Hyperthermal Environments Simulator for Nuclear Rocket Engine Development

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Abstract. An arc-heater driven hyperthermal convective environments simulator was recently developed and commissioned for long duration hot hydrogen exposure of nuclear thermal rocket materials. This newly established non-nuclear testing capability uses a high-power, multi-gas, wall-stabilized constricted arc-heater to produce high-temperature pressurized hydrogen flows representative of nuclear reactor core environments, excepting radiation effects, and is intended to serve as a low-cost facility for supporting non-nuclear developmental testing of high-temperature fissile fuels and structural materials. The resulting reactor environments simulator represents a valuable addition to the available inventory of non-nuclear test facilities and is uniquely capable of investigating and characterizing candidate fuel/structural materials, improving associated processing/fabrication techniques, and simulating reactor thermal hydraulics. This paper summarizes facility design and engineering development efforts and reports baseline operational characteristics as determined from a series of performance mapping and long duration capability demonstration tests. Potential follow-on developmental strategies are also suggested in view of the technical and policy challenges ahead.

Keywords: Nuclear Rocket Engine, Reactor Environments, Non-Nuclear Testing, Fissile Fuel Development.

INTRODUCTION

Solid core nuclear thermal rocket (NTR) engines, which directly heat hydrogen propellant in high temperature fuel elements, represent a practical alternative for effective deep space transport of large masses and people but only if reactor core temperature can be made to approach or exceed 3000 K. The enormous performance potential of nuclear thermal propulsion was long ago recognized, and several large technology development programs were instituted at US National Laboratories and former Soviet Institutes during the 1960's for the purpose of realizing a practical nuclear flight engine.   These programs were well funded, well led, and well directed, and great technological strides were indeed made toward this goal before the need faded in importance and projects were defunded and canceled (Beveridge, 1965; Durham, 1969, 1972; Balcomb, 1972; Koenig, 1986; Robbins and Finger, 1991; Wetch *et al*., 1991; Ponomarev-Stepnoi *et al*., 1999). It should be noted, however, that these efforts did reveal a number of performance and life limiting mechanisms for graphite- and carbide-based fuels that were never fully resolved. Of principle significance was the observation that many interrelated and competing physical processes were acting in concert to degrade structural integrity and accelerate fuel mass loss (Taub, 1975; Lyon, 1973; Storms *et al*., 1991; Pelaccio *et al*., 1995). Chief among these were the formation of liquid, vaporization (sublimation), creep of material defects, local corrosion, and structural degradation.

All of these highly complex physical phenomena give rise to challenging reactor core design problems, and straightforward engineering solutions are generally difficult to identify and implement. The critical technical obstacle to a practically useful NTR engine, therefore, continues to be the development of innovative high-temperature reactor core materials that can endure 2500–3000 K hydrogen environments with minimal corrosion under pressures in excess of 3 MPa while also possessing sufficient strength and resilience to resist breakage from intense vibration loads and thermally induced stresses (El-Genk and Pelaccio, 1994). Moreover, the need to optimize propulsion system power density invariably leads to extremely high radiation flux operating conditions, which can create material point defects as an onset to cracking thereby accelerating corrosion rates.

In view of the limited knowledge on phase relationships and stability of these carbon systems as well as the significant advances in high temperature material formulations and processing over the intervening years, it is suggested that reactor fuel technology be revisited and thoroughly re-examined prior to embarking on a modern NTR engine development path. Promising contemporary approaches for realizing additional extensions in operating temperature and lifetime, for instance, include utilization of modern coating techniques and advanced high-temperature materials such as uranium bi/tri-carbides, carbon-nitrides of U and Zr, and CERMET based on a W matrix.

A critical obstacle to the development of these engines is the high-cost and safety/security concerns associated with developmental testing in nuclear environments. A key innovation for circumventing this obstacle is the utilization of non-nuclear test and evaluation methods for reactor fuel/structural materials development and for thermal-hydraulic simulation. Previously, R&D efforts under NASA's Prometheus Program resulted in the development and demonstration of a basic arc-heated hyperthermal environments simulator for long-duration exposure of material specimens under the corrosive action of hot hydrogen at temperatures as high as 3000 K (Litchford *et al*., 2007), but it was subsequently deactivated and mothballed due to shifting agency emphasis and funding restrictions. This paper describes recent efforts to resurrect and reactivate this unique non-nuclear testing capability.

