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# THE SIRIUS-1 NUCLEAR THERMAL PROPULSION FUELS TRANSIENT TEST SERIES IN THE IDAHO NATIONAL LABORATORY TREAT REACTOR

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*Nuclear Thermal Propulsion (NTP) fuels and component materials are subjected to extreme temperature transients through nuclear heating to NTP system from space cold to operational temperatures. Methodology for transient testing conceptual NTP fuels is presented in addition to the capsule design for static testing under the SIRIUS-1 series at the Idaho National Laboratory Transient Reactor Test (TREAT) reactor.*

## I. INTRODUCTION

Nuclear Thermal Propulsion (NTP) fuels when brought to a targeted operational temperature from a cold zero-power condition may be subjected to thermo-mechanical stresses. Understanding the limitations to any fuel system must be determined in order to facilitate operational system performance, specifications and service ratings. Modern modeling and simulation tools such as the Department of Energy's Nuclear Energy Advanced Modeling and Simulation tools (e.g. MOOSE framework, Ref. 1) can couple nuclear physics with materials properties to estimate performance. However, for licensing (e.g. in compliance with Nuclear Regulatory Commission NUREG Guide 0800 (Ref. 2) for performance under severe accident conditions) and operations purposes, several energy thresholds and power ramp rates must be empirically measured (Ref. 3). Similarly, launch safety and approval processes will likely require determination and demonstration of materials performance under the conditions that are prescribed for nominal operations and postulated accidents. These measured values include:

1) Fuel fragmentation threshold enthalpy rise and ramp rate.
2) Coolable / functional reactor geometry maximum enthalpy rise.
3) Energy deposited during fuel-coolant interactions.
4) Fuel and fission product loss rate as a function of temperature and time.
5) Submersion criticality environment fuel behavior.

The Idaho National Laboratory's Transient Reactor Test (TREAT) reactor is a digitally controlled test reactor which can be pulsed to a peak power of the order 19 GW or ramped to a prescribed power through the maneuvering of banks of control and transient drive control rods. The complexity of the power profile that can be derived within a test specimen is limited fundamentally only by the tolerance of the specimen, the capsule or specimen holder, and the maximum permissible enthalpy rise of the TREAT driver core of ~2500 MJ at or under which, no damage to the fuel/cladding system can occur. The driver core is composed of a 19x19 array of fuel-reflector assemblies, Ref. 4. Each fuel assembly is approximately 9 feet long and has a cross section of approximately 4 inches by 4 inches and has an active fuel length of approximately 4 feet. The active fuel region of an assembly is a $UO_2$-graphite dispersion fuel within a zircaloy cladding. Unfueled graphite reflectors, approximately 2 feet in length above and below the active fuel region are housed within the cladding of a fuel assembly. Fuel or other test specimens are encapsulated within an irradiation test vehicle that offers either static or flowing environments inside doubly encapsulated containment. These irradiation test vehicles can be installed within any of the 19x19 grid positions by displacing one or more fuel assemblies. Typically, experiments are placed, but not limited to the center of the reactor, Ref. 4.

**Fig. 1.** The Idaho National Laboratory's Transient Reactor Test (TREAT) Reactor. (Left) View of 19x19 array of driver fuel assemblies. An irradiation test vehicle is visible at the center position of the core. (Right) Ariel view of the TREAT facility at the Idaho National Laboratory Materials and Fuels Complex.

As shown in Figure 2, a combination of transient shaping and clipping can be used to derive an aggressive heating rate within a specimen, e.g. a ramp to full temperature, followed by a sharp decrease in driver core power to sustain specimen temperature for a period of time. Such transient shaping may be executed for static capsule testing of NTP specimens, although the magnitude of the reactor power will differ to the historical transients illustrated in Figure 2.

