Nuclear and Emerging Technologies for Space
Knoxville, TN, April 6 – April 9, 2020, available online at https://nets2020.ornl.gov

DESIGN OF THE IN-PILE EXPERIMENT SET (INSET) APPARATUS TO SUPPORT NUCLEAR THERMAL PROPULSION FUEL AND COMPONENT TESTING

Richard Howard, PhD

Oak Ridge National Laboratory
One Bethel Valley Rd., Oak Ridge, TN 37831

865-576-4867, howardrh@ornl.gov

There is renewed interest in space travel, and domestic support for research and development activities to enable crewed missions to the moon and beyond is currently very strong. Nuclear thermal propulsion (NTP) is considered the most mature and viable nuclear propulsion technology available, but NTP fuel remains an Achilles heel of the system because it must withstand extreme conditions: temperatures ranging from cryogenic to an excess of 2,500 K, corrosive and erosive hydrogen working fluid, and power densities on the order of 5 MW/l.

To prove that NTP is fit for manned missions, fuels and reactor components must be tested and qualified. Moreover, test facilities must be cost effective and rapidly deployable so that the qualification effort does not financially cripple the development effort. This work describes the In-pile Experiment Set (INSET) apparatus design. This apparatus is intended to employ sub-scale fuel and component specimens to facilitate in-pile radiological tests to support the NTP effort.

I. INTRODUCTION AND BACKGROUND

The topic of exploring the solar system is exciting, and it is evolving into more serious plans and technology development to support crewed missions. To support these missions, propulsion technologies that provide sufficient thrust and specific impulse (a measure of propulsion efficiency) must be developed so that mission times are long enough to allow crews to perform sufficient exploration while minimizing personnel exposure to the adverse conditions of space. Current proven propulsion technologies such as chemical rockets provide adequate thrust, but the specific impulse is around 450 s and does not allow for optimal mission times. Other advanced technologies such as electronic propulsion and light sails have specific impulses on the order of 1,000–5,000 s but currently do not provide sufficient thrust for crewed missions.

The current frontrunner for improving performance for crewed spaceflight is nuclear thermal propulsion (NTP), which involves using nuclear fission to heat a working fluid, in this case hydrogen, and accelerate it through a nozzle to produce thrust. NTP is not a new technology; it was pioneered during the 1950s–1970s under Project Rover/NERVA [1]. During that time, much work was performed to demonstrate and test NTP engines, and the outcomes were encouraging. However, the work required employing tens of full-scale reactor tests, some of which were even deliberately destroyed in fiery explosions, with a price tag on the order of $10B (inflation adjusted). After Project Rover/NERVA was cancelled, advances in NTP slowed or stopped all together. Much of what was known was lost over time, making it imperative to undertake a large-scale development effort to establish and modernize NTP for current use. Despite current public and political excitement about space travel, obtaining funding and tolerance for nuclear testing similar to that provided during previous decades is unlikely. Therefore, a more cost-effective, rapidly deployable platform for qualifying fuels and components is needed to successfully develop an infrastructure for NTP engine development. The work described herein details the In-pile Experiment Set (INSET) apparatus, which is designed to meet this need.

II. TESTING STRATEGY AND DESIGN OUTLINE

A testing strategy to efficiently qualify NTP fuels and components is necessary to understand the requirements of the affiliate experiment designs and facilities needed to carry out qualification work. Benensky and Qualls [2] outlined a fuel qualification plan that identified several deficient NTP areas to be addressed to ensure development of a qualified NTP fuel. In response to this plan, a strategy was proposed to develop and evolve out-of-pile testing to in-pile testing by using general experiment designs and research reactors. [2]. This strategy includes three phases; a simplified graphical representation is seen in Fig 1.

The out-of-pile testing observed in Phase 1 of the strategy includes demonstrating that an experiment facility can reliably provide NTP conditions to candidate specimens and then gather data on specimens to understand performance. This initial testing stage allows

This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

researchers to decide whether to optimize a promising candidate or downselect those that perform poorly.

