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Fuel performance studies using the Bison Fuel Performance code were performed to see the influence various pulse narrowing techniques in the Transient Reactor Test facility (TREAT) can have on postulated LWR fuel response during Reactivity Initiated Accident (RIA) events.

I. INTRODUCTION / BACKGROUND

The Transient Reactor Test facility (TREAT) was constructed in the late 1950′s, provided thousands of transient irradiations before being placed in standby in 1994, and resumed reactor operations in 2017 in order to reclaim its crucial role in nuclear-heated safety research[1]. While the facility′s flexible design and multi-mission nature saw historic experiments for numerous reactor fuels and transient types, TREAT was never specifically adapted to address very-brief pulse transients akin to postulated Light Water Reactor (LWR) Reactivity Initiated Accidents (RIA). Since the behaviors of fuel under these conditions depends strongly on energy input duration and resulting cladding time/temperature response under pellet cladding mechanical interactions, a research project at the Idaho National Laboratory (INL) was conceived to develop pulse-narrowing capabilities for the future of TREAT.

TREAT is currently capable of performing transients to achieve pulse′s whose Full-Width at Half Maximum (FWHM) duration is <100ms, and perhaps as narrow as 72 ms[2], but not squarely in the desired range of 25-65 and 45-75 ms FWHM required for simulating hot zero power RIAs for Pressurized and Boiling Water Reactors (PWR and BWR), respectively[3]. Kinetic models of TREAT were exercised to determine which nuclear parameters most affected pulse duration. These investigations showed incremental improvements for minor facility enhancements including increased reactivity step insertions (to initiate the power pulse) and slightly-increased transient rod drive speed for pulse termination (″clipping″) via uprated rod drive system pressure. These minor improvements may be able to enable TREAT to achieve pulse widths in the range for BWRs, but still well outside the range for typical PWRs. An enhanced clipping method utilizing a He-3 injection system is currently being designed and analyzed that can get the pulse width <50ms. More detail about the options for narrowing the pulse width are detailed in[4,5]. This work focused on performing reactivity-initiated accident (RIA) fuel performance studies on the various enhanced clipping methods and comparing fuel performance metrics deemed as important to values expected during a typical PWR RIA event.

II. KINETIC STUDIES

The effects of various parameters on a power excursion in TREAT were studied in order to reduce the pulse width and make it more prototypical of a commercial PWR. A RELAP5-3D point kinetics model of TREAT was used in this study. The RELAP5-3D model was used to investigate the effects of various parameters on pulse width. The parameters that were investigated included the magnitude of the step reactivity insertion that initiated the power excursion, the speed at which negative reactivity can be inserted during the transient, and the total power peaking factor in the core. The initial temperature and power of the core were assumed to be 25°C and 50 W in all of the calculations[6].

The cases selected for the fuel performance analysis were the cases with enhancements most likely possible to implement at TREAT or capable of getting pulse widths in the range of interest. These cases are shown in highlighted in blue in Table 1. The case numbers are not consecutive and kept as the same value as in other references[6]. Case 1 is the realistic PWR type pulse that will be used as a baseline to compare the other cases to. Case 5 represents a pulse using the current capabilities in TREAT. Cases 8 and 9 use enhanced clipping techniques investigated in this project[4,5] to narrow the pulse. Case 12 uses a higher step insertion of 5.1%Δk/k to initiate the transient with no modifications in pulse clipping capabilities, and case 13 uses a combination of enhanced clipping and a larger step insertion.

III. FUEL PERFORMANCE MODEL

Fuel performance studies using the Bison Fuel Performance code were performed to see the influence pulse narrowing techniques in TREAT can have on postulated LWR fuel response during RIA events. Bison is a finite element based three-dimensional code developed specifically to evaluate the performance of nuclear fuel. The baseline PWR case was selected with a pulse width of 30 ms FHWM from literature[3]. All cases used a similar rodlet geometry that will be used for future TREAT experiments[7]. These simulations were performed on pre-irradiated fuel at 70 GWd/MTU. The PWR fuel geometry and operating conditions from[8] were input into a BISON to generate a fuel rod with an average burnup of 70 GWd/MTU that was used as the initial fuel rod geometry and condition for all RIA simulations in this work.

