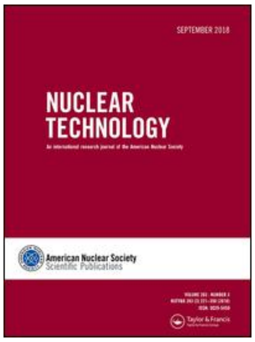

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Transient Reactor Test Facility Advanced Transient Shapes

Thomas Holschuh,* Nicolas Woolstenhulme, Benjamin Baker, John Bess, Cliff Davis, and James Parry

Idaho National Laboratory, 2525 North Fremont Avenue, Idaho Falls, Idaho 83415

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Abstract — *The Transient Reactor Test (TREAT) facility restarted transient operations in 2018 and has met or exceeded expectations for reactor experiments. TREAT's flexibility in power shaping provides the ability to prescribe a variety of operating conditions for test specimens, including shaped transients, steady-state irradiations, natural pulses, and clipped pulses, to deliver the necessary energy deposition and energy deposition rate. The initial operations following the TREAT restart were designed to mimic historical operations to confirm TREAT's capability. Then, studies were performed to evaluate the minimum pulse width possible in the facility as well as reactor power profiles characteristic of a loss-of-coolant accident (LOCA); both were achieved with excellent results.*

This paper highlights the following:

1. *The TREAT facility has been restarted to resume nuclear fuel safety research.*
2. *Initial reactor operations have mimicked historical operations.*
3. *A minimum pulse width has been achieved by control rod reinsertion during pulse.*
4. *Power profiles characteristic of a LOCA accident were performed.*

Keywords — *Nuclear fuel safety research, irradiation testing, reactor kinetics, nuclear testing, transient testing.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The Transient Reactor Test (TREAT) facility is capable of performing a variety of transient operations to accommodate requirements for peak reactor power, total energy released, or full-width at half-maximum (FWHM). The TREAT facility performed 2885 transients from 1959 to 1994 and resumed transient operations in 2018. The TREAT facility's transient operations are capable of, but not limited to, steady-state operations, shaped transients (including ramp reactivity insertion and preheated transients), natural pulses (also known as temperature-limited transients), and clipped pulses, where control rod movement reduces the total energy deposition as compared to an equivalent reactivity insertion for a natural transient. The flexibility in capability allows for operations to be relevant in many avenues of nuclear research, including light water reactor (LWR) and liquid-metal fast breeder reactor (LMFBR) fuel designs. Since the restart of transient operations, the TREAT facility has executed operations that mimic historical actions to evaluate reactor performance following the extended shutdown. The TREAT facility also demonstrated the ability to provide a reactor power profile similar to one that occurs during a loss-of-coolant (LOCA) accident. Finally, a series of transients was performed to minimize the FWHM by reinserting the transient rods during reactor operations near the moment of peak power, named the narrow pulse width transients.

II. BACKGROUND

II.A. TREAT: A Uniquely Capable Shaped-Transient Reactor

The TREAT facility is an air-cooled reactor composed of graphite blocks encapsulated in zirconium alloy canisters.[1]

*E-mail: thomas.holschuh@inl.gov

A dilute concentration of uranium oxide is dispersed in the blocks so that transient nuclear heating is conducted rapidly through the graphitic heat sink/moderator to cause a neutron energy spectral shift with strong negative temperature feedback for safe self-limiting power excursions.[2] Automatically controlled hydraulic transient rod drives enable virtually any power history within the core's energy capacity of 2500 MJ, limited only by the speed of the rods. More than just a pulse reactor, TREAT is also a shaped-transient reactor where inherently safe core physics, nimble transient rod drive systems, and a philosophy of continual facility improvement work together to enable flexible power maneuvers relevant to current fleet nuclear plants, advanced reactors, and scientifically valuable power shapes. TREAT experiments are typically lowered into the core through an opening in the upper rotating shield. Radioactive experiments are handled outside of the reactor with shielded casks. Experiment devices typically displace a few driver fuel assemblies, each being approximately 10 cm square, in the central region of the 1.2-m active-length core. TREAT experiment vehicles are typically self-contained assemblies with engineered capabilities to safely contain any hazards, support specimens/instrumentation, and provide the desired specimen boundary conditions.[3] An isometric section view of TREAT's core, rod drive room, and shielding structure is shown in Fig. 1.

