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Development of Advanced Instrumentation for Transient Testing

A fuel safety research program centered on in-pile transient testing experiments is being developed to support assessment and qualification of advanced nuclear fuel systems using the recently restarted Transient Reactor Test (TREAT) facility at the Idaho National Laboratory (INL). While resumption of transient testing at TREAT is crucial to enable these programs, full recovery and cutting-edge transient testing capability also requires a well-coordinated and innovative instrumentation development and qualification program to support near-term and future objectives. This paper summarizes the experimental approach of transient testing to focus on measuring the response of nuclear fuel to off-normal (or power-cooling mismatch) conditions for modern and advanced reactor environments requiring capabilities extending over wide measurement and environment conditions. It also highlights unique attributes of transient testing of importance to in-pile instruments including relatively low total neutron fluence, high gamma heating, and the need for well-defined and possibly short time response. Historical approaches to instrumentation for transient testing are also reviewed to provide context to the modern instrument strategy. The instrumentation needs of a modern transient testing are detailed while summarizing several ongoing R&D activities are supporting the development of state-of-the-art and 'advanced' measurement technologies that will provide baseline capability for Light Water Reactor (LWR) and Sodium-Cooled Fast Reactor (SFR) experiment objectives, while extending to other advanced reactor needs and advanced sensing technology opportunities. Examples of specific sensors planned for near-term deployment with ongoing development includes prompt-response self-powered neutron detectors (SPND), miniature fission chambers, optical-fiber-coupled infrared pyrometer, cladding surface thermocouples, electrical-impedance based boiling detector, and Linear Variable Differential Transformer (LVDT) based sensors for fuel elongation and pressure measurement.

Keywords – transient irradiation testing, in-pile instrumentation, nuclear fuel safety experiments, TREAT

I. Introduction

Development of nuclear fuels requires experimentation and modeling for behavior during transient overpower and undercooling conditions to enhance safe fuel performance. The Transient Reactor Test facility (TREAT) will provide unique capability in the United States to perform controlled experimentation of such conditions in a nuclear environment [1]. The facility is designed to provide a safe platform to study fuel meltdown, metal-water reactions, thermal interaction between overheated fuel and coolant, extreme environment phenomena, etc. To this end, experiment instrumentation plays a critical role in meeting experiment objectives in TREAT, informing on fuel test specimen response while providing needed validation data for modeling and simulation tools.

The objective of experiment instrumentation is to monitor test specimen behavior (temperature, dimensional changes, relocation, microstructural evolution, etc.) and specimen boundary conditions (thermal, mechanical, nuclear) at various length and time scales with the ultimate goal of reducing uncertainties in experiment conditions. Test environments planned at the facility range from those corresponding to Light Water Reactors (LWR), Sodium-cooled Fast Reactors (SFR), to High Temperature Gas Reactor (HTGR), Molten Salt Reactor (MSR), and other advanced reactor systems. This paper presents an overview of historical instrumentation used in transient Material Test Reactors (MTR) and current instrument development objectives and progress for TREAT experiments with emphasis on near-term activities to support LWR and SFR technologies. Detailed reviews of instrumentation used at various MTR facilities are available in literature [2,3,4] with particular focus on steady-state MTR facilities.

A variety of instrumentation supports transient testing experiments classified into categories of reactor operations monitoring, pre- and post-irradiation test specimen characterization, fuel motion monitoring via in-situ ex-core detection system, experiment environment control and monitoring, and measurements directed at the in-pile test specimen. The classifications of instrumentation of focus for this paper are technology used to (1) monitor in-pile specimen behavior and (2) monitor/control experiment vehicle parameters. The physical and neutronic design of the TREAT reactor is described in [5]. The unique fuel motion monitoring capability, also called the fast-neutron hodoscope, available at TREAT has serves a crucial role in transient testing to measure real-time spatial fuel motion resulting from thermal expansion, fuel melting, fuel failure, etc., with time resolution of 1 ms [6]. With restart of the TREAT facility, the hodoscope system has also been revitalized[7] and is now operational with a modernized data acquisition system.

This paper provides a review of instrumentation used at transient test reactors in the U.S., provides an overview of the TREAT instrumentation environment and applications, details instrumentation needs for transient testing at the TREAT facility, and presents recent examples and findings of new in-pile instrumentation development to support TREAT experiments.

II. Historical Review of Instrumentation in Transient Reactors in the U.S.

Historical transient testing missions were supported in several reactors on the Idaho laboratory site. These missions were accomplished through experiments on entire reactor cores and expanded into capsule and loop-based experiments, beginning with testing in the TREAT reactor in 1959. Throughout the 1960's and 1970's, these transient testing experiment programs were supported by significant instrumentation development programs[8,9]. Beyond TREAT, other transient reactor facilities in the U.S. included the Special Power Excursion Reactor Test Capsule Driver Core (SPERT-CDC), the Power Burst Facility (PBF), and the Loss of Flow Test (LOFT) facility. An important distinction and much less restrictive consideration for in-pile instrumentation for transient testing as opposed to steady-state Material Test Reactors (MTR) is overall accumulated dose effects are much smaller (~10^{16} n·cm^{-2} in a TREAT experiment compared to ~10^{22} n·cm^{-2} in a steady-state MTR experiment). Many of the crippling aspects related to radiation damage to sensor materials are alleviated. Still, thermodynamic conditions and instantaneous radiation fields generally have great potential to be more extreme than steady-state irradiation conditions. Detailed treatment of transient irradiation effects on electronic devices is found in [10]. The purpose of this section to provide perspective on the current transient testing instrumentation program relative to those used in historical and international transient testing programs.

In particular, pre-irradiated fuel specimens pose challenges for instrumenting in a nonobtrusive and nondestructive fashion. Instrumentation possibilities are further limited by the difficulty of remote application in a hot-cell environment. Relatively few instruments have been employed to significant level on pre-irradiated specimens; a few common examples include thermocouples for coolant and cladding surface temperatures, linear variable differential transducers (LVDT) for cladding and fuel expansion measurements, and fuel rod plenum gas pressure, standard pressure transducers, etc.[11,12,13]. These instruments or their associated development efforts present challenges for implementation because of their obtrusive presence in or attached to a specimen. For example, historical records from transient testing programs in Idaho as well as Japan[14] indicate enormous efforts to develop and characterize a “simple” thermocouple. When purposed for cladding surface temperature, the measurement is severely complicated by size, geometry, material interactions, chemical reactions, irradiation effects, heat loss finning effects, electrical interference, and surrounding coolant phase change effects. An entire in-pile test series (12 irradiation tests) was carried out at the PBF in Idaho to study these complications and derive optimized solutions[15]. Many of the sensor technologies used in transient reactor experiments in the 1960s through the 1980s in the U.S. and internationally still represents state-of-the-art sensors used in similar facilities in the world today.

Relevant examples of instruments used historically of current interest for TREAT and their applications include:

(1) Thermocouples. Thermocouples are the general standard in-pile thermometry tool. They have been used for measurements supporting experiment operation to measure coolant condition and temperature in various locations across a nuclear fuel system, including outer and inner cladding and internal fuel temperatures. Significant development programs were carried out from the mid-1960s through the early 1980s in the U.S. for providing fuel centerline temperature measurement and implementing cladding surface thermocouples in water environments under simulated accident conditions. The purpose of these studies was to characterize the response and effect of thermocouples mounted to cladding surfaces on in-pile nuclear fuels testing with a particular focus on transient conditions in water coolant. An example of an advanced approach used by the PBF/LOFT programs is shown in Figure 1 with an embedded cladding surface thermocouple in Zircaloy[16]. Other examples from these programs include the use of Type C thermocouples with BeO insulation and Mo-Re sheaths to measure fuel centerline temperature and specially developed zirconium sheathed thermocouples for cladding surface temperature measurement[17]. These thermocouples were uniquely optimized for application to nuclear fuel rods in prototypic environments. The instrumentation strategy for the SFR experiments performed in TREAT, the primary historical mission of the facility, relied heavily on thermocouples to control and monitor loop and specimen behaviors. Type K sheathed thermocouples with 1 mm diameter were

typically used for these experiments with attachment to flow tube hardware near to specimens (not directly on specimens)[18]. The high thermal conductivity of the metal fuel and metal coolant allows for reduced uncertainty in thermocouple performance and extrapolation of temperature fields, decreasing some need to directly instrument fuel specimens.

