance with competing safety limits while at the same time producing a best estimate of experiment properties, the following method was implemented:

1. The experiment was modeled at the nominal planned power for the nominal planned cycle duration of 60 days per cycle.
2. The depletion was repeated at the maximum planned power (including +8.5% power measurement uncertainty) for 65 days per cycle.
3. The depletion was repeated at the minimum planned power (including -8.5% power measurement uncertainty) for 55 days per cycle.
4. The heat generation results of each depletion analysis were scaled to the powers used in the other two projections.

By performing three semi-independent projections, it is possible to bound the full range of planned reactor operations. By scaling the outputs of each depletion case to the powers used to perform the other depletions, it is possible to show how the heating rate produced at a power can vary based on irradiation history. The maximum power case depletion produces an estimate of burnup that will not be exceeded during irradiation unless the reactor significantly deviates from the planned cycle parameters. Likewise, by minimizing burnup, the heat rates from the minimum

power depletion can be scaled to the maximum power to bound the heat rates after reconfigurations between cycles. Finally, the differences between the cases can help to communicate the broad range of heating rates that could be produced by the planned range of reactor powers and cycle durations.

III. PROJECTION RESULTS

Selected results from these analyses are presented. III.A will present projected LHGRs for several rodlets within the final configuration which was irradiated. The results of an attempt to re-use a consumable Cd shroud will be shown in III.B. Finally, a preliminary configuration in which depletions at different powers made a difference between compliance with previously analyzed safety case limits will be show in III.C.

III.A. Final Configuration

The final basket configuration for the I-23 position determined through this analysis is shown in Table II. The capsules in axial position 2 of each channel were relocated from the I-24 position while the remaining capsules retained their positions in I-23 from the previous cycle.

TABLE II
Final Cycle 171B loading case for I-23.

Axial Position	Channel 1	Channel 3
1 (Top)	—	—
2	FAST-050 FAST-049	FAST-048 FAST-047
3	—	—
4	FAST-054 FAST-028	FAST-053 FAST-027
5	FAST-052 FAST-026	—
6	—	—
7 (Bottom)	—	—

Rodlet FAST-028 provides an example of a rodlet that remained in the same irradiation position between cycles. The projected power history for FAST-028 is shown in Figure 5. As expected, a downward trend in linear heat generation rate is observed over time. Trends from each

depletion case are effectively continuous with small variations due to shifts in driver fuel power distribution. At startup of the second cycle, a small step change can be observed in the cases scaled to the nominal power. This corresponds with the 1 MW increase in lobe power between cycles.

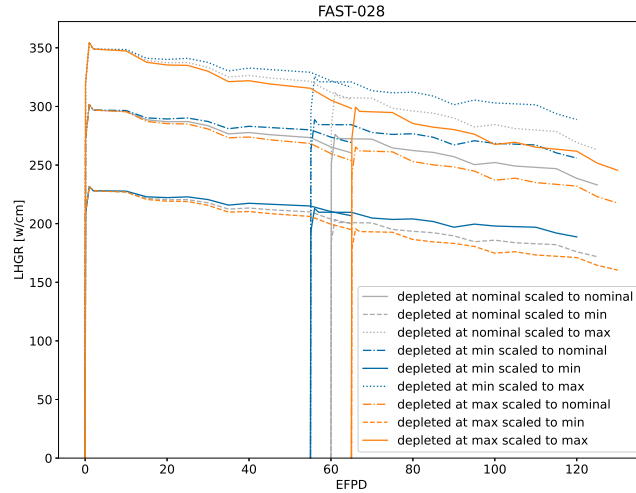


Fig. 5. Projected power history for rodlet FAST-028.

A second rodlet that was irradiated in the same position during both cycles was FAST-052, shown in Figure 6. Unlike FAST-028, there is a noticeable increase in linear heat generation rate at the start of the second cycle. The cause of this jump can be attributed to the removal of the capsule in channel 3 at the same axial position. This case is helpful in visualizing the relationship between numerous factors including current and past reactor power, cycle length, and changes in nearby experiments. It helps to reinforce that while the current reactor power is the dominant factor in experiment heating, other factors must be considered when predicting future behavior.