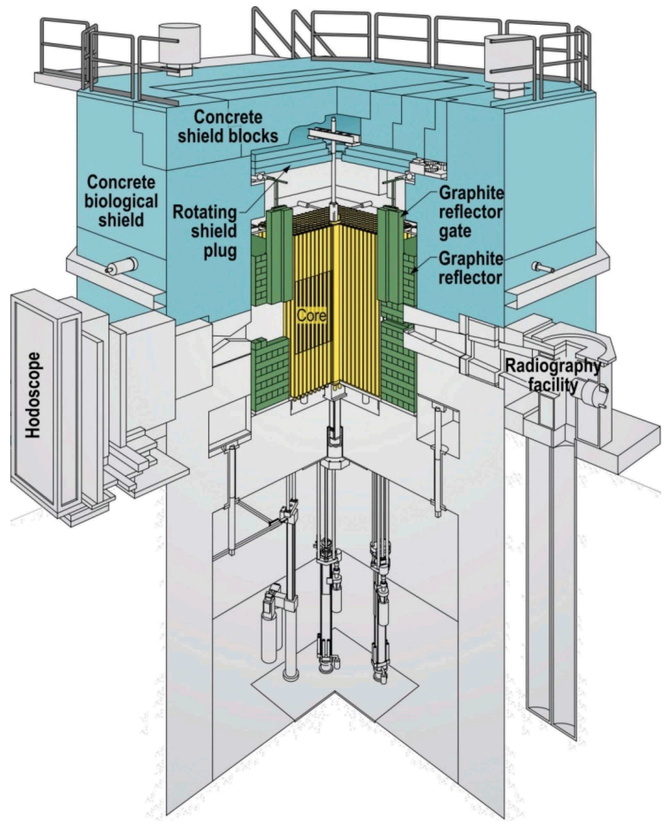

Fig. 1. Isometric overview of TREAT features (three-quarters section view).[4]

II.B. Historic Transient Shaping Supporting LMFBR Safety Research

The TREAT facility can perform many different transients to accommodate specific requirements of a particular experiment to evaluate nuclear fuel designs.[5] Transients can be shaped to vary over several orders of magnitude in power, total energy, and transient duration. Two major categories of TREAT transients are exponential or peaked bursts (natural) and shaped power bursts (shaped), where a flattop transient is a shaped transient with a constant elevated core power maintained for a period of time longer than encountered with a typical natural burst.[6] Exponential bursts are excursions that are temperature limited or rod and temperature limited (clipped); in the latter of which the control rods are dropped to reduce the length of the transient before the temperature limit is reached or to limit the energy deposited on the tail end of the transient. Shaped power bursts are produced by a step insertion of reactivity followed by reactivity insertion or removal at rates required to produce the desired burst shape; delayed neutron effects and the power history of a given transient impact the maximum energy available during a shaped transient. Up to 120 kW of thermal power can be provided during steady-state operation of TREAT (Ref. 7). Table I presents characteristics of several transients performed in TREAT's operational history that are shown in Figs. 2 through 4. Peak reactor power and total energy released are rounded to the nearest integer. Figure 2 illustrates the reactor power as a function of time for three transients that were performed in TREAT in the 1970s to evaluate EBR-II fuel pin designs. The transients, numbered 1362, 1406, and 1408, were subjected to relatively small reactivity insertions (~1%$\Delta k/k$) and are deemed "temperature-limited transients." A temperature-limited transient is characterized by a rapid introduction (step change) in positive reactivity, resulting in a rapid increase in reactor power followed by a decrease due to the negative feedback in TREAT associated with increased temperature. Once the desired total energy release was achieved for each transient, the transient was terminated.