This innovative technical approach utilizes a high-power multi-gas arc-heater facility to generate hot hydrogen flows with the appropriate thermal-hydraulic characteristics for exposing small material specimens to a simulated reactor environment in an attachable test fixture, as illustrated in Fig. 1. The purpose of this baseline testing capability is to enable low-cost science-based screening of candidate material specimens and to identify those methods worthy of more in-depth study and systematic development. The fundamental idea is to produce small, cheaply fabricated material specimens using state-of-art processing and manufacturing techniques and to expose these specimens to relevant hot hydrogen environments, excluding radiation effects. Materials and processing techniques could then be perfected by following an iterative developmental testing approach whereby understanding and knowledge gained from post-test analysis and inspections are used to validate physics based modeling efforts and improve fabrication/processing techniques. It is believed that this type of non-nuclear strategy will be most cost effective for arriving at optimal material candidates prior to engaging in actual nuclear environments testing, which can be orders of magnitude more expensive to conduct.
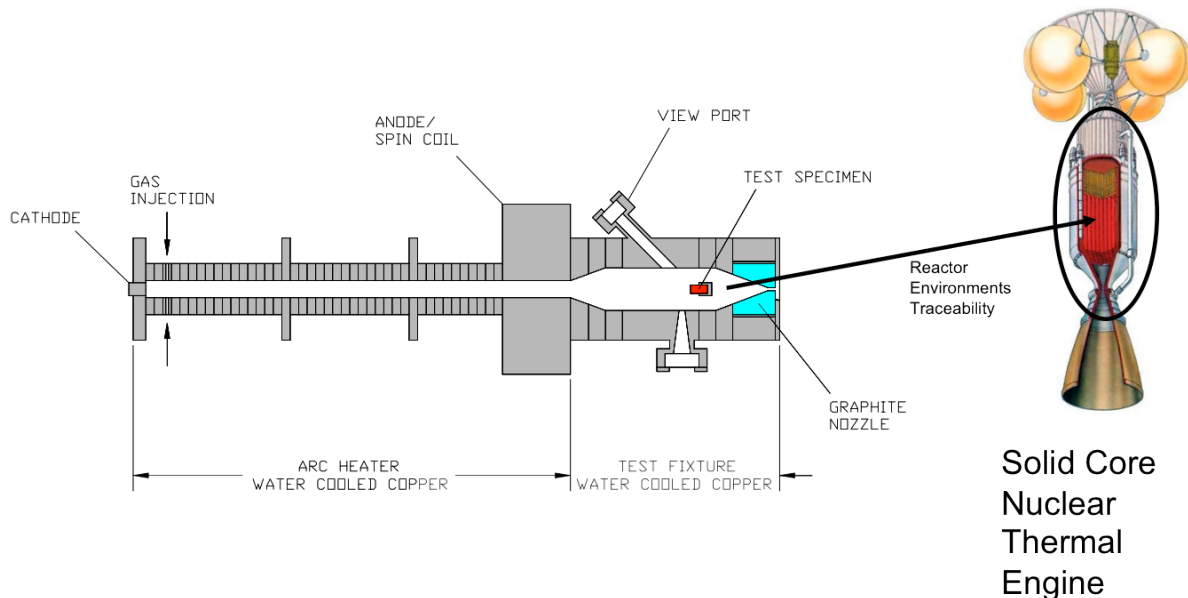

FIGURE 1. Schematic of Arc-heated hyperthermal environments simulator.

FACILITY, HARDWARE, AND INSTRUMENTATION

The basis for the hyperthermal nuclear reactor environments simulator is a 1-MW multi-gas arc-heater facility with attachable water-cooled test fixture in which small material specimens can be installed for long-duration hot hydrogen exposure. To support initial capability demonstration testing, a CERMET surrogate fuel materials specimen was fabricated and prepared by NASA-MSFC personnel. Detailed descriptions of the arc-heater facility, test fixture hardware, and material specimen are provided in the following subsections.