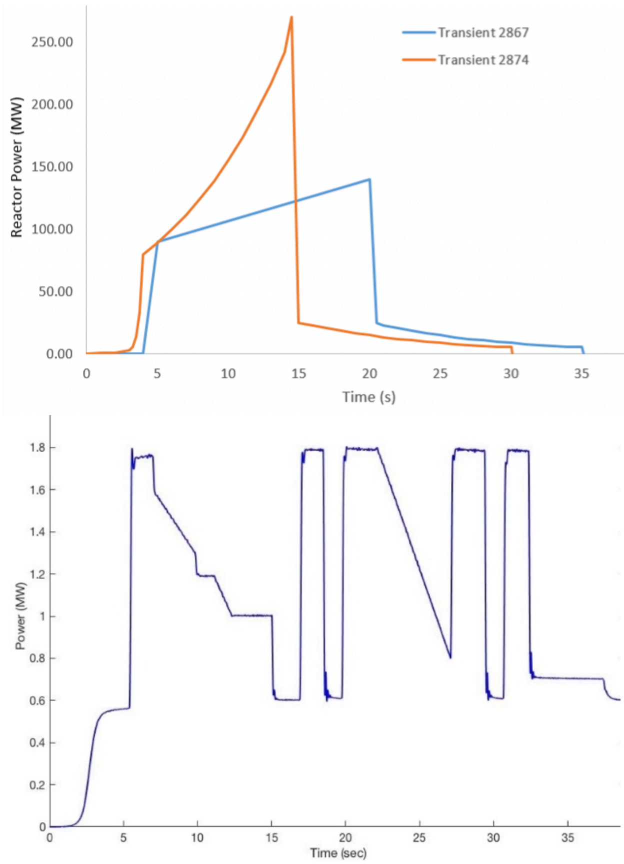


**Fig. 2.** Example power transients that can be prescribed, demonstrating the shaping complexity that can be achieved through TREAT digital control while restricting total enthalpy rise for the core to under 2500 MJ.

The Historically, the TREAT reactor has performed thousands of transient tests on fuel and reactor components, emulating the nuclear test environment of thermal reactor systems, epithermal and fast reactors. Sample temperature ramp rates have been prescribed and demonstrated in TREAT at up to 16,000 K/s (Ref. 5). Various chemical environments have been successfully tested within irradiation vehicles from light water, inert gas to hydrogen. The natural, unfiltered spectrum of the TREAT reactor central test position is highly analogous to the spectral environment of heavily moderated, low enriched uranium systems, such as those being explored under the current NASA programmatic efforts. Filtering and shaping of the neutron spectrum to which a TREAT capsule / specimen is subjected can be applied through the application of a collar (e.g. dysprosium foil) to the external surfaces of a capsule.

## II. THE SIRIUS TEST SERIES

The United States Department of Energy and NASA have funded the initial development of the SIRIUS-1 transient test series at the Idaho National Laboratory, Ref. 6. This work is focused on the development of a static capsule design, validation and verification of capsule and in-pile instrumentation for the transient testing of concept NTP fuels. Following demonstration of the capsule design with a dummy or baseline NTP fuel specimen fabricated via Spark Plasma Sintering at INL, the capsule(s) will be used to evaluate the performance of concept NTP fuels from NASA and Industry.

Static capsule testing within a safe gas atmosphere (3% H2 in 97% Ar) allows for incipient chemical interactions between hydrogen and fuels/claddings to be examined while preventing complete reaction and thus avoiding significant fuel disruption that would cause uncertainty in post-irradiation examination analysis. Since the SIRIUS-1 series of tests will be static capsule tests, the specimens will be ramped to their peak design temperature (approximately 2600-2850 K) at a rate of 95 K/s or otherwise prescribed rate (higher or lower). No coolant flow is possible in a static capsule, therefore the volumetric power density prescribed in a SIRIUS-1 test will be lower than prototypical operation, however, once at peak temperature, the specimen can be sustained through an isothermal hold for a prescribed period of time, seconds to minutes. This will allow prototypical thermal gradients to be established within the specimen and for chemical interactions, if any, to onset between the fuel system and the H2 species within static environment. Five or six transient tests / thermal cycles will be performed on each of the concept specimens tested under the SIRIUS-1 series to allow for restart behavior to be observed. A combination of in-pile instrumentation (TREAT Fast Neutron Hodoscope) and the TREAT neutron radiography station will be at intervals in transient tests to determine the location and integrity of the specimen. In the event that a specimen is severely disrupted, or fragmentation is observed during radiography, a test will be concluded on that specimen.

Following transient testing at the TREAT reactor, the capsule will be transported to the INL's Hot Fuel's Examination Facility (HFEF) by the HFEF-15 cask for detailed Post Irradiation Examination (PIE), including: high resolution neutron radiography and tomography, burnup distribution, fission gas retention within fuel systems, metrology, microstructural evolution and thermophysical properties.

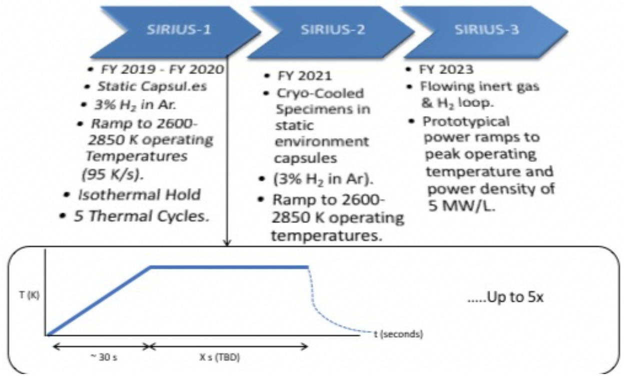


**Fig. 3.** The Sirius 1 Test Series objectives as currently funded. Notional objectives of potential follow-on experimental series beyond 2021 (currently unfunded).