However, temperature-limited transients are not the only type of operations available in TREAT. Figure 3 presents a ramp power insertion performed on multiple occasions in the TREAT facility, with transients 2867 and 2874 used as examples. The ramp reactivity insertion provides a controlled insertion of positive reactivity until the desired total energy release is achieved and the transient is terminated. Though it is possible to achieve similar values of total energy release

TABLE I

Characteristics of Historic TREAT Transients

Transient Number	Step Reactivity Insertion (%$\Delta k/k$)	Peak Power (MW)	Total Energy Released (MJ)	Date
1362	0.73	32	164	February 26, 1971
1406	0.885	81	197	October 8, 1971
1408	1.02	153	222	October 11, 1971
2422	0.97	1616	876	February 17, 1983
2867	—	152	2283	October 27, 1992
2874	—	286	2120	February 17, 1993

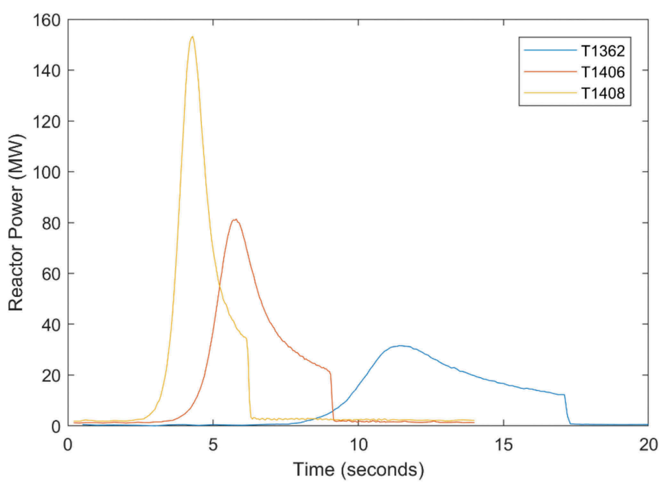

Fig. 2. Temperature-limited transients for LMFBR research.

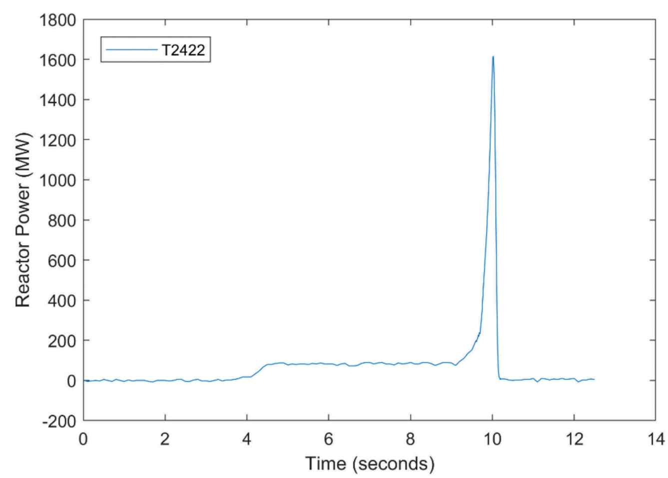

Fig. 4. Preheated transient shape example in TREAT.

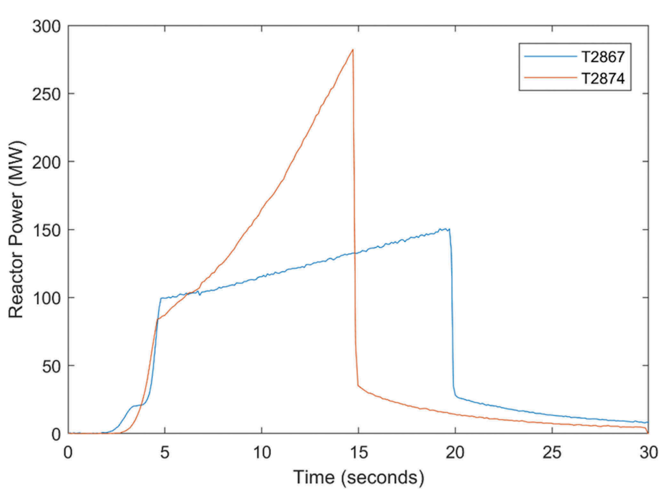

Fig. 3. Shaped-transient examples in TREAT.