Multi-Gas Arc-Heater Facility

The hyperthermal conditions for simulation of NTR reactor core environments are generated by a 1-MW_e (nominal) multi-gas segmented arc-heater, which operates in a wall-stabilized constricted arc DC discharge mode. This device was originally developed by Aerotherm Corporation in Mountain View, CA more than 30 years ago, but was decommissioned and transferred to NASA-MSFC in 1998 with the intent of supporting propulsion materials development and qualification testing, primarily solid motor nozzle materials. The system was never fully utilized as projected, however, and has therefore been generally available to support other R&D test programs, including nuclear thermal propulsion technology development efforts.

This particular arc-heater has a 1-inch internal bore diameter and follows the traditional segmentation design philosophy whereby alternating conductor/insulator wafers are stacked together to form the full length assembly. The 3/8-inch thick heat conducting copper segments are water cooled and are separated by boron nitride insulators in stacked pack subassemblies, which are held securely together by four Inconel-718 tie rods. These subassembly packs are then attached in a sequential manner to form the full arc-heater column, which spans an overall length of about 1 meter in the three-pack configuration shown. The working gas is injected tangentially through four 0.048-inch jets in a Primary Gas Injection (PGI) segment near the rear of the arc-heater, and a DC arc discharge is established between a tungsten cathode button in the rear sealing flange and a copper anode ring at the arc-heater exhaust. A magnetic spin coil is located around the anode ring to induce continuous rotation of the arc attachment point.

In order to start the device at atmospheric chamber pressure, a modest flow of argon is first introduced into the arc-heater and an initial gas discharge is established between the cathode button and a starting segment, which is located just downstream of the PGI segment. The anode power lead is then automatically switched from the starting segment to the anode ring by opening a vacuum contactor, which establishes a stable arc down the full length of the arc-heater. At this point, argon flow can be replaced with the desired working gas and the system can be ramped to the desired operating state.

The arc-heater is energized by a saturable reactor DC power supply capable of sustaining a continuous operating power of 0.75-MW_e on an indefinite basis or delivering an intermittent power burst of 1.5-MW_e for 5 to 10 minutes. This power supply can be configured in either parallel mode (2,500 volts open circuit) or series mode (5,000 volts open circuit) as needed to match the internal impedance characteristics of the gas discharge, and for high impedance hydrogen operation the power supply was therefore configured for series mode operation. Furthermore, the maximum electrical power input to the NTR reactor environments simulator was limited to no more than 750 kW_e in order to fully replicate the long duration reactor burn times (1 to 2 hours) required for most exploration mission scenarios of interest. The achievable hydrogen flow rates over the desired temperature range depend on the arc-heater efficiency characteristics. Historical data on arc-heater performance indicated an expected efficiency in the range of 50 to 60 percent for reactor-like conditions, which implied a hydrogen flow rate of 7 – 10 g/s over a temperature range of 2500 – 3500 K. Pressure effects were found to have only a minor perturbative effect within this temperature range.

Test Fixture Attachment

A modular water-cooled test fixture was previously designed in which small rod-shaped material specimens could be securely mounted and exposed to the arc-heated hydrogen flow through direct attachment to the arc-heater exhaust flange. The test fixture design also included optical access features for real-time pyrometer measurement of specimen surface temperature and for non-intrusive laser-based measurement of the hydrogen thermodynamic state. The baseline design specifications for the test fixture are summarized in Table 1.
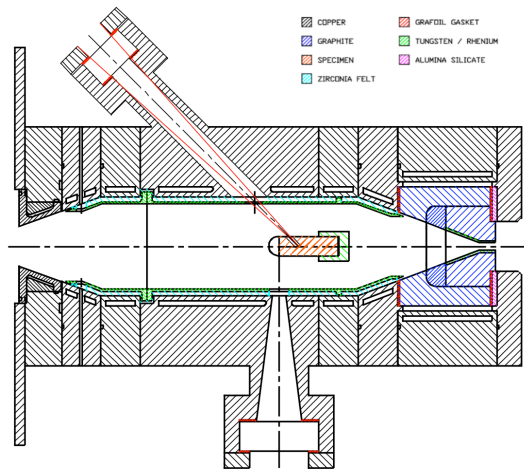
Table legend:
- COPPER
- GRAPHITE
- SPECIMEN
- ZIRCONIA FELT
- GRAFOIL GASKET
- TUNGSTEN / RHENIUM
- ALUMINA SILICATE

FIGURE 3. Test fixture assembly layout.

