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DEVELOPMENT OF HIGH-TEMPERATURE OUT-OF-PILE EXPERIMENTS FOR TESTING NUCLEAR THERMAL PROPULSION FUEL SURROGATES

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Nuclear thermal propulsion technology is designed to provide "in-space" vehicle propulsion by deriving thrust from a hydrogen working fluid that is heated via a thermal or fast nuclear reaction. Initial NTP fuel structures, primarily carbon/carbide-based materials, developed by the Rover/NERVA Nuclear Engine for Rocket Vehicle Applications program were designed to withstand temperatures exceeding 2400K and remain intact after tens of firing cycles. Current programs responsible for development of this technology expect the fuels to withstand temperatures in excess of 2550K under a similar duty cycle. Experiments that subject fuels to these conditions are being conducted to provide data and performance information for optimization and potential down-selection of the candidate materials. Initial tests will be designed for laboratory benchtop operation and will not expose surrogate specimens to the hydrogen working fluid or irradiation fields. The primary focus of these out-of-pile (OOP) experiments will be to study thermal performance and thermal failure limits of the candidate specimen materials.

OOP testing will provide proof-of-principle performance characteristics of the surrogate fuel in an electrically heated benchtop enclosure. The enclosure will be designed to mirror future in-pile capsule enclosures, where surrogate and fueled specimens will be heated through nuclear fission and gamma heating. This enclosure device must be robust and instrumented to test the surrogate specimen and ensure accurate and reproducible conditions can be achieved, thereby producing benchmark data for subsequent fueled experiments. This paper describes the OOP enclosure design, which includes materials selection for various components, preliminary heat transfer estimations, and instrumentation options for the experiment.

I. BACKGROUND

Nuclear thermal propulsion (NTP) technology is intended to provide propulsion by deriving thrust from a hydrogen working fluid that is heated via a thermal or fast nuclear reaction. This technology generates very high specific impulse (900 s) and thrust (1.1 MN); the former parameter is estimated to be over twice the specific impulse of contemporary chemical combustion rockets (Ref. 1). Domestic research and development traces its roots to the Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) program that was in operation from 1955 through 1973. During that time, multiple NTP engines were developed and tested to withstand multiple firing cycles and high temperatures (<2400K) (Ref. 2). After the Rover/NERVA program was discontinued, most domestic research and development for a high-temperature NTP fuel system was halted. Over the course of the next two-and-a-half decades, smaller efforts were made to model and improve potential NTP fuel technology, but no significant concerted effort to revive this technology was made. However, the United States' National Space Policy issued in 2010 dictated that "by 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth" (Ref. 3). To support this policy, National Aeronautics and Space Administration (NASA) and the US Department of Energy (DOE) have resumed efforts to qualify a propulsion system that uses nuclear fuel with a hydrogen working fluid in lieu of the less efficient chemical rocket system (Ref. 1).

A major component of this work is to demonstrate the usage and performance of the NTP system. As stated above, huge strides were made in the 1960s and 1970s to bring this technology into a mature state. Unfortunately, most of the equipment and key personnel who pioneered this work have been lost to time, and much of this development must be reproduced. The Rover/NERVA program did leave a reasonable amount of technical data to aid current researchers in jump-starting a modern NTP fuel program to support future crewed missions to Mars.

II. OUT-OF-PILE EXPERIMENT ENCLOSURE DESIGN

The out-of-pile (OOP) experiment system is being developed to provide performance data for NTP fuel surrogate materials (i.e., those not containing uranium) to aid in optimization of fabrication parameters and down-selection of potential NTP fuel candidates and to establish benchmark data for future irradiation experiments. This information will be gathered by exposing the surrogate fuel materials to prototypic temperatures and performing material characterization on the samples to understand degradation of material properties such as toughness, tensile strength, grain structure as a function of thermal cycling. The current fuel development program requires that the fuel withstand temperatures in the range of 2550 K–2900 K under a duty cycle similar to those performed in the NERVA program (Ref. 1, 4).

The experiment enclosure is designed for three basic functions:

- Provide electrical heating (directly, through induction, etc.) to allow the specimen to achieve target temperatures,
- Be flexible to accept various direct and indirect instrumentation techniques, and
- Impart and maintain a controlled vacuum or inert atmosphere.