with ramp and step change reactivity insertion, it is important to note that the peak power values will be substantially different for these two cases. Additionally, the duration of the transients with a ramp reactivity insertion is much longer than a comparable temperature-limited transient. Therefore, an experiment's requirements and boundary conditions dictate the type of transient performed in TREAT. Finally, Fig. 4 presents an example of preheating in transient 2422, where the reactor power is elevated to a constant power level (~80 MW for transient 2422) until a specified time or desired experiment sample temperature is achieved, at which point a step change in reactivity is initiated. The concept of preheating allows additional parameters in boundary conditions to be controlled during irradiation of test specimens.

III. ADVANCED TRANSIENT SHAPING FOR LWRs

TREAT's versatility allows for transient shapes that are applicable for LWRs. The estimated maximum enthalpy increase during a reactivity-initiated accident (RIA) for LWRs ranges from 80 to 450 J/g UO_2, and the estimated FWHM ranges from 25 to 75 ms (Ref. 8). Therefore, operating parameters for TREAT should be prescribed to satisfy these criteria. Historically, the TREAT facility focused on total energy deposition in the sample, which is a function of the total energy released in the core multiplied by a factor to account for the ratio of energy deposited in the sample position. Recent operational developments in the TREAT facility are designed to satisfy both FWHM and energy deposition in the sample. However, initial transients performed in TREAT attempted to evaluate reactor performance following the restart through similar transients to those performed just prior to the extended shutdown. Then, transient prescription tests demonstrated the ability to provide similar energy characteristics while varying the reactor power profile. For experiments that require a minimized FWHM, the TREAT facility performed large reactivity insertions and varied the clipping delay time to experimentally verify the minimal pulse width available in the TREAT facility. Finally, the TREAT facility performed simulated LOCA-type transients to illustrate the ability to provide characteristic reactor power for several minutes.

III.A. Historically Similar Transients

Since TREAT's restart of transient operations in 2018, temperature-limited transients consisting of reactivity insertions from 1.8%$\Delta k/k$ to 3.85%$\Delta k/k$ were performed to demonstrate the reliability of the facility following the extended shutdown period. Table II provides characteristics of historic TREAT pulses performed in 1992 in the first three rows, with the next four rows consisting of the characteristics of the similar pulses performed following the restart. All peak power and total energy released are rounded to the nearest integer. The peak power values and energy released are similar for comparable pulses. There are two pulses following the TREAT restart that were approximately 1.8%$\Delta k/k$. Figure 5 displays the reactor power profiles for the pulses in Table II. The reactor power profiles for the historic transients are shown as dotted lines, and there is good agreement between comparable pulses.

III.B. Transient Prescription Tests

In preparation for fuels testing in 2018, the TREAT facility performed several pulses, deemed transient prescription tests, designed to release between 600 and 800 MJ through different reactivity insertions. The 1.5%$\Delta k/k$ and 2.0%$\Delta k/k$ pulses were temperature-limited transients, and the 2.6%$\Delta k/k$ was clipped transients. The characteristics of the transient prescription tests are provided in Table III, and the reactor power profiles are shown in Fig. 6. It is important to note that the clipped transients are nearly indistinguishable from each other.

Transients 2892, 2893, and 2894 are all initiated with a 2.6%$\Delta k/k$ reactivity insertion, and the transient control rods are reinserted to clip the reactor power at the same instant in each pulse. One issue of concern is the repeatability of transient rod motions in TREAT. There are four transient control rod drives in TREAT, and the maximum rod position is at 40 in. withdrawn. However, each drive may respond

