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Testing Instrument Extremes in the TREAT Facility

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Changing the World's Energy Future

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Instrumentation under Extreme Conditions in TREAT

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Last fall marked the fifth-year anniversary of the restart of Idaho National Laboratory's Transient Reactor Test Facility (TREAT), following a 23-year period of dormancy. A remarkable effort was made to revitalize the facility and build an R&D program that tapped into long-neglected research needs, both domestic and international. This transient testing program has rapidly grown to include five primary experimental testbeds operated for Department of Energy programs and for various industry and international collaborators. These testbeds encompass light-water reactor fuels (accident-tolerant fuels and burnup extension efforts), sodium fast reactor fuels, nuclear thermal propulsion, other types of advanced reactor fuel designs, national security projects, in addition to a platform for in-pile instrumentation testing and development.

A crucial aspect of conducting transient testing on nuclear fuels and materials is in-situ diagnostics, necessary to unravel the complex evolution of these experiments. The program now executes dozens of highly instrumented experiments each year in order to accomplish a diverse range of technical goals, the most important being to advance the understanding of nuclear fuel safety and performance. This approach has impacted other Department of Energy test reactors by helping them overcome barriers to in-pile testing and various advanced sensor applications.

TREAT is a transient power-shaping reactor whose primary mission is to enhance safety performance by testing nuclear fuels and materials under thermodynamic and neutronic conditions ranging from off-normal to extreme. Transient testing of nuclear fuels is analogous to car crash testing, in that the dramatic changes commonly seen when comparing the test specimens' initial and final state points necessitate in-situ measuring in order to interpret and understand the evolution of the experiment. TREAT's experiment design strategy utilizes a highly reconfigurable and accessible reactor core that affords flexibility when installing experiment devices, thanks to the lack of a primary coolant boundary and the inclusion of multiple access points in the reactor bioshield. Within the experiment devices, the test specimens (which are integrated with their test environments), desired instrumentation diagnostics, and safety considerations are all contained in a single engineered package. The experiments encompass various types of environments (e.g., water, sodium, and gas at temperature and pressure), as well as a range of control options (e.g., static or flowing coolants). The experimental conditions are uniquely representative of advanced reactors, providing challenges to sensor performance but also affording a unique opportunity for development and qualification of sensors suited to these environments.

In early 2018, TREAT re-opened its doors for experimental testing. A key strategy for meeting the goals of the experiments was to incorporate a variety of crucial sensors and data acquisition technologies into the facility, starting at this earliest opportunity. The reactor and its safety basis enabled a streamlined approach to sensor deployment, with instrument-friendly access to the core (as there was no pressure boundary to pass), relatively short lead wire runs, and a conveniently located data acquisition system right next to the reactor yet outside the radiation buffer area. Nearly every transient irradiation performed since the restart has entailed a multitude of instruments, including self-powered neutron detectors (SPNDs), linear variable differential transformers (LVDT), ultrasonic sensors, and optical fibers. Prompt-response SPNDs were an initial target for TREAT testing, as their simple, robust design and ability to measure thermal neutrons via a fast temporal response on the scale of sub-milliseconds are well-suited for TREAT applications. The sensors demonstrated excellent performance, providing unique insights into the local TREAT flux, which can reach up to 10^{17} n·cm^{-2}·s^{-1} during high-power transient pulses.