(2) Linear-Variable-Differential-Transformer-based Sensors. LVDT-based sensors have proven to be versatile instruments with a long history of in-pile applications[19]. Examples extend back to fuel experiments in TREAT utilizing LVDT's integrated directly into fuel rods for fuel elongation measurements in the mid-1960's as shown in Figure 2[20]. Shortly thereafter, LVDT approaches were developed to measure fuel elongation directly through cladding walls[21]. Over the past several decades, the Institute for Energy Technology at the Halden Reactor Project (IFE/HRP) have been exemplary in utilizing LVDT technology for many high value in-pile measurements while providing sensors for other MTRs worldwide. Applications for LVDTs include designs for measurements of fuel plenum pressure, fuel elongation, cladding elongation, coolant flow rate, etc. Recent development at Halden has focused on extending the temperature limits of their sensors to high temperatures[22].

(3) Pressure Transducers. Pressure transducers based on a variety of transduction principles are typically used to measure test specimen environment pressure as well as fuel rod plenum pressure to assess transient fission gas release. A wide variety of pressure transducers have been used over many decades. Frequently commercial transducers have shown sensitivity to transient irradiation fields requiring experiment designs that place the sensor out of the high flux region of the experiment and/or the addition of shielding

materials around the sensor. Some designs have shown minimal influence from transient irradiation effects[23] with excellent response rate and a variety of measurement ranges.

(4) Ultrasonic Technologies. Historically, ultrasonic transducers were developed and used for high-temperature, fast-response measurement of fuel centerline temperature in irradiation experiments[24,25]. Ultrasonic technology also holds potential applications for characterizing coolant voiding, dimensional changes, temperature, etc. Currently, ultrasonic sensing technology is being utilized to detect onset of boiling events in experiments at the CABRI test reactor.

(5) Radiation Detectors. Self-Powered Neutron and Gamma Detectors (SPND and SPGD respectively) were used extensively in testing experiment test trains in the Power Burst Facility to measure transient neutron and gamma flux. Historically, neutron flux and radiation fields in TREAT were typically characterized using a combination of analytic and computational models, dosimetry experiments, and measurements made by ion chambers located in the biological shielding of the TREAT core. These approaches essentially provide total fluence within the core. Early in the life of TREAT, a significant physics characterization of a minimum-size core was performed using measurements obtained from dosimetry and special double chamber fission counters[26]. In the early-1990s, one study used SPND's to directly measure transient neutron flux in-core, perhaps the only known measurement of transient neutron flux in TREAT approaching peak levels from within the core[27]. These measurements provide valuable data supporting calculation of energy deposition in test specimens—a critical fuel performance parameter for transient testing.

(6) Dosimetry. Standard dosimetry techniques utilizing wires, discs, and foils to characterize reactor neutron spectra and fluence and fission coupling with the ultimate objective of understanding reactor-to-specimen power coupling (unit power generated in specimen per unit reactor power)[28].

(7) Accelerometer/Microphone. Acoustic detection has been used to provide data relating to timing of specific events of interest including boiling, fuel-coolant interaction, cladding rupture, etc. Results from sodium based experiments at the IGR facility show acoustic signals associated with fuel-coolant interaction events[29].

(8) Flow meters. Flow meters have been deployed in both LWR and SFR transient testing experiments. Many devices based on a variety of operating principles are available commercially. Turbine flow meters are commonly used in loop-type applications including PBF and CABRI. Unique permanent magnet flowmeters were used in the Mk-series loops in TREAT for SFR testing[18].

(9) Fission product detection systems. Systems used to detect the transport of fission products in experiments have been used in multiple historical transient testing facilities such as PBF[30]. Late in its operational history, TREAT incorporated an experimental system that detected gamma emission from fission products in the upper cover gas region of the experiment vehicle[13].

(10) In-pile high-speed videography. Multiple facilities have utilized in-pile video to directly image the behavior of nuclear fuel under transient conditions. High speed video has provided high value information on fuel motion and coolant voiding behaviors. The TREAT facility utilized an in-pile video system early in its history to image integral fuel rod behavior in dry and water environments[31]. Later, TREAT deployed a special video

system to monitor detailed behavior of irradiated fast reactor fuel under power transients in the M1 experiment. The Nuclear Safety Research Reactor (NSRR) in Japan[32] and the Annular Core Research Reactor (ACRR) at Sandia National Laboratory[33] have also incorporated real-time video devices to film fuel in water and dry environments respectively.

(11) Hodoscope. The fast-neutron hodoscope at TREAT is a crucial tool for in-situ monitoring of fuel movement during transient events. The technology was developed from a need to monitor fuel movement and relocation behavior through opaque test devices and sodium coolant. A summary of the hodoscope capability is provided in [6] and the restoration of the now operational system is summarized in [7].

III. Experimental Conditions for Transient Testing Nuclear Fuels

A wide range of experiments are possible in the TREAT reactor ranging from simple to complex such as testing small sensors to prototypic nuclear fuel accident simulations. The design of experiment devices at the TREAT facility is reviewed in [34]. The transient nature of the experiments provides unique opportunity for instruments, as they do not experience significant radiation damage as is typically a great concern in steady-state MTRs. Detailed studies of the TREAT neutronic environment is provided in [35,36]. The TREAT facility has several important inherent design characteristics for instrument consideration including:

(1) Dry core (air) design provides variety of options for access with many ports around the core.

(2) Experiment environments may be quite harsh (postulated reactor accident conditions) and varied (gas, liquid; H2O, Na, etc).

(3) Experiments typically arrive in packaged-devices with instrumentation, inserted into center core location; integration of instrumentation into experiment devices is generally non-trivial (feedthroughs, size constraints, etc.).

(4) Peak neutron flux ~10^{17} n·cm^{-2}·s^{-1} (Ref. 35,36).

(5) Max neutron fluence ~10^{16} n·cm^{-2} (Ref. 35,36).

(6) Gamma heating may be very high (up to150 ΔK for stainless steel).

(7) Response time and data acquisition rates are crucial for many experiment objectives, ranging from < 1 ms to seconds.

(8) Relatively short wire runs (~10-20 m).

Cross-cutting needs for instrumentation to support transient testing in the TREAT reactor are focused on testing of nuclear fuels and materials with primary emphasis on off-normal conditions such as reactor Design Basis Accidents (DBA) and Beyond Design Basis Accidents (BDBA). Transient testing is also particularly focused on testing the behavior of irradiated nuclear fuels requiring experiments to be assembled with materials irradiated in other steady-state MTRs or commercial reactor facilities, a crucial consideration for planning instrumentation for experiments.

The objectives of transient testing are intimately tied to the design of the nuclear fuel system which is the central component of any nuclear reactor design. In the near term, some of the primary customers for transient testing include R&D for light water reactors (LWR) and sodium-cooled fast reactors (SFR). Fuel designs for these systems generally have similar characteristics including liquid coolant, (mostly) metallic cladding, and cylindrical fuel within the cladding (see Figure 3.) However, other technologies have potential for developing transient testing programs including other advanced nuclear reactor designs like molten-salt and gas reactors as well as nuclear thermal propulsion.