Table 1. Test fixture design specifications.

T_{max}	3,500 K
p_{max}	35 atm
$\dot{m}_{hydrogen}$	5 – 10 g/s
d_{bore}	2.5 inches
$d_{specimen}$	0.5 inches
$l_{specimen}$	1.0 inches

A detailed mechanical design for the test fixture was developed based on these specifications, yielding the design layout shown in Fig. 2. The test fixture is essentially configured as a stack of water-cooled copper segments including an adaptor attachment to the arc-heater anode section and a converging nozzle section where the flow is throttled through a graphite nozzle with a tungsten throat insert. The mid-section contains features for insertion of a tungsten spider to hold small material specimens (1-inch long, ½-inch diameter rods) and has four windowed ports for optical access. One port is canted to allow pyrometer measurements of specimen surface temperature during exposure. Two diametrically opposed ports allow for focusing of a laser excitation beam at a location just upstream of the specimen nose, and a fourth port is rotated 90° out of this plane for capture of Raman scattering from diatomic hydrogen, which can be used to infer the rotational temperature and number density of molecular hydrogen.

Externally, the test fixture has a length of about 12 inches and a diameter of about 6 inches. Because all cooling water is drawn from a single 350-psig supply manifold, the water passages were sized to have the same pressure drop as the arc-heater segments in order to obtain proper flow rate splitting. This required the milling of 1/8-inch passages into the copper segments, which were sealed with e-beam welded ring plates. Stress considerations for the 2.5-inch inner bore diameter required a 1/8-inch thickness between the water passages and the inner wall surface. These dimensions may be compared with 1/16-inch passages and 1/16-inch wall thicknesses for the arc-heater segments, which have a 1-inch bore diameter.

Thermal hydraulic analyses were performed using an in-house three-dimensional computational fluid dynamics tool to assist in test fixture design and performance assessment. Multi-physics invoked in these analyses include turbulence, hydrogen dissociation, equilibrium thermodynamics, convective heat transfer, and radiation transport. The main goals of this supporting analysis was to quantify chamber wall heat flux and combined heat transport effects on specimen temperature so that the desired exposure conditions could be achieved during materials development tests.

Detailed analyses of a baseline configuration in which the copper wall were directly exposed to the hot hydrogen flow revealed unacceptably high heat flux values, and it was observed that radiation losses from the specimen to the cold copper wall through the highly transparent hydrogen were draining energy and significantly lowering the specimen temperature below the gas temperature. To circumvent these design problems, a 0.060-inch thick W/5%Re heat shield was designed with a 0.125-inch gap between the shield and the copper wall, as shown in the layout drawing of Fig. 2. A ring-shaped dam was also incorporated on the outer surface of the shield to prevent seepage of hot hydrogen flow through the backside gap.

CERMET Material Specimen

A significant component of previous nuclear thermal propulsion R&D efforts at NASA-MSFC was largely directed at materials related technical issues, and one of the principal focal points of these efforts was the development of

fabrication techniques for high-temperature CERMET fuels, such as W-Re/UO$_2$ and W-Re/UN, and carbide fuels such as (U, Zr)C and (U, Zr, X)C. Of considerable special interest was W and W-Re based CERMET materials containing 20-60 volume percent UN or UO$_2$ fuel particles.

Rather than proceeding directly to uranium containing samples, however, conventional processing techniques including press/sinter and Cold/Hot Isostatic Pressing (CIP/HIP) were employed to first fabricate samples containing surrogate fuel particles such as ZrN and HfN. With this approach it was possible to evaluate processing parameters such as particle size, composition, fuel loading, initial consolidation techniques, and sintering and CIP/HIP conditions while also producing specimens that could be exposed to hot hydrogen environments as part of our capability demonstration tests. For our purpose, W-5%Re/40%HfN surrogate fuel specimens were fabricated using a standard HIP/sintering procedure. HfN was chosen as the surrogate since it provided the best CTE match and density. First, high purity elemental W, Re, and HfN powders were blended in a Turbula mixer, and this blended material was then hot isostatically pressed and sintered in billets from which the test specimens were cut into the desired shape and size using a wire EDM technique.