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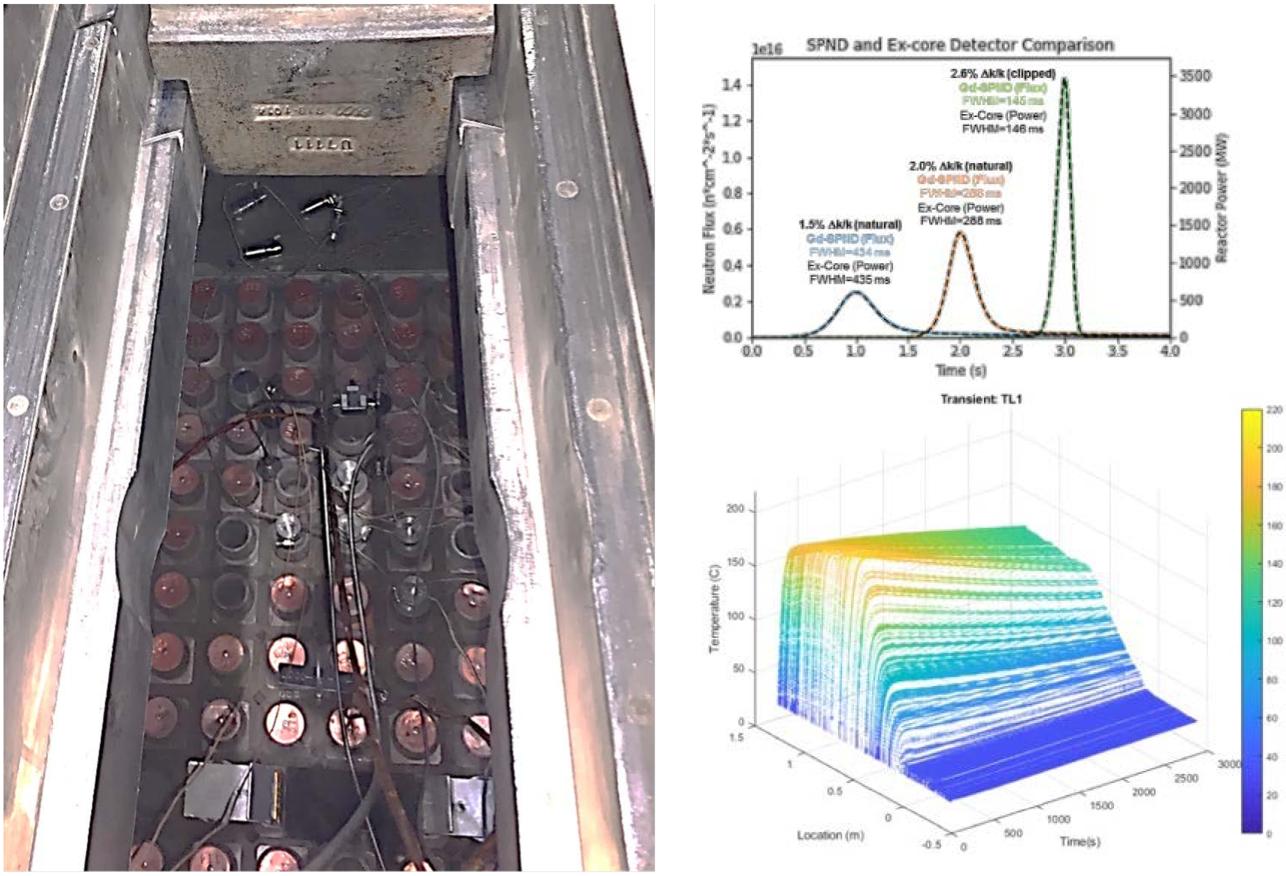

Figure 1. Testing of in-core sensors at TREAT. (Left) Top view of the TREAT core assembly, loaded with instruments and showing lead wiring. (Right) Example data results from instrumentation testing in TREAT. The top plot compares data collected from a Gd-SPND to the measured reactor power. The bottom plot shows the axial core temperature measurements taken by a distributed temperature optical fiber sensor.

These sensors have measured the local neutron flux in nearly every transient performed in TREAT to date, and were selected as a development target for enabling a small business to begin fabrication and testing of Gd-SPNDs. Figure 1 presents a top view of the TREAT core—with a common arrangement of instrument leads protruding out—and gives examples of in-pile measurements performed to evaluate sensor performance.

Several experiment devices have been developed and deployed in TREAT. In the years since its restart, experiment sophistication and complexity have continually increased, creating new challenges regarding the accompanying instrumentation packages. Figure 2 shows a recent experiment involving a static sodium capsule. Around 60 individual leadwires/fibers exit the capsule through leak-tight seals. As is seen, the standard instrumentation includes distributed temperature optical fiber sensors, optical-fiber-coupled infrared pyrometer, thermocouples, linear variable differential transformers, and acoustic sensors. Due to its unique requirements, the experiment was custom-built and assembled at Idaho National Laboratory. Off-the-shelf sensors are used whenever possible, though several custom devices such as custom-built optical fiber cables and connectors are built in-house. A primary challenge in these experiments is the overall assembly logistics and the ability to ensure the leak tightness of the many feedthroughs accompanying these devices.