In both LWR and SFR systems, the primary types of off-normal conditions considered of highest priority to transient testing include overpower and undercooling events. In each system, specific event characteristics are widely varied though many of the resulting phenomena are principally the same. Transient testing experiments have the objective of identifying and quantifying the physical mechanisms that lead to fuel failures. As described in [34], experiments are designed to investigate behaviors at a range of physics integrality (i.e. prototypic fuel temperature vs prototypic fuel and coolant behavior or electric vs neutronic heating), to fully evaluate fuel system behaviors under DBA conditions. A brief description of primary transient scenarios of interest for LWR and SFR systems follows as they represent primary events simulated in transient testing experiments.

In LWR systems, the DBA overpower event of most interest is the Reactivity Initiated Accident (RIA)[37]. During an RIA event, energy is deposited in the test specimen with Gaussian-like time dependency with Full-Width, Half-Maximum (FWHM) of approximately 10-1000 ms. During such events, energy is rapidly generated within the fuel specimen causing rapid thermal expansion and possible interaction with the cladding. The energy is transported down the temperature gradient from the fuel, across a dynamic gas gap, through the cladding, and into the coolant. Heat fluxes may rapidly reach levels of subcooled boiling and Critical Heat Flux (CHF), where cladding-to-coolant heat transfer enters film boiling until the specimen has cooled sufficiently for the vapor film to collapse and rewetting to occur. The violent thermal events can lead to fuel failure during: (1) Low-temperature failure by pellet-cladding mechanical interaction in the early heat-up stages (high burnup fuel with corroded cladding); (2) High-temperature failure by cladding ballooning and burst (consequence of film boiling and significant rod overpressure); (3) Failure by disruption of the cladding upon quenching from high temperature (consequence of oxygen-induced embrittlement due to high temperature cladding oxidation during film boiling); High-temperature failure by cladding melt through by molten fuel. Regulatory requirements limit reactor designs from allowing RIA energy depositions from surpassing empirically determined thresholds for fuel failure.

The Loss of Coolant Accident (LOCA)[38] represents an important DBA undercooling event of great interest to transient testing experiments for LWR systems. A LOCA is caused by a break in a reactor's coolant pressure boundary. Automatic emergency shutdown of the reactor will be activated, but the temperature of reactor continues to rise due to stored thermal energy, loss of coolant, and radioactive decay in the fuel. As cladding temperatures may reach over 1000°C, it may plastically deform due the decrease of pressure across the cladding wall and deteriorating mechanical properties, resulting in possible ballooning and rupture. At these high temperatures, the Zircaloy cladding also undergoes phase transformation and oxidizes in reaction with the coolant (steam) forming a brittle structure. Emergency core cooling systems are engaged which reflood the reactor causing the potential for brittle failure of the cladding during rapid quenching. Ballooning and rupturing of cladding can block coolant channel flow and eventual loss of coolable geometry of the core.

In SFR systems, Transient Overpower (TOP) events have been studied extensively for oxide and metallic fuel core designs. In an assumed Unprotected TOP (UTOP) scenario, a BDBA, a single, maximum worth control rod is withdrawn from the core resulting in reactivity insertion and power rising above nominal levels without scramming the reactor (a double fault event). This results in heating of the core and coolant and introduction of negative reactivity to return power gradually to equilibrium with the heat rejection rate of the system. Proper reactor design allows sufficient heat removal to prevent fuel failures. For full understanding of SFR fuel system behavior and potential failure mechanisms, hypothetical scenarios have been simulated through experimentation where power ramp rates are much greater than design scenarios driving towards failure. During these events, pre-failure fuel expansion results from both thermal expansion and expansion of trapped fission gases in the solid fuel. Cladding failures occur primarily due to a combination of pin pressurization and low temperature eutectic formation. The failure site is at the top of the fuel column due to the high thermal conductivity of the fuel, where peak coolant temperatures are achieved. Post-failure behavior of the fuel results in benign ejection of molten fuel near the top of the fuel pin with little tendency to form blockages[39,40]. For more information regarding oxide SFR transient behaviors see [41].

A BDBA Unprotected Loss of Flow (ULOF) accident in an SFR is an undercooling event in which loss of power to the primary and intermediate coolant pumps occurs. As flow decreases, core temperatures rise causing it to expand, resulting in negative reactivity feedback. As the reactor power falls, the coolant temperature also begins to decrease. The primary concern for these events is the possibility of introducing coolant voiding within the core. Coolant voiding in SFR systems introduces positive reactivity to the core, which can result in TOP behaviors. Once again proper reactor design should provide for no fuel failures under such conditions[40]. Modern metallic fuels have not yet been evaluated in in-pile experiments under loss of flow conditions.

IV. Instrumentation for Modern Transient Testing

In the context of cross-cutting applications, the primary target locations for in-pile instrumentation deployment in LWR and SFR fuel systems include: (1) fuel, (2) cladding, and (3) test environment including both coolant and reactor conditions. A general summary of instrumentation needs for nuclear fuels R&D is provided in [4] with a strong emphasis on steady-state operation. Though each target location may be critical for specific experiment objectives, the presented order represents roughly the order of complexity and thus overall cost for targeting experiment data. For this reason, the availability of in-pile experimental data for each target area also decreases moving from the environment to the cladding to the fuel. In addition to complexity in mechanical design and environment compatibility, the presence of instruments on experiment specimens also creates the concern of unacceptable alteration of specimen behavior or introducing other potential unknown uncertainties. For pre-irradiated specimens, application of instrumentation is significantly more complicated. Typically, installation requires remote assembly in a hot cell and even greater concern for disrupting the state of the fuel, such as spot-welding thermocouples to oxidized cladding or losing fission gas inventory by penetrating fuel rod cladding for attaching pressure transducers.

For these reasons, specific opportunities for sensor development include the following areas:

(1) Environment resistance – The expansion of the usable range of sensor technologies to those typical of fuel safety objectives accounting for conditions including irradiation, temperature, pressure, corrosion, etc.

(2) Non-intrusive – Instrument technologies allowing for non-contact and non-destructive application have many advantages for facilitating sensor installation on fuel as well as for minimal impact on specimen performance.

(3) Instrumentation for remote installation – Related to 2 above, instrument designs facilitating remote installation of instrumentation onto pre-irradiated specimens is of great interest.

(4) Miniaturization – Reducing the sensor size makes them less obtrusive allowing them to be potentially be located nearer to the locations of interest such as the fuel. Additionally, sensor miniaturization could provide improved resolution and allow for greater quantity of sensors.

(5) In-core electronics – Placing electronic devices such as pre-amplifier circuits or Analog-to-Digital (A-D) conversion devices in or near the core can provide many advantages for experiment design. A-D conversion within a device could greatly reduce the mechanical design burden for routing cabling out of an experiment and also create opportunity for more instrument capacity in a device.

(6) Other ideal sensor attributes include high resolution in space and time (accounting for response time intrinsic to the complete instrument design, e.g. sheathing and insulator material effect on time response of a sheathed thermocouple), and reliable calibration with practical implementation.

Categorization of specific parameter measurement targets in each target area include: energy deposition and neutron flux, temperature, mechanical behavior including fuel deformation and coolant dynamics, fission product transport behavior, thermal and mechanical properties (material properties), and microstructural and chemical behavior. In some cases, direct measurement data may be used to calculate indirect target parameters. E.g. specimen temperature monitoring may provide specimen calorimetry data related to reactor-to-specimen power coupling and energy deposition. State-of-the-art instrumentation capabilities includes means to measure the first three categories of parameters on SFR and LWR fuels including neutron flux (energy deposition), temperature, and mechanical behavior of fuel and coolant (pressure and deformation) (fuel movement and relocation is measured by the TREAT hodoscope). The remaining three parameters represent a higher level of instrumentation goals (in terms of challenge and scientific objectives) including fission product transport behavior, material properties, and material morphology. From a related perspective, these instrumentation target parameters represent a multi-scaled experimental approach in a similar vein to multi-scaled modeling approaches, from atomic-to-meso-to-bulk approaches. The following sections provide a detailed description of sensor target parameters.