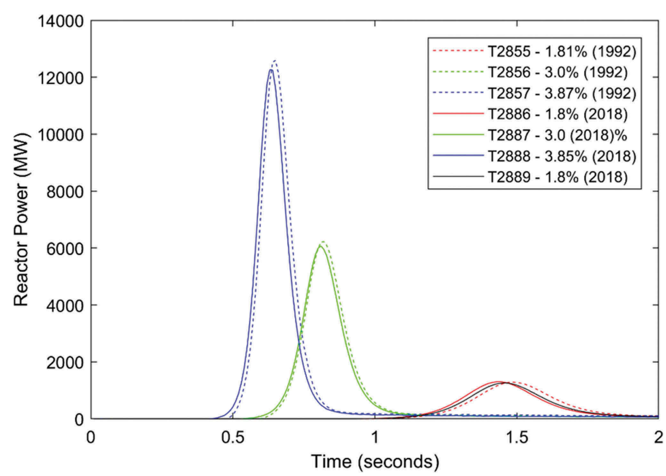

Fig. 5. Natural pulse transients to mimic historical operations.

TABLE II

Characteristics of Historically Similar TREAT Transients

Transient Number	Step Reactivity Insertion (%$\Delta k/k$)	Peak Power (MW)	Total Energy Released (MJ)	Date
2855	1.81	1 291	797	August 5, 1992
2856	3.0	6 242	1580	August 17, 1992
2857	3.87	12 630	2287	August 19, 1992
2886	1.8	1 341	635	January 17, 2018
2887	3.0	6 071	1293	January 24, 2018
2888	3.85	12 262	1890	January 30, 2018
2889	1.8	1 259	626	February 14, 2018

TABLE III

Characteristics of TREAT Transient Prescription Tests

Transient Number	Step Reactivity Insertion (%Δ*k*/*k*)	Peak Power (MW)	Total Energy Released (MJ)	Date
2890	1.5	610	574	May 2, 2018
2891	2.0	1413	779	May 3, 2018
2892	2.6	3544	620	May 10, 2018
2893	2.6	3538	617	May 14, 2018
2894	2.6	3549	619	May 15, 2018

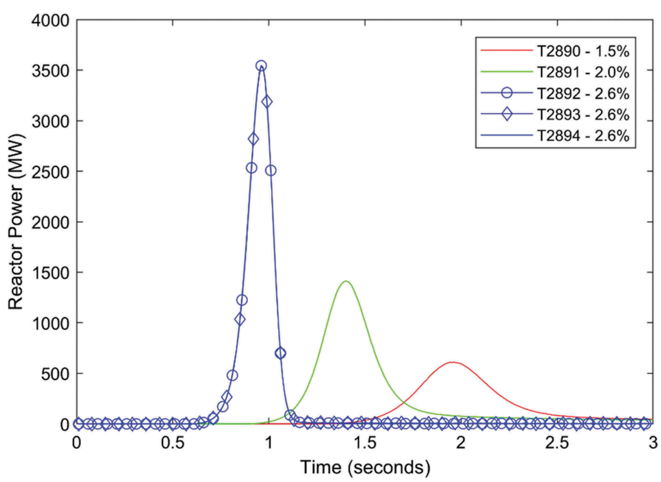

Fig. 6. Reactor power for transient prescription tests.

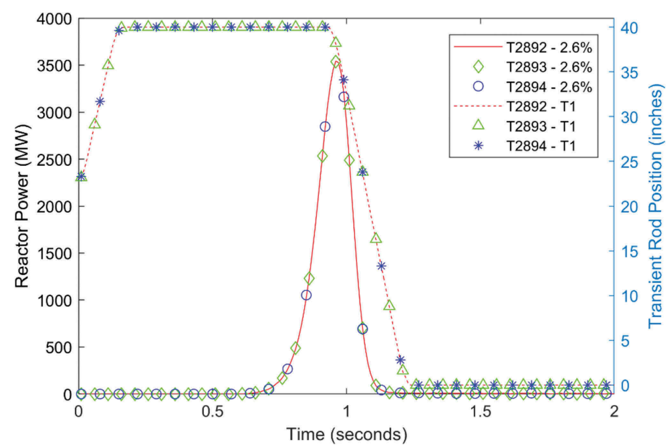

Fig. 8. Transient rod comparisons for transients 2892, 2893, and 2894.

differently. As can be seen in Fig. 7, the control rod drives move at slightly different rates during rod motion out and into the core. However, it was found that for all transients operated with clipping, the rod motions were repeatable and nearly identical in each transient operation for a single rod as displayed in Fig. 8, which provides the rod motion of transient rod drive 1 along with the reactor power for the three 2.6%Δ*k*/*k* clipped pulses.