Because of the large uncertainty associated with material emissivity, circumstances likely to be re-encountered in any innovative high temperature fuels development program, it was decided to fabricate the specimen with a small back body cavity into which a pyrometer could focus for emissivity independent determination of temperature. A photograph of a mounted W-5%Re/40%HfN specimen based on this modified design configuration is shown in Fig. 3 where the cavity was formed using a plunge EDM technique.

Figure 3. CERMET specimen with black body cavity.

Real Time Pyrometry

Direct measurement and monitoring of the material specimen temperature during hot hydrogen exposure is critical information for science-based developmental testing. Thus, provisions were incorporated into the test fixture design to provide for real time monitoring of the specimen surface temperature using a commercially available optical pyrometer (MIKRON Infrared Model MI-S140). This particular model uses a single color bandpass at 677 nm with adjustable focal length from 34 to 400 cm and has a laser sighting mechanism for alignment. The temperature range is 1100 to 3500 °C. Calibration of the pyrometer over the temperature range of interest was accomplished via a MIKRON M390 Black Body Calibration Source. For the proposed cavity measurement configuration, direct determination of temperature is independent of the material's spectral emissivity at the target wavelength and we may assume a black body emissivity of unity.

CAPABILITY DEMONSTRATION

Facility Performance Calibration

As a necessary preparatory step, baseline arc-heater performance calibration was established using a short axisymmetric assembly with sacrificial graphite nozzle, which was attached directly to the arc-heater anode flange. The sacrificial nozzle was machined from high-density graphite with a throat diameter matching the final test fixture design specifications so that the proper flow rate and chamber pressure would be produced at the specified mass flow rate and input power settings. This approach provided a reliable method for accurate performance characterization while test fixture hardware was being assembled. Initial facility calibrations with hydrogen had been previously performed during 2006 (Litchford *et al*., 2007), but given the passage of time it was deemed necessary to repeat a number of short duration calibration runs to confirm operational capability and to validate previous facility performance characteristics.

A series of hydrogen calibration runs were executed at selected operating points on the previously established facility performance map. Because steady-state operational conditions could be reliably established within 20 seconds of arc initiation, calibration tests were limited to 60 seconds in duration. Typical parameter traces for a 60-second hydrogen calibration run are illustrated in Fig. 4(a). The results of these hydrogen calibration runs were analyzed and combined with previously obtained calibration data from 2006 to generate the arc-heater performance map shown in Fig. 4(b). Here, the inferred chamber temperature has been correlated as a function of applied current and hydrogen mass flow rate, and the symbols (i.e., red for 2006 and blue for 2010) indicate data points used to construct the map. The chamber temperature at each point was estimated by using the inferred thermal input power to define a pseudo heat of combustion for a NASA CEA based rocket calculation. Analysis results for the new calibration test data were inline with the previous calibration data thereby validating the baseline facility performance map for current operating usage.
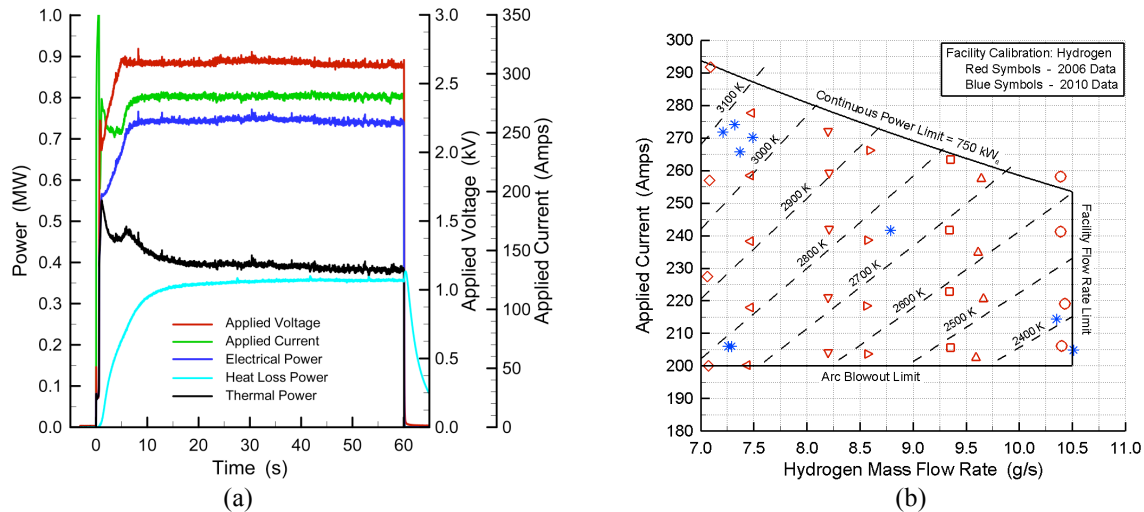