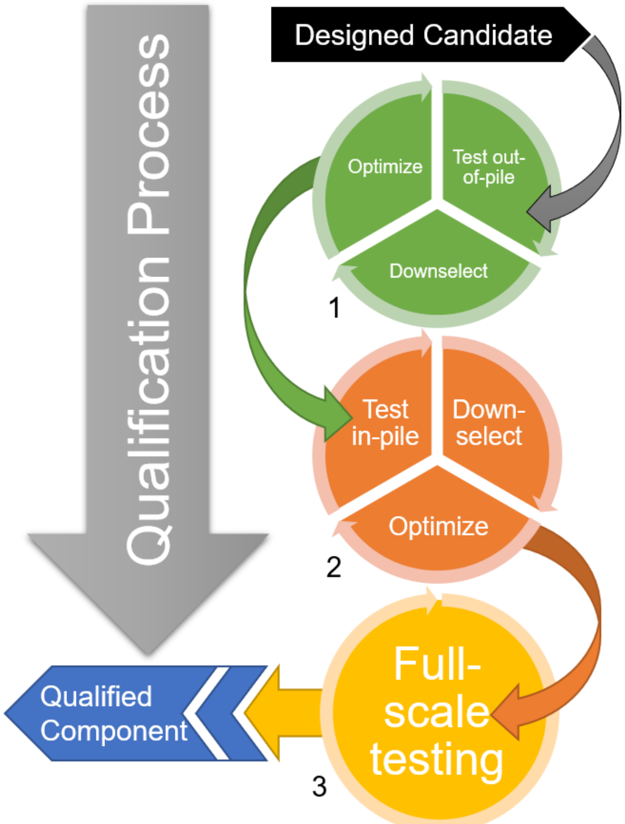

Fig 1. NTP qualification strategy.

Several out-of-pile experiment facilities are available, including the Compact Fuel Element Environmental Test (CFEET) facility [3], the Nuclear Thermal Rocket Element Environmental Simulator (NTREES) [4], and the Out-of-Pile Experiment Set (OUTSET) [5]. While CFEET and NTREES are stand-alone facilities explicitly for testing fuels and fuel surrogates, OUTSET was designed and deployed to demonstrate a direct current (DC), electrically heated capsule that could be scaled and modified for reactor, or it can be used for in-pile testing. The remainder of this paper focuses on the analogous In-pile Experiment set, or INSET.

II.A In-Pile Experiment Set (INSET) design details

INSET was designed to provide all the functionality of OUTSET. The INSET design requirements were developed as described in R. Howard's doctoral dissertation [6] and are listed below:

1. appropriate materials selection,
2. flexibility to accept various instrumentation techniques and electrical power delivery,
3. capability to provide and maintain a well-controlled atmosphere,
4. provision of thermal cycling,
5. temperature control and thermal management, and
6. establishment of a standard specimen geometry.

Howard's work [5], [6] provides a detailed overview of OUTSET and out-of-pile performance. A computer-aided design (CAD) model of the experiment is shown in Fig 2.

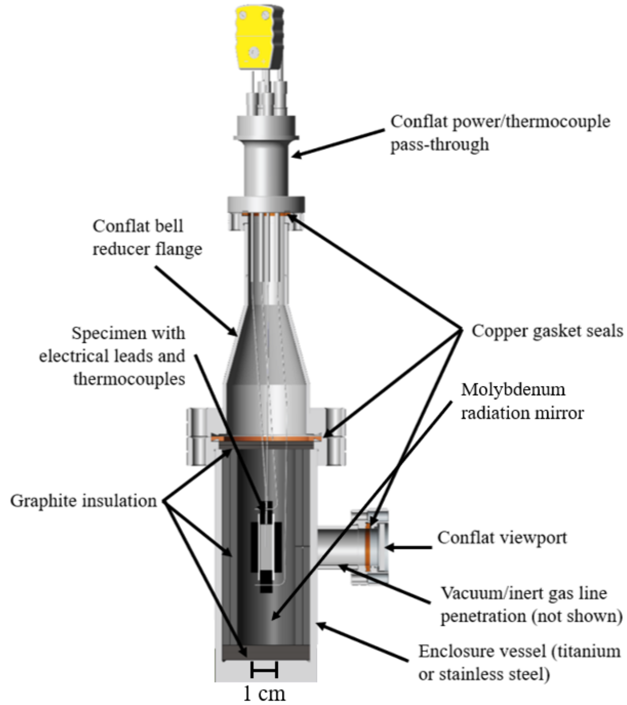

Fig 2. CAD rendering of OUTSET.

Fundamentally, the INSET design philosophy and operating processes are identical to OUTSET. However, INSET is intended to be used in-pile, and OUTSET is to be used for out-of-pile testing. The first iteration of OUTSET was to produce a proof of concept protoyope that would evolve into an in-pile experiment. Future iterations will likely have complimentary INSET and OUTSET instances so that design modifications can be demonstrated in the lower risk out-of-pile environment.