IV.A. Neutron Flux/Energy Deposition

The need for a transient reactor is largely driven by the need for prototypic energy deposition in experiment samples. TREAT is capable of delivering prescribed power transient covering a wide range of power levels, ramp rates, and power maneuvering as desired. Especially under transient conditions, spatial and temporal distribution of energy deposition plays a critical role in assessing fuel performance behavior. From the perspective of experiment design and interpretation, total energy deposition is critical to experiment safety analysis as well as the programmatic objectives of an experiment. In this discussion, this category of measurement is specifically addressing sensors used to measure neutron flux or to directly measure reactor power-to-specimen power.

Several instrument technologies are available that could be used to measure in-core flux up to levels corresponding to typical "steady-state" material test reactors of approximately 10^{14} $n \cdot cm^{-2} \cdot s^{-1}$ to 10^{15} $n \cdot cm^{-2} \cdot s^{-1}$. Sensor types include miniature fission chambers, SPND's, and self-powered gamma detectors for gamma ray detection. With neutron flux levels up to 10^{17} thermal $n \cdot cm^{-2} \cdot s^{-1}$ (Ref. 27,35), the required measurement range for TREAT presents a challenge to common approaches. Additionally, detector size is an important consideration for application to TREAT. Sensors that fit within the coolant channels (~0.625 inch square) of the core provide expanded opportunity for application with minimal effect on core configuration and simple sensor installation. In some cases, measurements near to fuel specimens, especially inside experimental devices, could be desirable to capture effects from neutron absorptive materials, surrounding moderator materials and/or flux shaping filters. Specific targets in this category include reactor-to-specimen power coupling, neutron flux, and gamma ray flux measurements

Reactor-to-specimen power coupling. Direct measurement of reactor-to-specimen power coupling. is a high priority measurement area as it is critical for all aspects of experimentation in TREAT. Historically in TREAT as well as in other modern transient reactors worldwide, classical passive dosimetry measurement techniques have been used to derive neutron flux and spectra and fission rates[28]. These techniques are based on activity counting and radiochemistry for flux/fission wires/foils and fresh fuel specimens. Burnup presents a significant complication to these studies as the morphological changes in the fuel can result in significant power coupling effects in the specimen. Historically, a variety of techniques, both experimental and analytical, were used to determine power coupling in pre-irradiated specimens. The approach relied on considerable redundancy and cross-checking. The process included experimental calibrations using fresh fuel and flux monitor wires to measure axial dependent power coupling to fresh fuel. Modeling and simulation techniques were used to estimate the neutronic effects of burnup and swelling and resulting radial distributions. Where possible, independent heat balance approaches based on monitoring capsule or coolant temperature rise were used to measure pin-average power coupling in-situ within experiment apparatuses[39]. Development of on-line sensors that measure reactor-to-specimen power coupling could provide improved understanding of time-dependent phenomena while making the power coupling calibration process more efficient.

Full characterization of the neutronic environment is critical to irradiation experiments in material test reactors. In transient reactors, the spectral and spatial shifts in neutron flux may be considerable. In addition, interactions effects resulting from materials in the experiment vehicle can play a significant role on the neutron flux seen by a test specimen. In all cases, data regarding both flux levels and spectra, with emphasis on time-dependent phenomena for instrument development activities, is crucial to understanding and describing specimen interaction with the fields. Ultimately, this information will improve experiment design and interpretation.

The gamma ray field in TREAT can be substantial causing typical structural materials as is used in experiment and sensor hardware to heat significantly. Measurements of gamma fields in the core could serve a variety of specific experiment objectives, including model validation and experiment design purposes. Material gamma heating in TREAT can be a significant consideration for design purposes related to any object entering the core.

IV.B. Temperature

Temperature plays a critical role in transient fuel behavior as power-cooling mismatch events typically result in high temperatures in the fuel system. Mechanisms leading to and at the root of failures are commonly associated with degraded material performance properties and/or temperature-dependent chemical processes. For many transient testing experiment designs, temperature behavior drives the target condition for the test materials. Because experiment behavior is closely linked to material temperatures, each of the target areas in the fuel system (see Figure 3) are applicable for sensor development. However, measurements on fuel and cladding still present several challenges even after decades of development and contemporary programs still report significant measurement uncertainties, especially in water environments undergoing phase change as described in the previous section on historical approaches. Like many nuclear fuel measurements, the dominant challenge for most temperature sensors is attachment of sensors requiring thermal contact with the specimen. Contacts must not induce artificial behaviors in the test specimen (i.e. failure points) or large heat transfer fin effects while many common thermocouple materials form low melting eutectics with Zirconium causing premature measurement failure due to changed contact conditions. Therefore non-contact approaches offer significant advantages and are of great interest to the domestic and international transient testing programs.

IV.C. Mechanical Behaviors

The mechanical behavior of nuclear fuel systems is a critical measurement target area for transient testing. Induced fuel deformation results in increased cladding interaction and can play a role in over core reactivity feedback behaviors. Thus, understanding fuel and cladding deformation is critical for performance and safety of nuclear systems. Some of the key target phenomena of interest include thermal expansion and deformation caused by fuel-cladding interaction, cladding failures mechanisms such as melt through or rupture, fragmentation and cracking in oxide fuels, and fuel melting and relocation. The fast-neutron hodoscope primarily supports understanding these behaviors. Its full capability in regards to measuring thermal expansion of fuel is still yet to be fully quantified. In addition to fuel and cladding dynamics, coolant characteristics are also play a critical role as the outer boundary condition driving fuel response and in its response and role in fuel failure and dispersal. In this case, coolant behaviors of interest include rapid pressurization, flow rates for system control and response purposes, voiding and transient critical heat flux and rewetting, and nuclear-to-mechanical energy conversion through coolant acceleration and rapid pressurization from rapid fuel-to-coolant thermal interaction.

IV.D. Fission Product Transport

Fission product transport behavior in nuclear fuel systems is a crucial area of fuel safety research contributing to mechanistic source term studies and ultimately to licensing of new fuel systems. Fission gases generally precipitate into bubbles resulting in fuel swelling, which promotes fuel-cladding gap closure and ensuing fuel-cladding mechanical interaction. On the other hand, fission gas release to the fuel rod free volume (ultimately the plenum) causes pressure build-up and thermal conductivity degradation of the rod filling gas (when present). In transient heating scenarios, fission gas confined in the solid fuel can be freed to expand as fuel fragments and/or melts and can be an important driver for subsequent fuel behavior. Understanding and predicting fission gas release and, more generally, tracking of radionuclides from the fuel to the plenum to the coolant and beyond is extremely important for both performance and safety of nuclear fuel systems. Fission products play an intrinsic role in many failure mechanisms, post-failure effects, and source term predictions in fuel systems.

IV.E. Microstructural and Chemical Behaviors

Ultimately, measurements down to the molecular and atomic scale of fuel behavior is important for driving towards more complete mechanistic understanding and predictive capabilities regarding fuel performance. A wide range of microstructural and chemical behaviors occurs in fuels undergoing irradiation and a variety of thermodynamic transients. Important related engineering scale effects of interest include fuel constituent redistribution (related to previous paragraph on Fission Product Transport), fuel cladding chemical interaction in metallic SFR fuels, and cladding oxidation in LWR fuels.

IV.F. Material Properties

For typical transient testing experiments, online measurements of thermal and mechanical properties is not an area of great exploration. Though very important for transient performance, pre-test properties provide much of the required information for understanding material behaviors. No sensor is currently identified for providing online measurement during experiments. However, an area of high potential for TREAT facility applications is to perform measurements of material properties under irradiation under controlled and carefully instrumented experiments. Very few of such measurements have ever been performed and irradiation impacts are known to exist. For such an experiment, TREAT would allow neutron flux to be a controllable test parameter while provide required thermal conditions to a specimen.