Expansion of the SIRIUS test series will be possible through future funding opportunities to include flowing loops and refrigerated specimen holders for pre- test conditioning and full power testing.

## III. SIRIUS-1 STATIC CAPSULE DESIGN.

The capsule that will be used in the SIRIUS-1 test series will be manufactured in Grade 5 titanium alloy, produced by powder bed additive manufacturing. The capsule will be lined with a high purity, low density multi-layer crucible, inside which a specimen will be suspended on a refractory alloy pedestal and mirror hanger. Highly polished molybdenum mirrors will minimize thermal losses from the specimen and minimize heating of and hence protect the capsule integrity during the test. A combination of in-pile instrumentation will be used to gather safety and programmatic data during each test. Optical pyrometry will be used to measure specimen temperature. High temperature thermocouples will be attached to the surface of the specimen for low power, low temperature calorimetric calibration for transient prescription confirmation tests and during the full power transient to full prototypical temperatures. It is understood that during the first ramp to full temperature, the thermocouple junction will be lost, but a correlation and confirmation of pyrometer performance will be obtained during this first full transient. The pyrometer will perform measurement of the fuel specimen surface temperature via an optical assembly located a stand-off distance to minimize radiant heat damage of the optic. Light gathered through the optical assembly will be transmitted via a fiber optic cable to the out-of-pile spectrometer and data acquisition system.

The SIRIUS-1 capsule design is evolved from the TREAT Static Experiment Test Holder (SETH) capsule that was originally designed to support the Department of Energy's Accident Tolerant Fuels Program. A Computer Aided Design (CAD) rendering of the SIRIUS-1 capsule is provided in Figure 4. A combination of MCNP, STARCCM+ and ABAQUS codes have been used to perform preliminary design of the SIRIUS-1 Capsule. MCNP is used to estimate the heat generation rate per gram of specimen, and the effective energy coupling factor (ECF) between the TREAT driver core and the specimen for transient prescription purposes. The MCNP model is used to provide heat generation data for the specimen and neutron/gamma heating of the capsule components under a given transient prescription. This is used to model heat transfer and temperature distribution within a specimen. Example results of this transient analysis is provided in Figures 5 and 6.

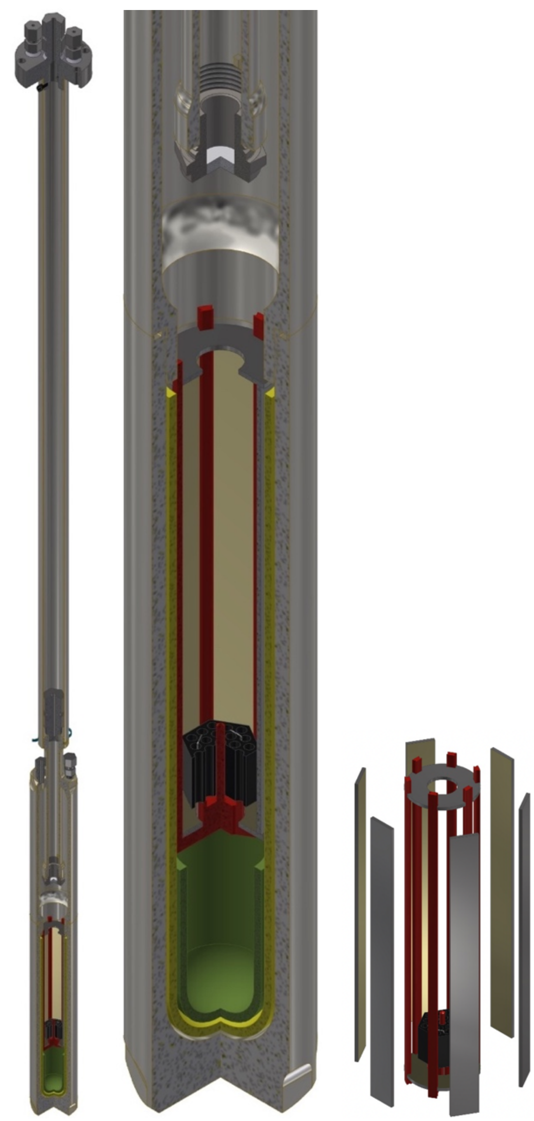

**Fig. 4.** Preliminary design of the SIRIUS-1 Capsule. (Left) Overall Capsule Assembly. (Middle) detailed view of the specimen test section of the capsule showing standoff for the pyrometer optic assembly. (Right) Explosion view of the Mo mirror assembly.