Both formats use Conflat® flanges and components to establish the experiment container, the commercially available DC electrical power and thermocouple passthroughs to deliver power and instrumentation, the high-temperature resistant graphite felt insulation, and reflective foils to establish NTP temperatures in the heated region. Moreover, both experiments are operated under vacuum conditions, and the heated region, which contains the heating element and specimens, are common to both designs. Lastly, the experiments are both instrumented with type C (W-Re) and type K (Ni,Cr) thermocouples to verify heated region and containment temperatures, respectively.

The INSET design deviates from the OUTSET design in three primary areas:

1. The INSET containment size is larger;
2. The INSET material selection was optimized to minimize neutron activation; and
3. INSET power limits may be larger than those in the OUTSET platform.

INSET containment was enlarged for several reasons. Primarily, the assembly of OUTSET was tedious, requiring the use of fine tools to mate parts together and to connect instrumentation and power wires. A larger container provides a more ergonomic interface for researchers assembling the experiment. Also, a larger containment volume provides additional space for accommodating a larger heated region or specimens. As the purpose for INSET is to test fuels and components for NTP, its larger experiment plenum provides a more versatile interface for unqualified instrument candidates and other infrastructure that may not yet be identified. See Fig 3 for a comparison of OUTSET and INSET containments.

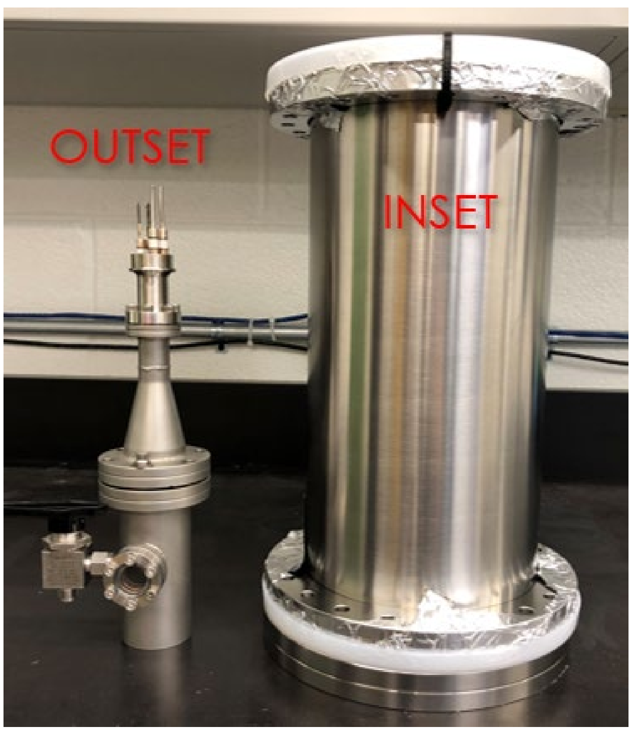

Fig 3. Size comparison of the 120 cm^3 internal volume OUTSET (left) and the 6,000 cm^3 internal volume INSET (right).

The OUTSET experiment containment was fabricated from 304L stainless steel, an alloy notorious for producing ^{60}Co as a neutron activation product that emits high-energy gamma rays, which can be problematic and costly to shield during shipping and handling. For INSET, Al-6061 alloy was selected to replace the 304L stainless steel, because the Al alloy produces less activation products, making it more manageable during post-irradiation shipping and handling. Neutronic analyses were performed to verify that the material change was beneficial and are documented elsewhere [7].

The OUTSET design was power limited because the power passthrough used was rated for a maximum of 15 amps-DC. Howard's work [6] showed that to reach higher heated region temperatures, a 15 A source was not feasible. Therefore, a 30 A power passthrough and larger gauge electrodes were incorporated into the INSET design. INSET's increased containment size made incorporating the larger passthrough and electrodes easier to deploy. A CAD rendering of INSET is shown in Fig 4.