V. Recent Development Activities

The development of advanced instrumentation for transient testing is led by INL with close domestic collaborations between INL, other national laboratories, and university partners. The following examples of instrument technology development are being led by INL[43,44].

V.A. Recent Sensor Development

The desire to monitor real-time neutron flux in TREAT requires sensors to have fast-response, compact form, and in some cases robust thermal-mechanical design. Two sensors currently under development and evaluation for TREAT applications are prompt-response SPNDs and the Micro Pocket Fission Detector (MPFD), a miniature fission chamber device.

Prompt response SPND's were shown successfully measure in-pile transient neutron flux at TREAT to very high flux values[27]. The MPFD and SPND have recently been undergoing in-pile testing in the TREAT facility for various transients to quantify their performance under a wide range of irradiation conditions. Figure 4 shows an example of Gd measured response compared to ex-core ion chambers at TREAT. The Gd and Hf SPNDs tested in the TREAT facility thus far have demonstrated excellent performance to measure neutron flux with time response of less than 1 ms over a range of fluxes exceeding approximately $5 \cdot 10^{16}$ $n \cdot cm^{-2} \cdot s^{-1}$.

The MPFD is a unique neutron flux measurement technology developed by the U.S. Department of Energy (DOE) for several years. The MPFD contains small ceramic components that form four distinct chambers. Each chamber contains a neutron-reactive coating which detects signals arising from gas ionization in each chamber through fission product recoil[45]. Important features of the sensor currently under R&D include high flux performance and high adiabatic energy deposition effects in the sensor. These efforts have required the development of current mode electronics for the sensor, pulsed-irradiation experiments at university reactors and at the TREAT facility, and multi-physics modeling of the sensor performance.

Temperature measurement capabilities currently planned for TREAT experiments include state-of-the-art approaches utilizing a variety of thermocouple configurations for cladding temperature measurements and next generation approach using non-contact infrared pyrometry. Thermocouples applied to LWR environments presents many challenges as discussed previously. Ongoing activities are focused on developing materials and processes for attaching bare wire and sheathed thermocouples to cladding materials to support a variety of coolant environments and experiment responses. This activity includes integration of thermocouple welding devices with nuclear materials handling facilities and characterization of the performance of the thermocouple under representative thermal conditions. Figure 5 presents examples of thermocouple-to-cladding weld development activities.

Infrared (IR) pyrometry offers non-contact, high-temperature, and fast time response capability for temperature measurement on cladding surfaces. There is effectively no theoretical temperature limit for pyrometry measurements, and existing systems to beyond the melting point of uranium dioxide (2865°C). This measurement capability has strong advantages for the accident condition testing in TREAT where specimen temperatures can reach extreme temperatures, accessible to few measurement techniques. Both in and out-of-pile testing and qualification of IR pyrometry has been underway at INL. The out-of-pile testing has encompassed varying emitting material properties, optical alignment, time-response, with ongoing evaluation of coolant medium effects. Preliminary in-pile testing of the pyrometer in TREAT have shown promising results which can be seen in Figure 6a. An image from the out-of-pile testing of the pyrometer optical line can be seen in Figure 6b.

Table 1 presents a comparison of important figures of merit for thermocouple and pyrometer measurements currently used for experiments at the TREAT facility. These values are generalized for comparison purposes and caveats may exist in some cases. The IR pyrometer provides a distinct advantage for time response and high temperature measurement. The thermocouple figures stand little chance of improvement in the future. While IR pyrometry is undergoing continued development to improve performance.

Depending on the objective of the experiment, mechanical measurements of the experiment system may be of high interest. Fuel stack and cladding elongation are commonly of interest in and often use LVDT's for the measurement. They have regularly been deployed at the in the Halden Boiling Water Reactor for these purposes demonstrating their reliability and accuracy[46]. A test rig has been developed to perform out-of-pile testing of LVDT's for preparation of their use in experiment vehicles. This test rig has been used to test LVDT's and other dimensional instruments up to 700 °C to quantify their performance.

For water based tests, a high-speed electrical-impedance based boiling detector has been under development. This instrument measures the electrical impedance between two electrodes on opposite sides of a fuel rodlet. The impedance is a function of the capacitance between the two plates, which is dependent on the permittivity of the material between the plates. The relative permittivity of water and steam significantly differs resulting in good measurement sensitivity to the presence of steam in water. This sensor has been undergoing out-of-pile qualification using a high-speed camera for comparison to sensor data is shown in Figure 7.

V.B. Advanced Sensing Technologies

The current instrument development strategy focuses on establishing baseline sensors for measuring key experiment data, which include thermocouples, SPNDs, and LVDTs. Next generation instrumentation will expand on the baseline capability to increasingly include focus on mechanical response and fission product transport behaviors of fuel systems. As evidenced in the previous sections, fiber-optic, ultrasonic, and electroimpedance instrumentation technologies are already important R&D areas with active development and are expected to increase as the focus for next generation measurement technologies. Each of these technologies has non-contact measurement modes as possibilities and represents a leap in state-of-the-art for transient test reactors and may quickly become the backbone of many experimental devices and objectives. In the areas of material properties and microstructural/chemical, no instruments are currently identified as being relevant to specific cross-cutting objectives. However, multiple experiment development projects are currently developing instrument technologies in these areas.

Fiber optic sensors have the potential to span each R&D measurement target area for transient testing. Several characteristics of optical-fiber sensors make them well-suited for TREAT measurements: (1) the irradiation-induced darkening of optical fibers is minimal in TREAT experiments; (2) various fiber compositions (sapphire, quartz, glass) are available to meet temperature, pressure, and material compatibility requirements; (3) very fast response times are possible (<< milliseconds); (4) optical measurements are immune to electromagnetic interference and do not conduct electricity; (5) optical fibers are inert and safe in nuclear environments; (5) fiber sensors are generally highly compact and non-obtrusive; and (6) fiber-optic sensors can be combined to have multiple measurements in a single fiber. An additional prospective benefit of fiber-optic approaches includes the possible modularity of required infrastructure and engineered mechanisms to support in-pile deployment for a wide-range of possible measurement targets.

V.C. Instrument Qualification

Instrument development may be closely linked to the qualification process. Instrument qualification is formally defined as using a science-based approach to provide documented evidence that an instrument is capable of consistently operating within established limits and tolerances for its intended purpose when properly installed, maintained, and calibrated. Specific qualification requirements are closely tied to a given instrument and its intended application and objectives. The ultimate desired outcome is to provide needed experimental data with acceptable, high-confidence uncertainties. Therefore, the steps taken to achieve full qualification are likely to include a variety of testing involving components, subsystems, prototype systems through actual systems. For transient testing applications, these components and subsystems include feedthroughs, electrical and optical lines, preamplifiers and other electronic or optical components, data acquisition, etc. Out-of-pile testing is performed to characterize instrument response under prototypic thermal-hydraulic environments while in-pile testing is crucial to fully evaluate performance under prototypic neutron and photon fields. Expected testing for a given instrument begins in development laboratories at National Laboratories, universities, commercial entities, and international R&D labs. The flexibility afforded by the TREAT facility design facilitates a variety of separate-effects in-pile testing of sensors prior to full integration into experiments going into the reactor. Figure 8 presents a summary of the key development and qualification development areas used for transient testing experiments.