FIGURE 4. Facility performance characterization: (a) typical parameter traces; (b) operating map calibration.

Long Duration Demonstration Tests

The primary objective of this research effort, following establishment of the hydrogen operating map and fabrication of the test fixture hardware, was full-up assembly and execution of basic capability demonstration tests. These tests were principally intended to demonstrate long duration hot hydrogen operation, validate hardware, expose any major design flaws, and evaluate a pyrometer diagnostic for real-time monitoring of specimen surface temperature.

Test Results

From an operational perspective, full demonstration testing necessitated an ability to ramp and hold arc-heater power level while controlling primary and dilution flow rates as well as an ability to maintain thermally stable operating conditions over a time interval representative of a nuclear thermal rocket engine burn. In order to demonstrate both performance and operational goals, it was therefore decided to conduct back-to-back 30-minute duration tests on the same day with the former targeting a moderately energetic flow condition and the latter targeting an extreme hyperthermal flow condition.

The first attempt, designated as Test-I, was restricted to the high end of the established flow rate range with a steady-state set-point corresponding to 10 g/s hydrogen and an arc column current of approximately 260 amps. With reference to the performance map in Fig 4(b), we therefore anticipated a nominal gas temperature close to 2700 K. From a technical perspective, it was felt that this particular state point would be less stressful on the hardware for a first test yet would be energetic enough to effectively demonstrate practical testing capability. To reach the desired on-point state condition, the facility would be started at 10 g/s and 205 amps with hydrogen dilution flow added through secondary injection ports to limit thermal shocking intensity. Once facility operation becomes stable at this initial startup condition, the arc column current is automatically ramped to the desired set-

point current while the hydrogen dilution flow is simultaneously ramped to zero. The facility is then held at final set-point conditions for the remainder of the 30-minute test duration.

The second follow-on attempt, designated as Test-II, was intended to fully validate hardware design and systems operability under extreme hyperthermal flow conditions within the low flow rate operating regime using a steady-state set-point corresponding to 7 g/s hydrogen and an arc column current of approximately 290 amps. Inspection of the facility performance map in Fig. 4(b) would therefore indicate an anticipated nominal gas temperature near 3100 K. As in Test-1, the facility would be started at 10 g/s and 205 amps with hydrogen dilution. Ramping to the set-point condition would then occur in two steps. First, the flow would be automatically ramped down to 7 g/s while holding current constant. Then, the current would be ramped to the final set-point value while holding the flow rate fixed. The facility is then held at final set-point conditions for the remainder of the 30-minute test duration.