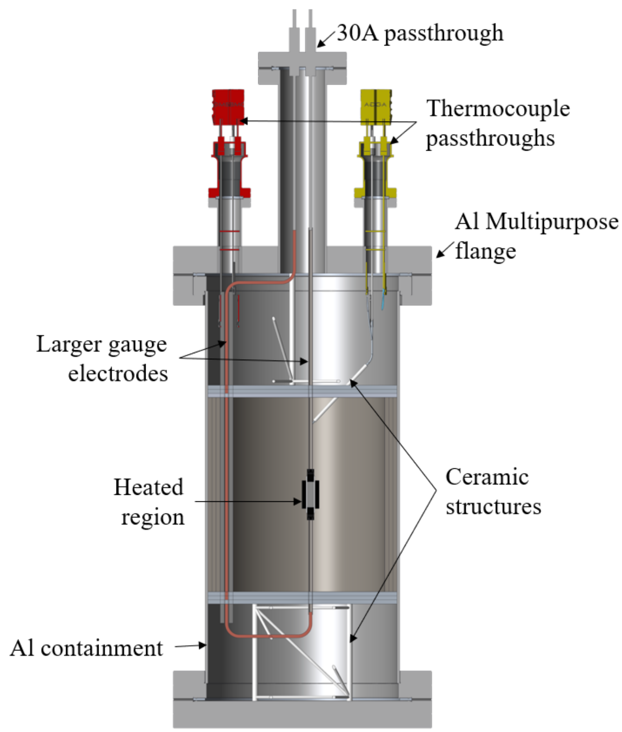

Fig 4. CAD rendering of INSET.

Other design changes that were not included in the earlier list are as follows:

- incorporation of a multipurpose flange to provide more penetration points for instrumentation and gas communication,
- Al alloy Conflat® metal gaskets compatible with the flanges and reduced activation,
- zirconia "paper" to provide an electrical barrier between the larger electrode and the containment wall, and
- ceramic structures to support internal insulation and wiring.

III. ONGOING AND FUTURE WORK

The INSET design is currently being tested, and its thermal performance is being characterized. A scale stainless steel OUTSET version (out-of-pile) prototype was fabricated for this purpose. Many modifications incorporated into INSET have been shown to improve functionality. For example, power levels as high as 1 kW have been safely delivered, whereas earlier powers were limited to ~350 W. However, the experiment platform's design should be considered as evolving, and improvements are expected to be incorporated to further simplify assembly and reliability.

To date, INSET has successfully undergone its first irradiation experiment to test NTP fuel surrogates at the Ohio State University Research Reactor. This work is fully detailed in other submissions to the Nuclear & Emerging Technologies for Space (NETS 2020) conference proceedings [7], [8]. OUTSET and INSET were developed to provide the NTP research community with a viable experimental platform that is rapidly deployable and relatively inexpensive to use. The outcomes of this initial irradiation and experiment demonstration are considered to be a successful beginning to providing a new experimental capability to the NTP community.

ACKNOWLEDGMENTS

This work was funded by the National Aeronautics and Space Administration through the US Department of Energy office of Nuclear Energy.

The author also acknowledges Dr. Thomas J. Harrison and Dr. Dianne Ezell of the Oak Ridge National Laboratory, along with Mr. Tyler Steiner and Ms. Emily Hutchins of the University of Tennessee, Knoxville, for their support of this work. Also, we acknowledge the Ohio State University Nuclear Reactor Laboratory for providing us with the opportunity to use their facility.

REFERENCES

1. S. K. BOROWSKI, D. R. MCCURDY, and T. W. PACKARD, "Nuclear Thermal Rocket (NTR) Propulsion: A Proven Game-Changing Technology for Future Human Exploration Missions," Global Space Exploration Conference (GLEX-2012.09.4.6x12341), Washington, DC (2012).
2. R. H. HOWARD, T. J. HARRISON, and J. D. RADER, "*Technology Implementation Plan: Irradiation Testing and Qualification for Nuclear Thermal Propulsion Fuel*, Oak Ridge National Laboratory, ORNL/TM-2017/376, Oak Ridge (2017).
3. K. BENENSKY, M. BARNES, D. BRADLEY, C. ROMNES and R. HICKMAN, "Operational Characterization and Testing of NASA MSFC's Compact Fuel Element Environmental Test (CFEET)," Nuclear and Emerging Technologies for Space, Richland, WA (2018).
4. W. J. EMRICH, "Initial Operation and Shakedown of the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)," AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH (2014).
5. R. H. HOWARD and A. E. RUGGLES, "Design and Out-of-Pile Testing of a Novel Irradiation Experiment Vehicle to Support Qualification of Nuclear Thermal Propulsion Components," *Nuclear Engineering and Design* **361** (2020).
6. R. HOWARD, *A High Temperature Out-Of-Pile Experiment for Testing Nuclear Thermal Propulsion Surrogate Fuels*, Doctoral Dissertation: The University of Tennessee, Knoxville (2019).
7. E. HUTCHINS et al., "Activation Analysis of Subscale Experimental Testbed: Towards Simulating Nuclear Thermal Propulsion Prototyping Conditions for Material Testing," Nuclear & Emerging Technologies for Space, Knoxville, TN (2020).
8. T. STEINER et al., "Nuclear Thermal Propulsion Subscale Experimental Testbed for Material Investigations Using the Ohio State University Research Reactor," *Nuclear & Emerging Technologies for Space*, Knoxville, TN (2020).