III.B. Alternative Case Exploring Extended Use of Cd Basket.

The 2500 MWD adjacent lobe exposure limit upon cadmium baskets is in place to allow for cadmium baskets to be re-used without significant re-analysis. The design of these baskets was performed based on ATR cycle lengths not exceeding 60 days, generally with lower nominal lobe powers than in current cycles. The original intent was to be able to utilize each basket for 2 cycles with adequate margin for longer operation or higher power [9]. As the power and duration of ATR

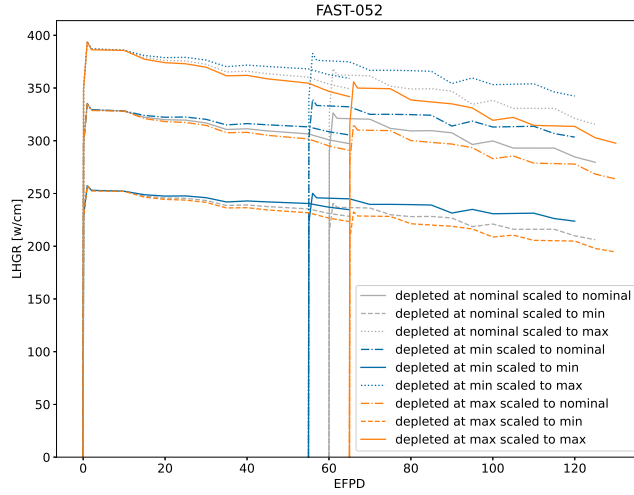


Fig. 6. Projected power history for rodlet FAST-052.

cycles has increased over time, it is no longer possible to assume that each basket can be re-used. For the NW lobe powers of Cycle 171A and 171B, operating at nominal power for 60 days per cycle results in an adjacent lobe exposure of 2400 MWD. If one cycle were to increase to 65 days, the cadmium basket would be expected to exceed the limit.

An effort was made to evaluate the impact of a second irradiation cycle upon the same cadmium basket with the goal of potentially updating the existing limits to account for longer cycles. Figure 7 shows the results of this cadmium basket re-use on rodlet FAST-003, with the re-used cases marked with an x and overlaid upon the fresh basket cases. The results are immediately visually compelling. The depletion performed at the maximum power case clearly shows that the cadmium basket no longer performs its intended function by the end of the second cycle. A similar, but less drastic, trend can be observed for the nominal case depletion with the projected power beginning to trend upward after 100 days of operation. This would suggest that the 2500 MWD limit was appropriately selected and is unlikely to be practical to revise upward. It would also suggest that at current cycle durations and powers, it is unlikely that a cadmium basket can be re-used without first accounting for the as-run conditions of the first cycle while relying on one or both cycles to have a lower exposure.

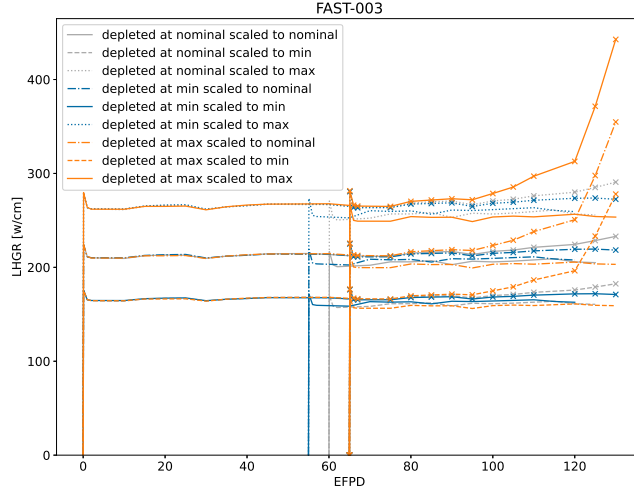


Fig. 7. Projected power history for rodlet FAST-003 with and without cadmium basket re-use. Cases using Cd basket for Cycle 171B are marked with an x.