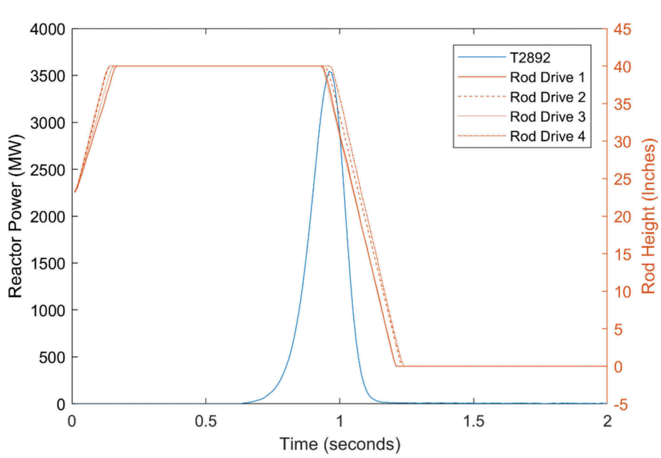

Fig. 7. Reactor power and rod position during transient 2892.

III.C. Narrow Pulse for Reactivity-Initiated Accidents

It is of interest in the LWR community to alter TREAT operations to minimize the pulse width during transients to more closely match expected values of FWHM during RIAs, such as a hot-zero-power rod ejection accident for pressurized water reactors or a cold-zero-power rod drop accident for boiling water reactors. TREAT historically performed many clipped transients (approximately 50) by initiating a temperature-limited transient and reinserting the transient control rods near the peak power to "clip" the reactor power and prematurely end the transient by adding negative reactivity to the natural temperature feedback in the reactor. The characteristics of the largest peak power and total energy released in a clipped pulse in TREAT are shown in Table IV. Figure 9 provides the reactor power and transient rod position for transient 2626.

As shown in Table V, transient 2626 was not optimized for a minimum pulse width since the transient rods were not reinserted until after the peak power was

TABLE IV

Characteristics of Transient 2626 in TREAT

Transient	Reactivity Insertion (%$\Delta k/k$)	Peak Power (MW)	Total Energy Released (MJ)	FWHM (ms)	Date
2626	4.61	15 314	1761	104	July 3, 1985

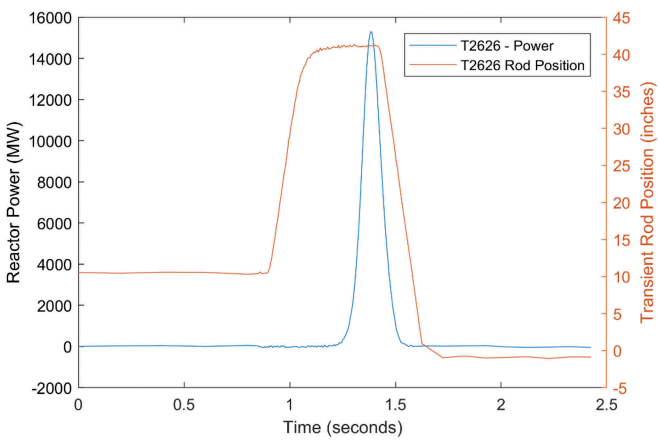

Fig. 9. Reactor power and rod position during transient 2626.

achieved. To minimize the pulse width with clipping, the transient rods should be reinserted prior to the peak power. Since the TREAT restart, several clipped pulses were performed with the goal of minimizing the FWHM in the current TREAT core configuration. All transients were initiated with a step change in reactivity of 4.2%$\Delta k/k$ but varied the clipping delay time in each transient. The characteristics of each transient operation are presented in Table V. As the clipping delay increases, larger peak power and energy released are achieved. If the clipping delay time is increased further, the transient will result in a temperature-limited transient.