Over the past 5 years, dozens of experiments have been performed in TREAT, utilizing a wide array of instrumentation. Although, by and large, the sensors used in these experiments performed successfully, the

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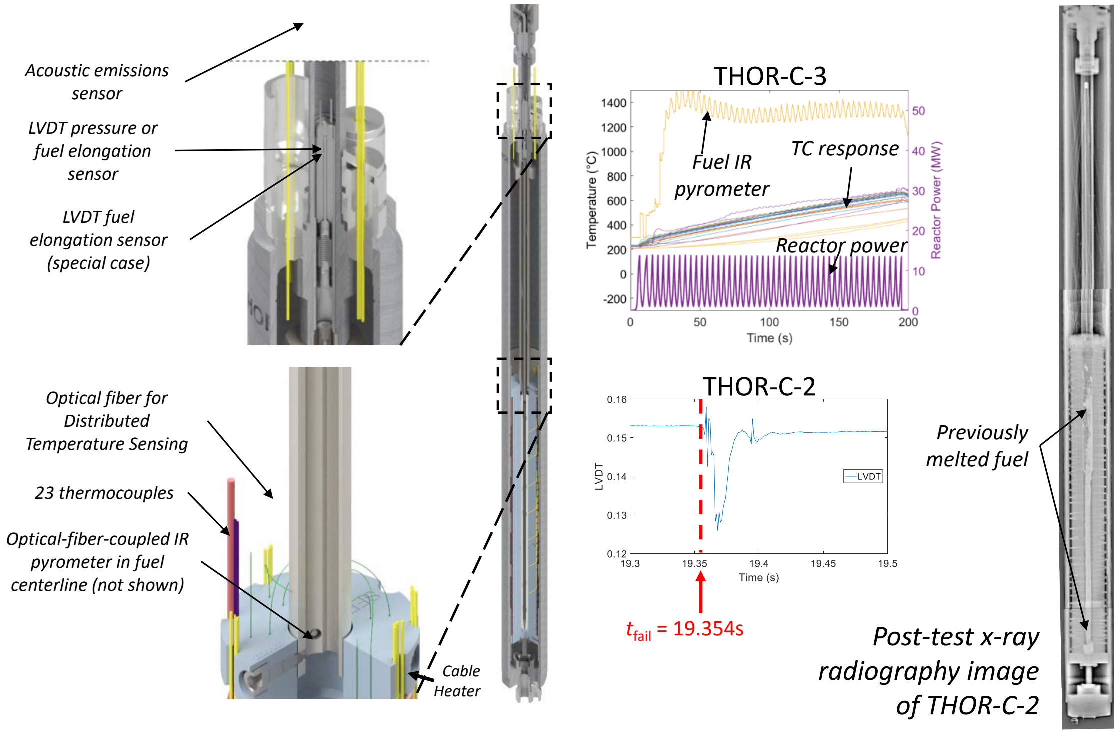

Figure 2. Example highlighting the instrumentation of a newly deployed sodium capsule used in TREAT. (Left) Capsule instrumentation design. (Right) Example data collected using this device.

designs have also included less mature, first-of-a-kind instrumentation to drive rapid maturation and readiness for application. As expected, experience with—and an increased understanding of—these devices has led to improved reliability and performance. Experiments performed last year on the TREAT sodium capsule serve to provide representative examples of sensor results (see Figure 2 for example data collected during some of the first experiments involving this capsule). Two of the first experiments conducted using this test device were performed on an advanced metallic alloy fuel. They were conducted to characterize fuel failure under extreme conditions, in addition to the thermal transport in the fuel. The data results from the first experiment, THOR-C-2, clearly reflect fuel failure and corroborate the data from the TREAT fuel motion monitoring system (not shown). Post-test radiography showed the final state of the fuel in the aftermath of the very extreme event with fuel melting and cladding rupture. The second experiment, THOR-C-3, was performed to characterize the thermal transport in the fuel. This experiment device was a complete measurement system that used thermal measurements, in combination with heat input from the reactor to extract the thermal properties of the fuel. The in-situ diagnostic equipment performed as desired, revealing the temporal sinusoidal temperature response of both the fuel and the surrounding metal. Detailed evaluation of the experiment results is underway, along with a series of non-destructive/destructive examinations to derive final conclusions and data for model benchmarking.

After 5 years of testing and development, in-pile instrumentation continues to play a central role in transient experiments. Much of this instrumentation has matured rapidly thanks to the steady development that has occurred thanks to the unique nuclear environments generated in TREAT experiments, and strategies applied to in-core testing in TREAT are now being extended to other test reactors (e.g., the Advanced Test Reactor) to accelerate the development of nuclear materials. The unique experimental capabilities developed at TREAT currently support a wide range of advanced reactor technologies still under development, and will aid in establishing licensing data to foster their eventual deployment. Future experiments in TREAT will rely on novel capabilities, building upon the progress achieved to date, to measure the challenging multiphysics characteristics of the environments it produces, and strategic development of such in-pile measurement devices is crucial for achieving success in this regard.