Both long duration firings were successfully run back-to-back on 9 Sept. 2010 according to test plan. Following completion of Test-1, the nozzle retainer plate and nozzle were immediately removed to allow for internal inspection of the test fixture hardware and material specimen, both of which were found to be in excellent condition. The nozzle and retainer plate were then reinstalled, and facility preparations and sequence changes were implemented for the follow-on test. Test-II was initiated within 2 hours of the first test thereby demonstrating rapid facility turnaround and highly flexible operations capability. Images of the test fixture and plume from both long duration tests are shown in Fig. 5.
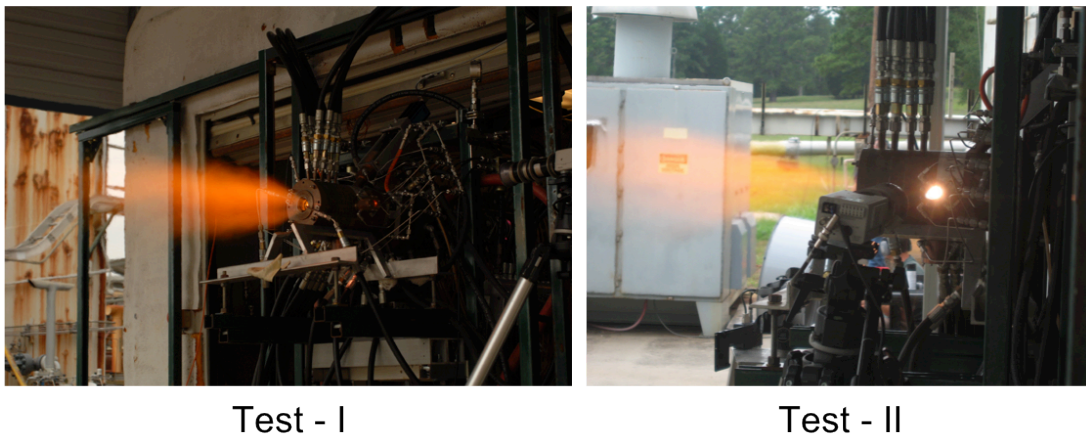

Test - I   Test - II

FIGURE 5. Images of test fixture and hydrogen plume during long duration tests.

Following the initial start-up/ramp transient, the arc-heater facility exhibited excellent on-point stability characteristics and the monitored operational parameters displayed little or no drift/fluctuations. Both tests ran for the full 30-min duration, and the key time-average test parameters are summarized in Table 2 along with results of the single 26-min demonstration test from 2006. Note that the actual arc column current was slightly higher than the desired set-point value, which yielded input power levels a little higher than intended though within acceptable bounds. This inability to set the actual input power with high accuracy is a byproduct of the power supply control scheme since the set-point saturable reactor current is not directly correlated to power supply output current.

Given the time-averaged current and hydrogen mass flow rates, we may reliably deduce the arc-heater efficiency using correlations derived from the facility calibration test data. This efficiency value can then be used to deduce the hydrogen enthalpy at the test fixture entrance, which may be subsequently used in combination with the measured chamber pressure as input to the NASA CEA code for obtaining a temperature estimate of the hydrogen gas impinging the material specimen, as summarized in Table 1.

Specimen temperature traces via real-time pyrometer measurements are shown in Fig. 6 with the steady-state equilibrium hydrogen gas temperature overlain as a dashed line. Here, we observe that the specimen temperature is lower than the implied gas temperature by 300 – 400 K due to radiation losses to the heat shield. This level of radiative heat loss was higher than expected but within acceptable bounds for near term testing requirements supporting NTR fuels development. Over the long term, reductions in radiation losses through evolutionary design modifications will be required to meet projected ultra high-temperature conditions for hot hydrogen material exposure testing.

Table 2. Time-averaged performance parameters from long duration demonstration tests.