The transients listed in Table V are compared in Fig. 10 to illustrate the effect of rod position and clipping delay time on the peak power and transient shape. Finally, Fig. 11 provides the energy released and FWHM as a function of clipping delay time. The transients in Table V were specifically chosen to minimize the pulse width, and the predicted U-shape of the FWHM curve is observed. Without clipping the control rods, the FWHM would be at least 100 ms. From Fig. 11, as expected, a longer delay time for clipping results in increased energy released. However, a minimum of FWHM is achieved in TREAT with a clipping delay time of approximately 475 ms. It is important to note that these transients are the first TREAT operations ever to achieve a FWHM less than 100 ms.

III.D. Extended-Duration Transients for LOCAs

TREAT is also capable of simulating LOCAs by operating steadily at an elevated power level for a period of time and then rapidly inserting the control rods and operating steadily at a low power level. Two transients, transients 2902 and 2903, were performed in TREAT following its restart to demonstrate this capability. Table VI presents characteristics of the simulated LOCA transients 2902 and 2903. The peak power during the steady elevated power level did not exceed 47.5 MW, and the total energy released for each transient was approximately 2100 MJ. The duration of elevated power for each transient was approximately 30 s and approximately 195 s for the low power operations. Figures 12 and 13

TABLE V

Characteristics of Clipped Transients Since TREAT Restart

Transient	Reactivity Insertion (%$\Delta k/k$)	Peak Power (MW)	Total Energy Released (MJ)	Clipping Delay Time (ms)	Pulse Width (FWHM) (ms)	Date
2904	4.2	8 840	949	475	89	July 3, 2018
2905	4.2	11 178	1209	500	90	July 11, 2018
2906	4.2	12 277	1327	513	90	July 12, 2018
2907	4.2	13 240	1451	525	92	July 17, 2018
2908	4.2	5 758	643	450	92	July 19, 2018

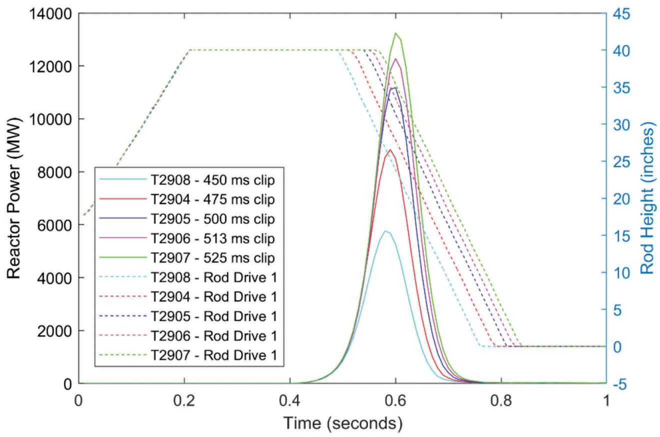

Fig. 10. Reactor power and rod position during various clipped transients.

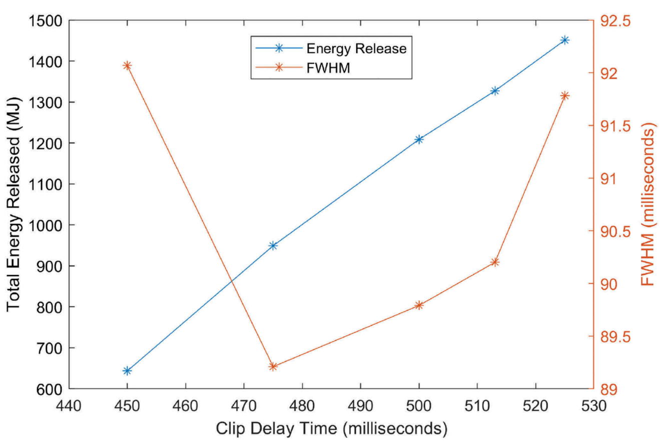

Fig. 11. Energy released and FWHM as function of clip delay time.

provide the reactor power and energy released, respectively, as a function of time for transient 2902. Additionally, each plot contains the rod motion as a function of time to illustrate the reactor operations required to obtain the simulated LOCA transient. Only the rod motion for rod drive 1 is reported; however, all transient control rod drives are maneuvered similarly. The data obtained from transient 2903 are nearly identical to transient 2902 and are not presented.