VI. Summary and Conclusions

Development of innovative instrumentation approaches for transient irradiation experiments at the TREAT facility will play a critical role in the success of creating, attracting, and carrying out new experimental programs for fuel behavior during transient conditions. The focus of key measurement technologies is on measuring parameters up to extreme DBA conditions for modern and advanced reactor designs and the possibility of integrating into experiments where irradiated test specimens are assembled into an experiment via hot cell operations. For in-pile testing of nuclear fuels and materials, transient testing experimentation has the unique advantage of low total neutron fluence making many technologies viable compared to testing in steady-state MTRs. In particular, the simple, dry-core design of the TREAT reactor facility allows for flexible instrument implementation facilitating in-pile testing and experiment integration for a variety of testing environments. Many instruments spanning state of the art to next generation are currently at various levels of development and qualification for use in transient irradiation experiments at the TREAT facility to measure in-pile online flux, cladding temperature, pressure, fuel and cladding elongation, and coolant voiding. Examples of baseline instruments with near term applications include prompt-response SPNDs, cladding surface thermocouples, and LVDT-based elongation and pressure sensors. Advanced sensors under development include an impedance-based boiling detector, an infrared pyrometer, and a miniature fission chamber. Preliminary in-pile testing sensors is underway with good preliminary performance by SPNDs and an infrared pyrometer. A variety of other important complementary instrument development efforts are also underway in coordination with TREAT facility experiment programs and are not discussed in this paper.

VII. Acknowledgments and Disclaimer

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VIII. References

1. D. M. WACHS, "Transient Testing of Nuclear Fuels and Materials in the United States," JOM-J. Min. Met. Mat. S. **64** (2012) 1396.
2. B. KIM, et al., "Review of Instrumentation for Irradiation Testing of Nuclear Fuels and Materials," Nucl. Technol, **176** (2011) pp. 155-187.
3. M, GIOT, et al., "Nuclear instrumentation and measurement: a review based on the ANIMMA conferences, EPJ Nuclear Sci. Technol., **3** (2017) pp. 1-49.
4. J. REMPE, "New In-Pile Instrumentation to Support Fuel Cycle Research and Development," INL/EXT-10-19149, January 2011.
5. C. POPE, et al., "TREAT Design and History," Nucl. Technol., **205** (2019) (submitted for publication).
6. A. DE VOLPI, et al., "Fast-neutron hodoscope at TREAT: methods for quantitative determination of fuel dispersal," Nucl. Technol. **56** (1982) 141.
7. D. L. CHICHESTER, et al., "The TREAT Fast-Neutron Hodoscope and Plans for Restoring it to Operation," Trans. Am. Nucl. Soc., **112**, 377 (2015).
8. N. WILDE, T. J. BOLAND, S. D. ANDERSON, "Instrument Development Branch Annual Report," IDO-17234 (1966).
9. G. L. SMITH, "Instrumentation and Control Branch Annual Report," ANCR-1074 (1971).
10. L. COHN, et al., "Transient Radiation Effects on Electronics (TREE) Handbook," DNA-H-95-61, (1995).

11. T. G. TAXELIUS (ed.), “Annual Report SPERT Project,” IN-1370, (1970).
12. C. L. ZIMMERMANN, et al., “Experiment Data Report for Test RIA-ST,” Report NUREG/CR-0473, TREE-1235, (1979).
13. T. H. BAUER, et al., “First Overpower Tests of Metallic IFR Fuel in TREAT: Data and Analysis from Tests M5, M6, and M7,” Report ANL-IFR-124, (1989).
14. T. TSURUTA and T. FUJISHIRO, “Evaluation of thermocouple fin effect in cladding surface temperature measurement during film boiling,” J. of Nucl. Sci. Technol. **21** (1984) pp. 515-527.
15. R. W. GARNER and P. E. MACDONALD, “Power Burst Facility Thermocouple Effects Test Results Report,” Report NUREG/CR-2665, EGG-2190 (1982).
16. S. C. WILKINS, “Embedded Cladding Surfacae Thermocouples on Zircaloy-Sheathed Heater Rods,” Report TREE-NUREG-1072 (1977).
17. EG&G Report, “Specification: LOC-7 Test Experiment Configuration Specification,” ES-50448, February 1979.
18. C. J. ALDERMAN, “Series Data package Addendum for Long-Lifetime (CDE) Fuel Experiments in TREAT: HEDL CDT-1 Transient Test,” HEDL-TC-2832-1, March 1987.
19. S. SOLSTAD and R. V. NIEUWENHOVE, “Instrument Capabilities and Developments at the Halden Reactor Project,” Nucl. Technol. **173** (2011) pp. 78-85.
20. N. WILDE, T. J. BOLAND, S. D. ANDERSON, “Instrument Development Branch Annual Report 1966,” IDO-17234, July 1967.
21. R. G. MORRISON, J. B. COLSON, S. R. GOSSMAN, N. WILDE, “Instrument Development Branch Annual Report 1968,” IDO-17299, July 1969.

22. R. V. NIEUWENHOVE, “Irradiation Capabilities at the Halden Reactor and Testing Possibilities Under Supercritical Water Conditions,” J. Nucl Eng. Rad. Sci. **2** (2016) 021013.
23. R. S. SEMKEN, et al., “Reactivity Initiated Accident Test Series RIA Scoping Tests Fuel Behavior Report,” NUREG/CR-1360 (1980).
24. S. FAM, L. C. LYNNWORTH, E. H. CARNEVALE, “Ultrasonic Thermometry in LMFBR Systems,” NYO-3906-01 (1968).
25. M. LAURIE, et al., “Ultrasonic High-Temperature Sensors: Past Experiments and Prospects for Future Use,” Int. J. Thermophys. **31** (2010) pp. 1417-1427.
26. F. KIRN, J. BOLAND, H. LAWROSKI, “Reactor Physics Measurements in TREAT,” ANL-6173 (1960).
27. G. IMEL and P. R. HART, “The performance of hafnium and gadolinium self powered neutron detectors in the TREAT reactor,” Nucl. Instrum. Meth. Phys. Res. B **111** (1996) pp. 325-336.
28. M. D. DEHART, B. A. BAKER, J. ORTENSI, “Interpretation of energy deposition data from historical operation of the transient test facility (TREAT),” Nucl. Eng. Des. **322** (2017) pp. 504-521.
29. K. KONISHI, et al., “The result of a wall failure in-pile experiment under the EAGLE Project,” Nucl. Eng. Des. **237** (2007) pp. 2165-2174.
30. D. A. PETTI, et al., “Power Burst Facility (PBF) Severe Fuel Damage Test 1-4 Test Results Report,” NUREG/CR-5163 (1989).
31. G. H. GOLDEN, C. E. DICKERMAN, L. E. ROBINSON, “Facility for Photographic In-Pile Meltdown Experiments in TREAT,” ANL-6457 (1964).

32. T. FUJISHIRO, S. TANZAWA, and S. SAITO, “Inpile Test Rigs for RIA Experiments in the NSRR,” Proc. of International Topical Meeting: Irradiation Technology, Eds. P. von der Hardt and H. Rottger, p. 191 (1983).
33. P. ROYL, et al., “Contributions from the ACRR In-Pile Experiments to the Understanding of Key Phenomena Influencing Unprotected Loss of Flow Accident Simulations in LMFBRs,” Nucl. Eng. Des. **100** (1987) pp. 387-408.
34. N. WOOLSTENHULME, et al., “Development of Irradiation Test Devices for Transient Testing,” Nucl. Technol. 205 (2019) (submitted for publication).
35. J. D. BESS, et al., “Nuclear characterization of a general-purpose instrumentation and materials testing location in TREAT,” Ann. Nucl. Energy **124** (2019) pp. 270-294.
36. J. D. BESS, et al., “Narrowing transient testing pulse widths to enhance LWR RIA experiment design in the TREAT facility,” Ann. Nucl. Energy **124** (2019) pp. 548-571.
37. OECD NEA, “Nuclear Fuel Behaviour Under Reactivity-Initiated Accident (RIA) Conditions,” ISBN 978-92-64-99113-2, NEA/CSNI/R(2010)1, NEA No. 6847, (2010).
38. OECD NEA, “Nuclear Fuel Behaviour Under Loss-of-coolant Accident (LOCA) Conditions,” ISBN 978-92-64-99091-2, NEA No. 6846, (2009).
39. T. H. BAUER, et al., “Behavior of Modern Metallic Fuel in TREAT Transient Overpower Tests,” Nucl. Tech. **92** (1990) pp. 325-352.
40. T. SOFU, “A Review of Inherent Safety Characteristics of Metal Alloy Sodium-Cooled Fast Reactor Fuel Against Postulated Accidents,” Nucl. Eng. Tech. **47** (2015) pp. 227-239.
41. J. PAPIN, “Behavior of Fast Reactor Fuel During Transient and Accident Conditions,” Comprehensive Nuclear Materials **2** (2012) pp. 609-634.
42.