Table 1. Overview of TREAT enhancements

Case No.	TREAT Modifications	Step Ins. (%Δk/k)	Core Energy Release (MJ)	Clipping	FWHM (ms)
PWR baseline	n/a	n/a	n/a	n/a	30
3	None	2.6%	500	Tran rods 140 in/sec	133
5	None	4.5%	625	Tran rods 140 in/sec	95
6	Rod drive pressure increased	4.5%	625	Tran rods 200 in/sec	84
8	Drive pressure and follower mass mods	4.5%	625	Tran rods 250 in/sec	77
9	He-3 injection or other rapid clipping system	4.5%	625	-5% Δk/k in 5 ms	46
10	Pre-transient core chiller	4.8%	625	Tran rods 140 in/sec	92
11	Mod. SAR and RTS set points (50 °C increase)	4.8%	625	Tran rods 140 in/sec	94
12	Mod. SAR and RTS set points (100 °C increase)	5.1%	625	Tran rods 140 in/sec	92
13	He-3 injection, mod. SAR (100 °C increase)	5.1%	625	-5% Δk/k in 5 ms	50

IV. FUEL PERFORMANCE RESULTS

The results for a number of parameters of interest during RIA events for the highlighted cases in Table 1 are shown in Table 2. The power pulses for these cases are plotted in Fig. 1a; also plotted on a log scale (b) to show the influence of the pulse tail due to delayed neutrons. When comparing many of these cases to the realistic PWR type pulse (Case 1) it can be seen that the TREAT pulses only slightly underperform the PWR case with respect to fuel radial average enthalpy and fuel centerline temperature (Fig. 2). The current TREAT capabilities (Case 5) pulse results in 4% lower radial average enthalpy and 1.3% lower max fuel centerline temperature. Cases 8 and 12, using faster transient rod speeds or a larger step insertion, show almost no difference compared to Case 5 for fuel enthalpy and temperature predictions.

Concerning the mechanical results for cases 5, 8, and 12 compared to case 1, there is only a very small decrease in predicted cladding hoop strain (~2-3%), but the cladding hoop stresses shows where the narrow pulse width limitations in TREAT may affect the actual fuel rod performance. The cladding stresses are ~25% lower than a more realistic 30 ms pulse in a PWR. The cladding hoop stress and strain is shown in Fig. 3.

Cases 9 and 13, using a He-3 injection system to insert -5%ΔK/k in 5 ms, result in the narrowest pulse widths of 46 and 50 ms, respectively. When comparing the results for these cases in Table 2, unexpected results are seen. The narrower pulses should be expected to increase the peak fuel radial average enthalpy, fuel centerline temperature and hoop stress closer to the baseline PWR case, but all those values are lower than the wider TREAT pulses (cases 5, 8, 12). The reason for this discrepancy can be seen by observing Fig. 1b and the last two rows in Table 2. The He-3 clipping system, as modeled, results in a narrower FWHM pulse along with a larger power tail. All these cases were modeled using the same amount of total energy injected into the fuel ~525 J/g, but the He-3 clipped pulses result in ~80% of the total energy injected before the power tail where the other cases are ~91%. Literature states the energy injected during the tail has very little influence on the peak fuel radial average enthalpy and cladding stresses[9], so cases 9 and 13 effectively experience a ~10% less energetic pulse than the other cases. A similar result can be seen by comparing the percent of total energy deposited into the fuel at the time of peak fuel radial average enthalpy. The He-3 clipped pulses are ~79% at this point compared to ~90% for the other pulses.

The results for case 9 and 13 do not mean that the shorter pulses from a He-3 clipping system will result in less realistic fuel performance parameters during a RIA as compared to the 30 ms pulse. These results indicate the complicated relationship of fuel radial average enthalpy and total energy deposited into the fuel. This relationship needs to be better understood or defined in such a way to properly account for the energy in the tail due to delayed neutrons. Future work should be performed where the achieved peak radial average enthalpy is equilibrated, rather than the energy injected, for a more-direct comparison of the effect of pulse width on fuel performance parameters.