The enclosure must be hermetically sealed and able to sustain high-vacuum conditions or possibly slight levels of internal pressurization (i.e., maintain an internal inert atmosphere). It is expected that, during thermal cycling, the enclosure will be flooded with hydrogen or helium to simulate thermal shock stresses and accelerate cooling of the fuel surrogate. The internal contents of the container should also be easily accessible, so that the samples may be loaded and retrieved for post-heat testing. Therefore, Conflat® flanges with metal gaskets were selected as a versatile, off-the-shelf solution for sealing any penetration in the experiment containment. Aside from being vacuum tight and pressure resistant, these flanges can be modified to contain power pass-through connection, tubing fittings, and optical windows, which provides experiment interface flexibility to instrument and power the OOP experiment. Fig. 1 shows a conceptual rendering of the enclosure.

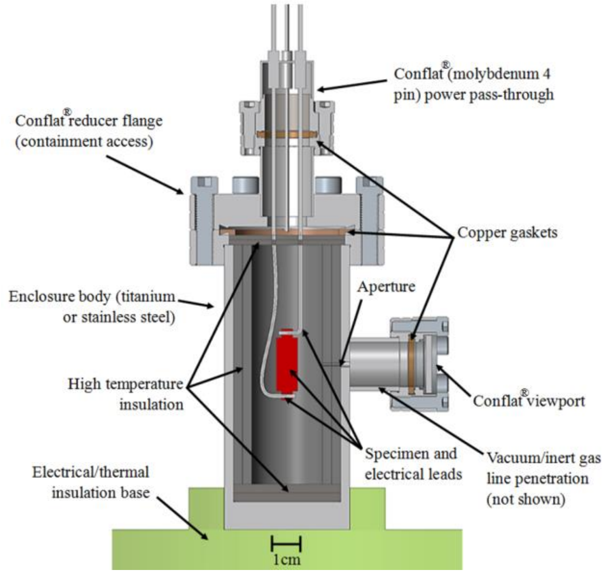

Fig. 1. Out-of-pile experiment enclosure concept.

The OOP enclosure is being designed to mirror future irradiation experiments, in which surrogate and fueled specimens will be heated via nuclear fission. This aspect of the experiment is important to note because the data produced by the OOP experiment must be justified as usable for benchmarking the performance of the irradiation experiments, which may have less sophisticated instrumentation schemes and be passively controlled.

II.A. Materials Selection for the OOP Enclosure

The external containment material was selected considering weldability, thermophysical properties, and radiation tolerance and activation. Initial candidates include aluminum-6061, 300 series stainless steel, and grade 5 titanium. However, welding aluminum alloys can be extremely challenging due to the formation of porosity in the weld joint resulting from surface contaminations (e.g., Al_2O_3, hydrocarbons, contaminated shield gas), and dissolution of hydrogen gas from the weld metal during solidification (Ref. 5). On the other hand, stainless steel alloys and titanium alloys, when welded under a tightly controlled atmosphere, generally have good weldability (Ref. 6, 7).

Thermophysical properties of interest to this study include structural properties and thermal conductivity. The latter parameter is crucial because of the heat transfer implications at the boundary (i.e., heat sink). Aluminum alloys have very high values of thermal conductivity, where both stainless steels and titanium alloys have roughly an order of magnitude less than that of aluminum (Ref. 8). However, given that all candidate materials are metal alloys, stainless steel and titanium still have moderately good thermal conductivity.

The final criteria are radiation tolerance and activation. While all candidate materials have reasonably good resistance to irradiation damage (i.e., swelling and embrittlement), stainless steel tends to highly activate with isotopes such as ^{59}Fe and ^{60}Co. These two isotopes have decay schemes that produce high-energy gamma radiation, making the material somewhat harder to ship, handle, and dispose. Grade 5 titanium activation products are much more attractive than stainless steel. Given that grade 5 titanium exhibits superior welding, acceptable thermal conductivity, and minimal activation, it is the best choice for the OOP enclosure material.

The enclosure internal atmosphere operates under vacuum or inert gas conditions. Therefore, heat transfer from the fuel surrogate will be primarily controlled by radiation and convection. However, a suitable insulating material is required to ensure the extremely high target temperatures are met. SIGRATHERM® GFA soft graphite felt (SGL Group, St. Marys, PA) is an ideal candidate insulator. This material is compliant, easily cut and shaped, and manufactured in thicknesses that range from 3 mm to 11.5 mm. SIGRATHERM® has extremely low thermal conductivity (~0.13 W/m-K at 1000°C) and usable range up to 2200°C (Ref. 9). It can be used in both vacuum and inert atmospheres, with comparable thermal conductivity performance over a wide temperature range.

Graphite is also compatible with reactor applications, but this material tends to swell under irradiation due to neutron damage, which leads to a sizeable amount of internal energy in the material. The stored energy can spontaneously release (referred to as the Wigner effect) at a threshold irradiation temperature of roughly 200°C (Ref. 10). However, the felt density is roughly 4% of solid graphite, and negative impacts on thermal performance of the insulator (and enclosure) resulting from graphite swelling and release of Wigner energy should be minimal.