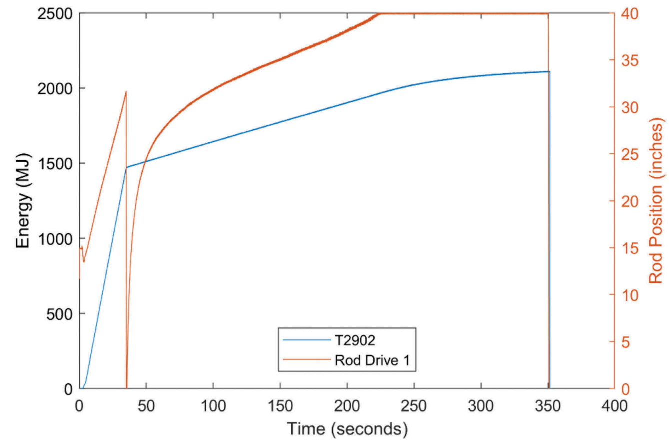

Fig. 12. Reactor power and rod position during transient to simulate LOCA.

As can be observed in Fig. 12, because of temperature increase in the reactor while operating, the transient control rods must be withdrawn following the change to low-power-level operations. However, once the transient control rods are fully withdrawn to their maximum height of 40 in., the negative reactivity associated with elevated temperature becomes dominant, and the reactor power decreases until the transient is terminated.

IV. CONCLUSIONS

Since the TREAT facility restarted transient operations in 2018 following an extended shutdown, the reactor performance has been compared with historical transients with good agreement and has met or exceeded expectations for reactor operators and experimenters. TREAT's flexibility in reactor power shaping historically and since the restart provides the ability to prescribe a variety of operating conditions for test specimens that require specific values of total energy released and pulse width. Through the use of shaped transients, steady-state irradiations, natural pulses, and clipped pulses, the TREAT facility can cover a wide range of fuel design evaluations, including those for LWR and LMFBR applications.

TABLE VI

Characteristics of LOCA Transients Since TREAT Restart

Transient	Peak Power (MW)	Total Energy Released (MJ)	Duration at Elevated Power (s)	Duration at Low Power (s)	Date
2902	47.5	2113	30	195	June 26, 2018
2903	47.4	2141	30	195	June 27, 2018

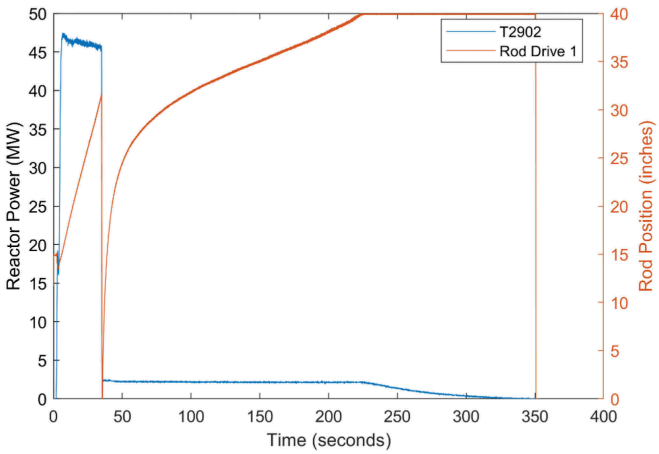

Fig. 13. Energy released and rod position during transient to simulate LOCA.

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ORCID

Thomas Holschuh http://orcid.org/0000-0002-1521-4314
Nicolas Woolstenhulme http://orcid.org/0000-0002-7881-3314
Benjamin Baker http://orcid.org/0000-0002-6274-2478
John Bess http://orcid.org/0000-0002-4936-9103
Cliff Davis http://orcid.org/0000-0003-3426-2773
James Parry http://orcid.org/0000-0003-2837-2626

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