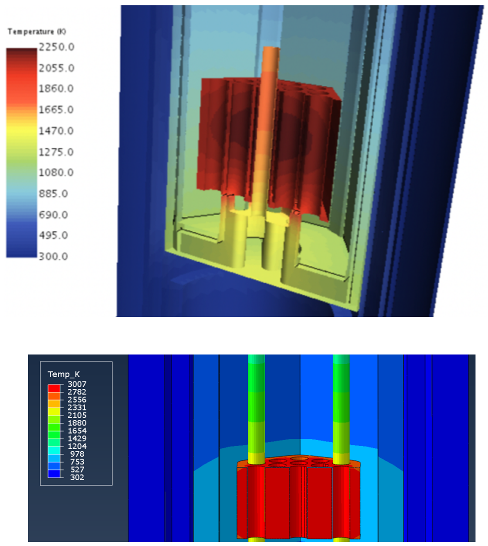


**Fig. 5.** Example predictive analytical results of specimen holder designs and specimen held at constant heat generation rate. The analytical modeling techniques are used to optimize capsule and fixture design while informing mechanical behaviors under transient testing. Here, a cross section of specimen and support pedestal nestled inside a crucible is shown during the ramp to peak temperature. (Top) during ramp to temperature, (Bottom) during isothermal hold – See Figure 6 for temperature ramp profile.

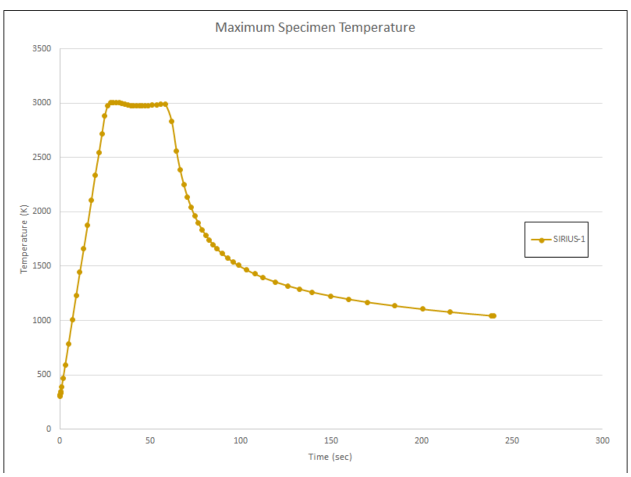


**Fig. 6.** Predicted temperature-time response curve for the preliminary SIRIUS-1 baseline capsule test.

## IV. BEYOND STATIC CAPSULE TESTING

While static capsule testing offers an affordable approach to testing of NTP fuels, the nature of capsule testing limits the volume of propellant that can be exposed to a specimen. For incipient performance phenomenological studies, capsule testing is therefore relevant and attractive in many cases, especially where unpredicted adverse chemical reactions with propellant species are limited by the initial number of moles present within the capsule upon closure. However, in the absence of flowing propellant, it is not possible to sustain both the full volumetric power density and the peak operational temperature of fuels in typical prototypical fuel specimens, unless the cross-sectional area of a fuel specimen is very small. Therefore, in order to perform testing with both prototypical heat generation while maintaining NTP operational temperatures, flowing loop testing is required in order to target a specific heat removal rate.

The extreme stresses that will be experienced within space based NTP system fuels as they are ramped from space cold, as low as cryogenic temperatures (-192 C) to full operating temperatures, can be explored within transient reactor experiments at TREAT. For example, ramping at a low rate of temperature rise from space cold through the ductile to brittle transition temperature may be required to mitigate fracture behaviors in coatings, claddings and fuel meat. The development of a dedicated refrigerated specimen holder can accomplish the exploration of these needs in a static capsule design, either refrigerated via the use of a cryogenically cooled cold finger and liquid nitrogen heat exchanger, or another mechanical chiller (e.g. Stirling cryo-cooler).

Understanding fuel performance under submersion criticality accidents may be required to satisfy a launch safety review process and/or civil regulatory licensing. The development of static capsule steam and/or sea water environmental loops may be of importance, especially where fission product release and fuel system corrosion behavior must be characterized. Such testing will be possible through future extension of a SIRIUS1 capsule or SIRIUS-3 loop.

## V. CONCLUSIONS

The TREAT reactor offers great flexibility and versatility for the testing of NTP fuels which can be used to accelerate the screening and technology readiness level (TRL) of a concept fuel system or design. Similarly, the TREAT reactor can be used to prescribe beyond nominal operating conditions to determine fuel fragmentation thresholds and performance phenomena that may be exhibited under postulated accident conditions, e.g. submersion criticality. Overall, TREAT testing of fuels is an economical approach towards escalating TRL of a fuel system prior to full NTP system design, development and demonstration testing.

## ACKNOWLEDGMENTS

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