43. C. JENSEN et al., “FY17 Report for Instrumentation Development for Transient Testing Program,” INL/EXT-17-43444 (2017).

44. C. JENSEN et al., “FY18 Report for Instrumentation Development for Transient Testing Program,” INL/EXT-18-51613 (2018).

45. T. UNRUH, et al., “NEET Micro-Pocket Fission Detector – Final Project Report,” INL/EXT-14-33026 (2014).

46. S. SOLSTAD and R. V. NIEUWENHOVE, “Instrument Capabilities and Developments at the Halden Reactor Project,” Nucl. Technol. **173** (2011) pp. 78-85.

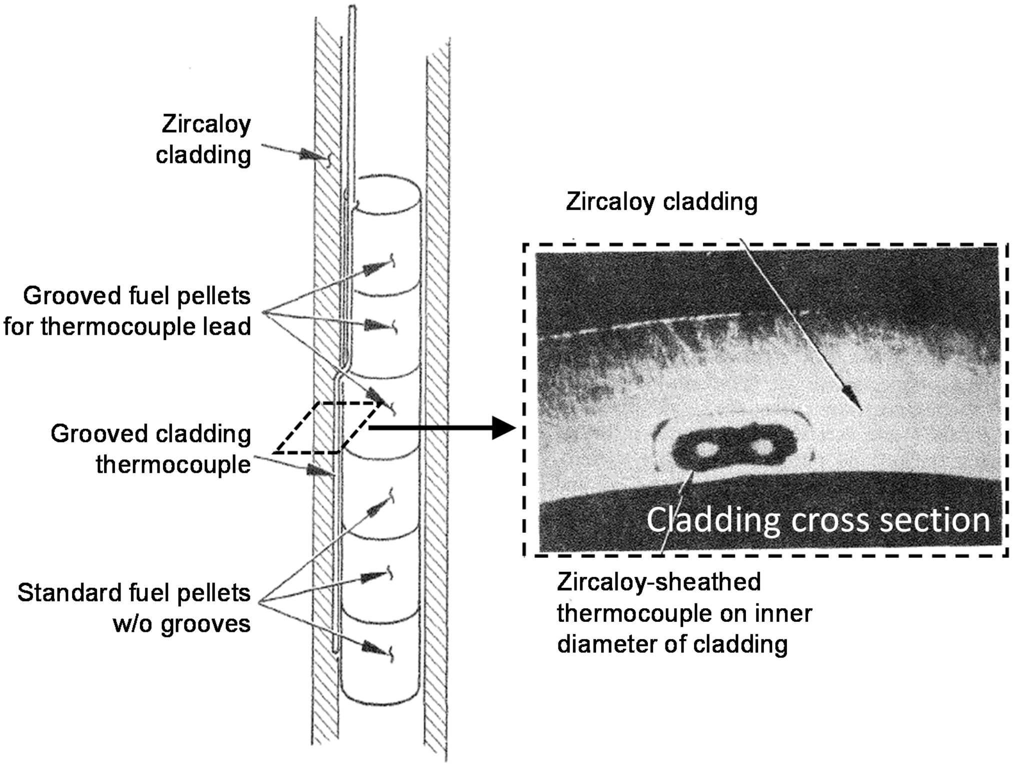


Figure 1. Example of advanced thermometry developed for PBF/LOFT experiments. A thermocouple embedded in a cladding wall (adapted from [15]).

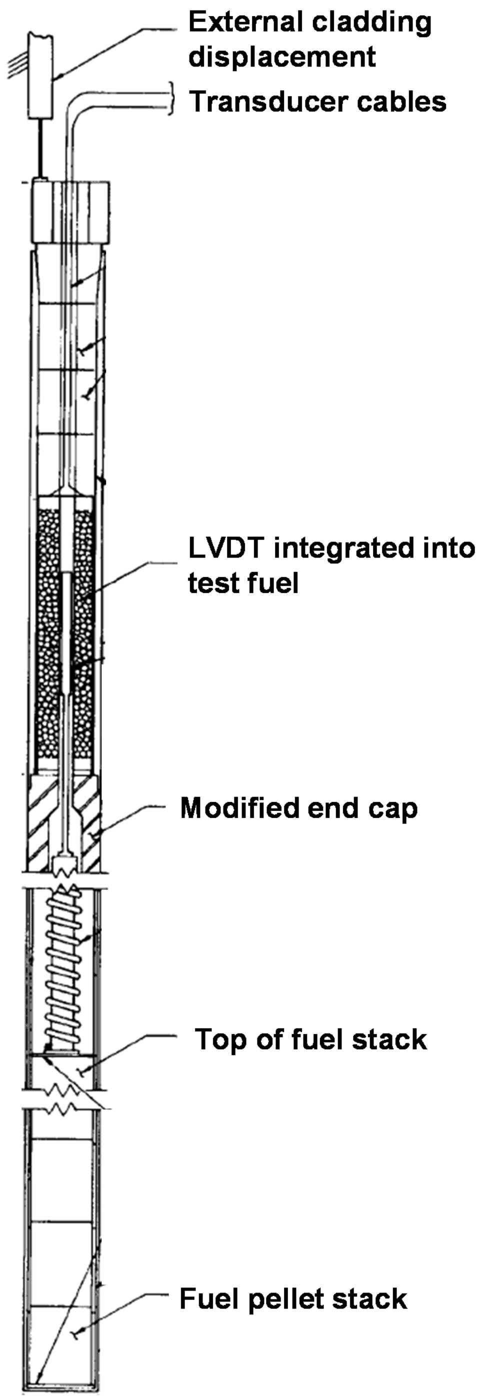


Figure 2. Instrumented prototype PBF fuel pin tested at TREAT in the mid-1960's utilizing LVDT for fuel stack elongation[8].

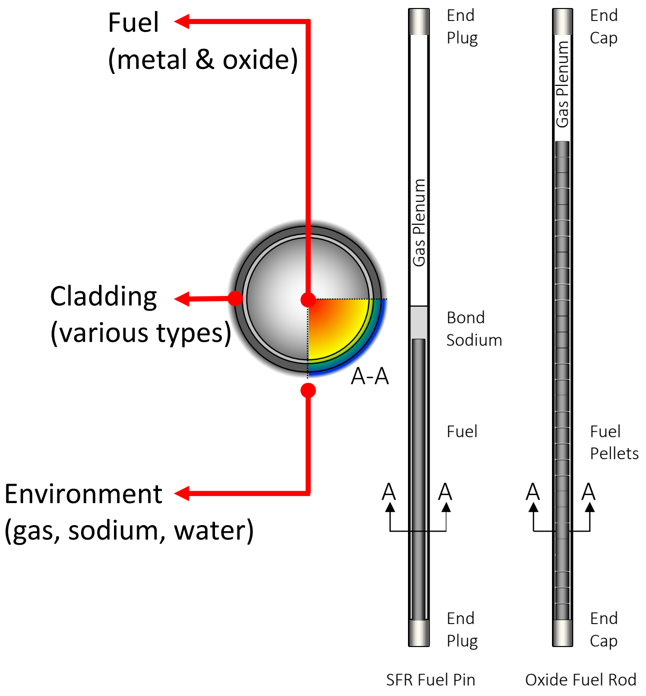


Figure 3. Primary instrument target locations for representative fuel designs for SFR and LWR systems and general component descriptions of fuel designs.