V. SUMMARY

The fuel performance studies on the effect of various TREAT pulse width enhancements show that there are very small deviations from the baseline case regarding fuel thermal parameters. Cladding surface temperature variations showed about 5% lower temperatures compared to the baseline PWR case. The large variation is seen when comparing cladding mechanical properties with deviations of over 25% in the maximum hoop stress and ~60-70% lower strain rates which are important to cladding plastic deformation and ductility.

The He-3 clipping system showed unexpected results due to the amount of energy contained in the tail or the pulse as compared to the main pulse in the first few milliseconds. The simulations kept the total energy deposition into the fuel constant and may require further work to investigate a better comparison metric.

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Table 2. Results from TREAT pulse width cases and a realistic PWR pulse

	Case 1	Case 5	Case 8	Case 9	Case 12	Case 13
Energy Deposited (J/g)	525.2	525.9	525.9	526.3	528.7	526.4
Peak Radial Avg. Enthalpy (J/g)	513.6	493.1	498.3	453.5	493.8	432.2
Max Fuel Centerline Temp (K)	1850	1825	1825	1751	1830	1717
Max Fuel Surface Temp (K)	1512	1315	1345	1263	1317	1217
Max Clad Surface Temp (K)	1007	984	991	954	984	933
Max Clad Hoop Strain (mε)	1.36	1.31	1.32	1.22	1.31	1.16
Max Clad Hoop Strain Rate (mε/s)	400	120	150	190	130	170
Max Clad Hoop Stress (MPa)	550	410	430	420	410	390
Max Clad Hoop Stress Rate (MPa)	31200	8100	10200	14000	8400	13900
% of Total Energy Deposited Excluding Tail	91	91	91	83	91	79
% of Total Energy Deposited at time of Peak Radial Avg. Enthalpy	90	90	90	81	89	77

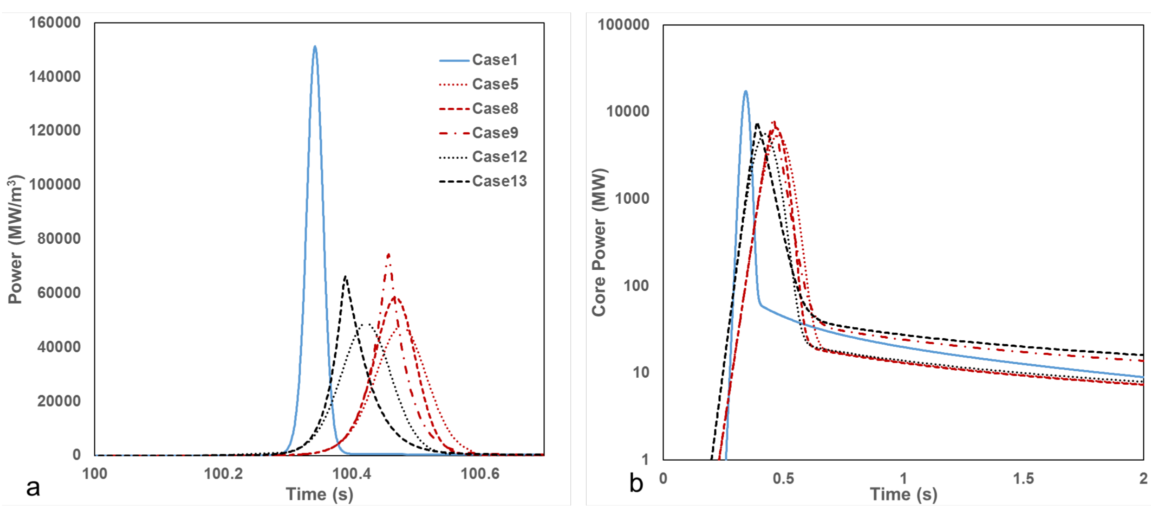

Fig. 1. Power pulses for cases in Table 6 plotted on a normal scale (a) and on a log scale (b) to show the influence of the tail