II.B. Preliminary Heat Transfer Estimations

A simplified one-dimensional, r-θ finite element analysis model was generated using ANSYS® finite element analysis software to estimate power requirements for the OOP experiment. The software resident radiation and conduction solvers were used to solve the enclosure thermal problem. However, custom contact conductance methods developed by researchers at Oak Ridge National Laboratory were incorporated to assist in modeling the heat transfer between the insulation and enclosure contact interface (Ref. 11). This scoping calculation assumes a monolithic graphite specimen is encapsulated in a vacuum environment, with graphite felt insulators. Heat transfer is dominated by radiation between the specimen and the insulator and relies on conduction between the insulator and enclosure wall. It should be emphasized that the emissivity values used for this calculation are taken from commercially available data and are fraught with performance uncertainty. Therefore, prototyping the experiment—higher dimensional modeling of the experiment—will provide more accurate thermophysical properties and performance data for the enclosure. Note that the ultimate heat sink boundary condition is assumed to be 50°C. Fig. 2 shows a contour plot of the analysis results.

This study showed that less than 1 kW of electrical power should be sufficient for bringing the fuel surrogate to 2760K (2489°C), assuming negligible heat losses through the electrical leads. Electrical conductivity of carbon is relatively high, which implies a low voltage–high current power supply will likely be required to heat the OOP experiment. Operating the experiment with the enclosure flooded with an inert gas such as helium or argon is also possible. The heat input can be scaled to account for higher gas thermal conductivities. This estimated power demand is on the order of 8–10 kW.

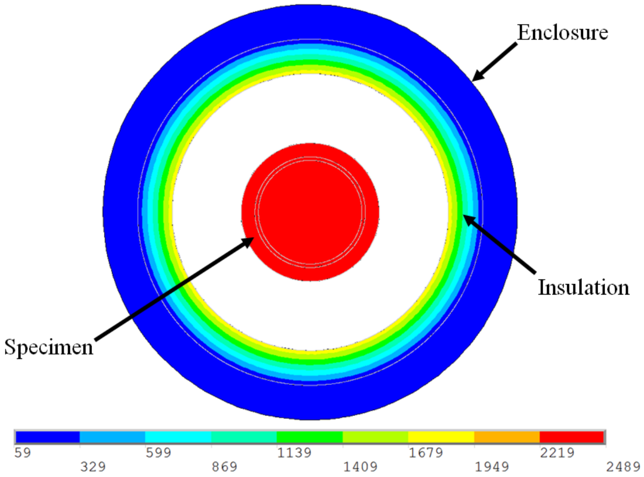

Fig. 2. Temperature contour plot results (°C) for the OOP experiment.

II.C. Instrumentation Options

Instrumentation for this experiment can either be directly measured with a high-temperature thermocouple or indirectly measured with optical diagnostics. High-temperature thermocouples made from tungsten–rhenium alloys have operating temperatures up to 2000°C. They tend to be very brittle and can deteriorate in the presence of oxygen at high temperatures. However, these instruments have been in use for decades and have good reliability when used in an inert or vacuum environment (Ref. 12). On the other hand, thermocouples can be sources of heat loss, given that they are in direct contact with the experiment. Therefore, having a complimentary indirect temperature measurement method is favorable.

Measuring infrared light intensity is a reliable indirect temperature measurement technique that is well suited for this experiment. However, certain emission spectrum characteristics for the fuel surrogate must be known to select the appropriate instrument. It was shown that graphite nanotubes have an emission intensity peak that corresponds with 1–2 μm light wavelength at 2600K. This implies that a shortwave infrared (SWIR) camera may be used to detect this signal. A suitable camera is the FLIR® A6261sc InGaAs, with an operability range of 0.9–1.7 μm.

Both the thermocouple and SWIR camera will be used to measure temperature data. Independent measurements can be made with both systems, and the resulting data will be compared to verify consistency between the two systems and to ensure the accuracy of the optical diagnostic system. Furthermore, the thermocouple can be used to calibrate the optical diagnostic system.

III. CONCLUSIONS

This work details the OOP experiment enclosure that will be used to test fuel surrogates to support nuclear thermal propulsion technology. The paper establishes high-level design requirements for this experiment and lays out a suitable enclosure that will be used to test fuel surrogates in a laboratory environment. Various details that include material selection, power (i.e., heating) requirements, and instrumentation options are also described. Future work will include fabricating and assembling the experiment enclosure, as well as testing graphite surrogate specimens to demonstrate the experiment performance. The experiment is also designed to be general enough to test actual fuel surrogates such as cermet and carbide materials.

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