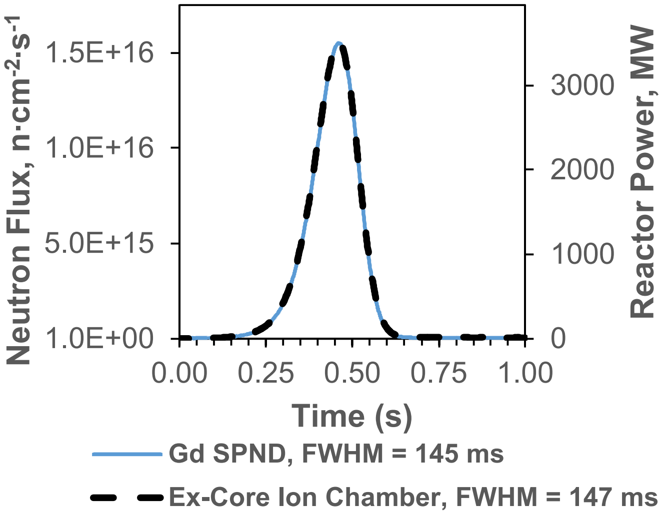


Figure 4. Example of measured flux obtained from in-pile Gd SPND at TREAT compared to ex-core ion chamber measurements.

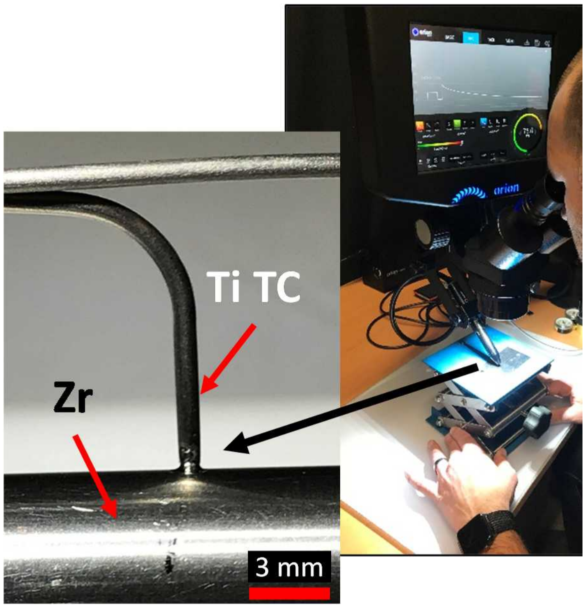
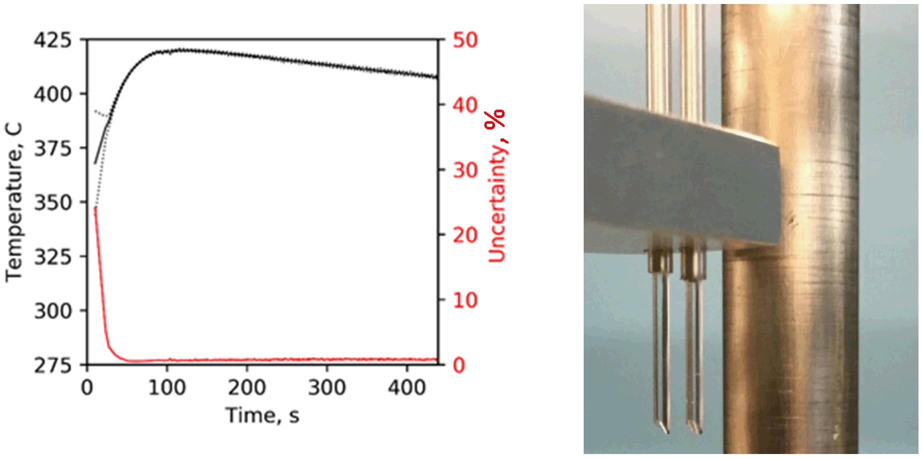


Figure 5. Thermocouple attachment to nuclear fuel cladding showing example of Ti sheathed TC attached to Zircaloy cladding and micro-welder utilized to make the weld. A variety of thermocouple configuration options and attachment processes are under development for different testing purposes.



a) b)

Figure 6. a) Plot of the temperature measured in the coolant channels of TREAT via the fiber optic based IR pyrometer. This testing was conducted as part of the in-pile qualification of the infrared pyrometer for deployment in TREAT experiments. b) Image of the distal end of the optical line

for the fiber optic-based IR pyrometer aimed at a surrogate fuel rod as part of the out-of-pile qualification.

Table 1. Performance comparison of temperature measurement techniques used in TREAT experiments.

	Thermocouple	**Infrared Pyrometer (*current capability*)**
Minimum Time Response (ms)	100 (approximate for 6 mil wire bare junction)	5
Device Uncertainty (ΔK)	2 for T < 1700 K 4.5 for T < 2600 K	<5
Fin Effect (ΔK)	150 K	Not applicable
Maximum Temperature (K)	2600 (Type C)	3300

* all values are approximate

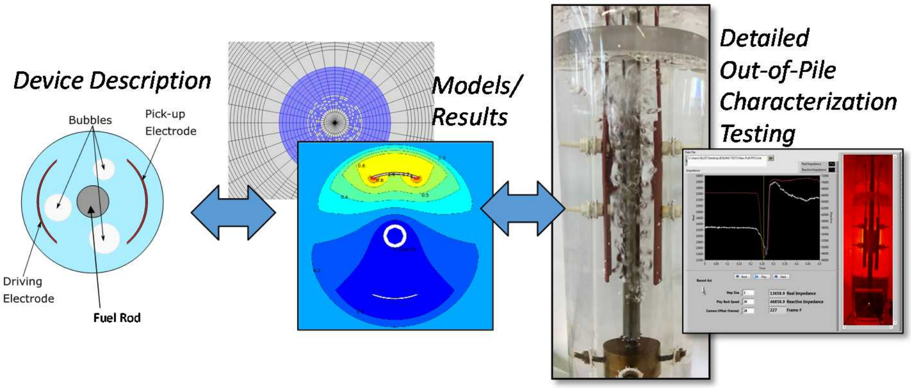


Figure 7. Impedance-based boiling detector instrument development summary. The device is shown in the figure at left to measure void formation on nuclear fuel in water environments. The center figures show finite element modeling results that predict sensor performance based on void fraction and spatial distribution. A high-speed imaging device has been developed to perform detailed characterization of the sensor response based on void location.

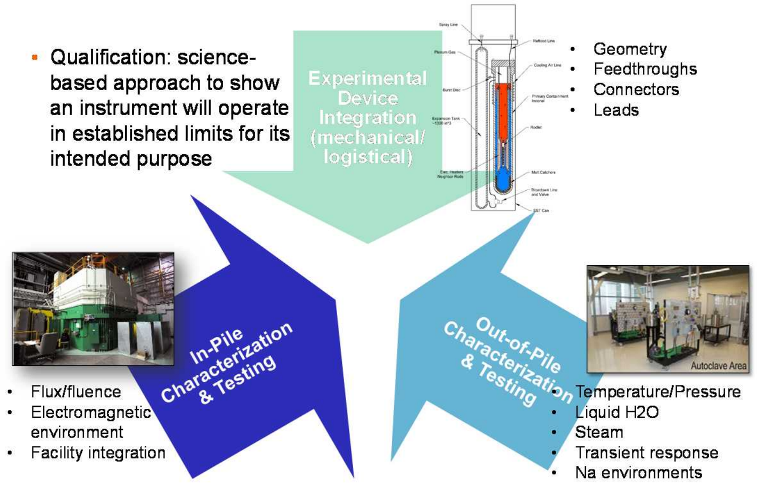


Figure 8. Three characterization and qualification focus areas for instrument development for TREAT.