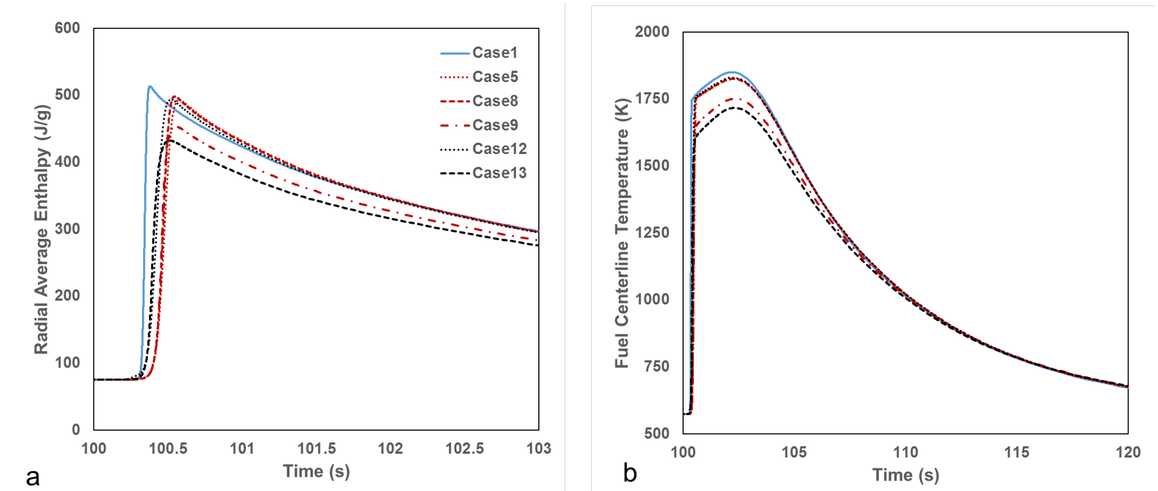

Fig. 2. Fuel radial average enthalpy (a) and fuel centerline temperature (b) for cases in Table 6

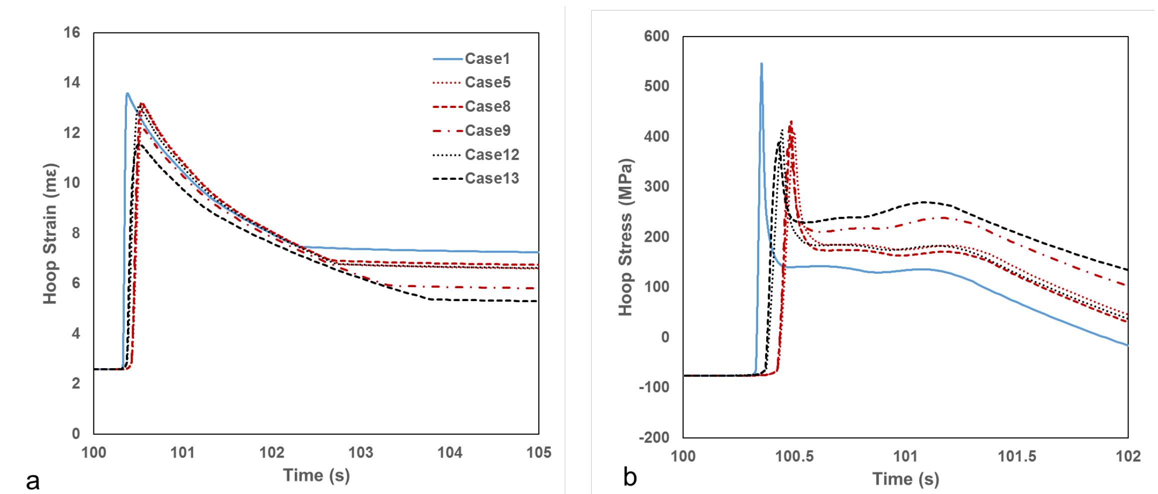

Fig. 3. Cladding outer surface total hoop strain (a) and hoop stress (b) for cases in Table 6

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