III.C. Preliminary Loading Case

The differences in maximum heating rates between the minimum and maximum power depletion cases is generally small. It is unlikely, but possible, for a sample which meets safety requirements in the nominal power depletion case to violate these requirements in the minimum or maximum power depletion case. In performing this analysis, a single example was encountered. After ATR Cycle 171A, all FAST-SI capsules from the I-24 position which had not yet reached their burnup targets were relocated to the I-23 position. This change from the NW lobe to the SW lobe increased the power of the nominal case for these capsules by 20%. To maximize burnup rate, the initial configuration analyzed for this change moved the capsules containing these rodlets to the third axial position of channels 1 and 3 in the I-23 position. Table III shows this configuration.

In the nominal case depletions, this change successfully maximized burnup rates while remaining under the 500 W/cm safety limit. The highest observed nominal depletion case LHGR from this configuration was 497 W/cm when scaled to the maximum adjacent lobe power (+8.5% uncertainty), occurring in rodlet FAST-049 during the first timestep after startup of Cycle 171B. To be clear, this is a linear heat generation rate which is effectively indistinguishable from the pre-

viously analyzed safety case. Engineering judgement would suggest that while the configuration is allowable, it is likely not ideal as any uncertainties in burnup during the previous cycle could make the difference between falling under the safety limit and exceeding the safety limit. The minimum power case depletion for this rodlet matches this scenario perfectly, predicting a maximum LHGR of 506W/cm. Figure 8 shows the results of the three depletion cases for this initial configuration overlaid on the final configuration LHGRs for FAST-049.

TABLE III
Preliminary Cycle 171B loading case For I-23.

Axial Position	Channel 1	Channel 3
1 (Top)	—	—
2	—	—
3	FAST-050 FAST-049	FAST-048 FAST-047
4	FAST-054 FAST-028	FAST-053 FAST-027
5	FAST-052 FAST-026	—
6	—	—
7 (Bottom)	—	—

IV. RECOMMENDATIONS AND CONCLUSIONS

The modeling and simulation of AFC-FAST capsules in ATR Cycles 171A and 171B provided the data needed to support insertion in those cycles. At the same time, by modeling and formally documenting the results of bounding projection calculations, it was possible to justify assumptions on future analyses that such extensive measures are not necessary in most cases. Projection analyses for AFC-FAST have been completed for ATR Cycles 173A and 173B in which depletion was performed at only the nominal case power. Instead of relying on multiple computationally expensive simulations to account for maximum and minimum power, simple ratios were calculated to demonstrate that a sufficient margin exists to account for uncertainties. Additionally, this analysis was documented for multiple cycles far in advance of the startup for the first cycle. No additional modeling and simulation efforts are required for insertion in the second cycle, effectively

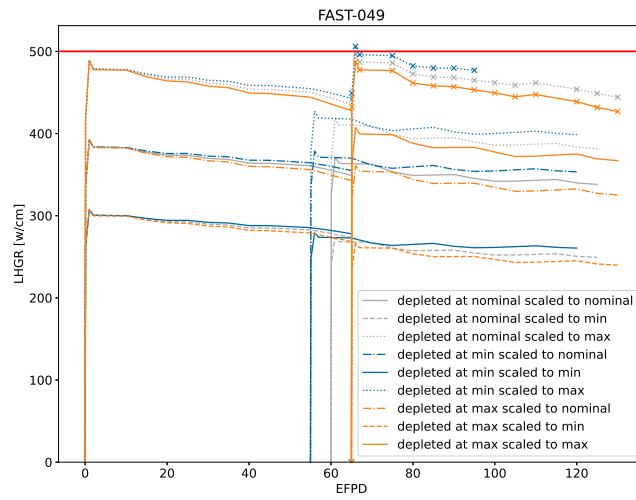


Fig. 8. Projected power history for rodlet FAST-049 with preliminary configuration maximum power scaling marked with an x.

removing the experiment from the critical path for startup of future cycles. By investing the extra effort to demonstrate uncertainty in routine calculations, a significant recurring obstruction to multiple irradiation experiments has been mitigated.

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