	2006 Demo	Test-I	Test-II
Applied Voltage, V (volts)	2843	2814	2436
Applied Current, I (amps)	243.8	274.6	311.9
Applied Power, P (kW)	693.1	772.5	759.7
Heat Loss, Q (kW)	317.4	360.8	360.1
Efficiency, η (%)	54.2	53.3	52.6
Flow Rate, $\dot{m}$ (g/s)	10.3	10.09	7.11
Chamber Pressure, p_c (psig)	148.7	160.6	121.8
Equilibrium Gas Temperature, T_g (K)	2516	2716	3157
Measured Specimen Temperature, T_s (K)	—	2431	2789
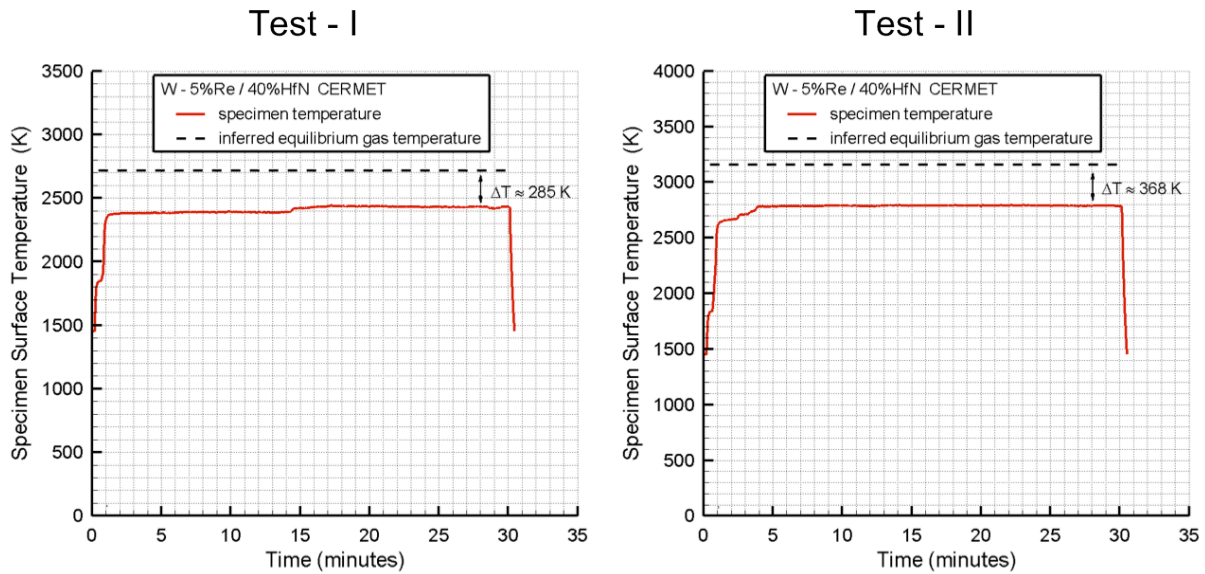
FIGURE 5. Specimen temperature traces via real time pyrometry.

Observations and Lessons Learned

At the conclusion of the long duration test series, the apparatus was completely disassembled for detailed inspection. No serious deficiencies were uncovered, and, generally speaking, test fixture hardware fully met performance requirements with no major design flaws or operational limitations. Post-test visual inspection of the graphite nozzle and tungsten throat insert did indicate significant erosive action, particularly hydrogen erosion of the graphite at extreme temperatures, but the observed erosion rate was low enough to accommodate long duration testing requirements. Thus, the expendable nozzle design approach was deemed minimally adequate for future practical usage. For improved durability and operational robustness, however, fabrication of a reusable pure tungsten nozzle would be strongly recommended.

Following the previous long duration exposure test during 2006, post-test inspection of the W-5%Re/40%HfN CERMET specimen revealed the formation of a gold-like discolorization between granular structures at the material surface. The specimen also experienced significant swelling during that initial exposure test, expanding from 0.500-inch $\varnothing$ to 0.512-inch $\varnothing$ (i.e., 2.4%). Both the discolorization and swelling were attributed to a hot hydrogen induced reaction with the HfN, although this was not rigorously confirmed through analysis.

During the internal inspection following Test-I and preceding Test-II, no notable changes in the CERMET specimen were visible other than this ubiquitous gold-like surface discolorization. Upon completion of Test II at extreme hyperthermal conditions, however, the CERMET specimen was removed from the test fixture and found to have undergone extreme melting as shown in Fig. 6, which indicates a gold braze-like melt flow down the sides with a globular structured residual melt zone at the nose. This was extremely surprising since all of the constituent materials in the CERMET have melting temperatures much higher than the measured specimen temperature during hot hydrogen exposure (2789 K). Current evidence points toward the unexpected formation of a ternary eutectic, but further detailed analyses will be required to reach a conclusive explanation.
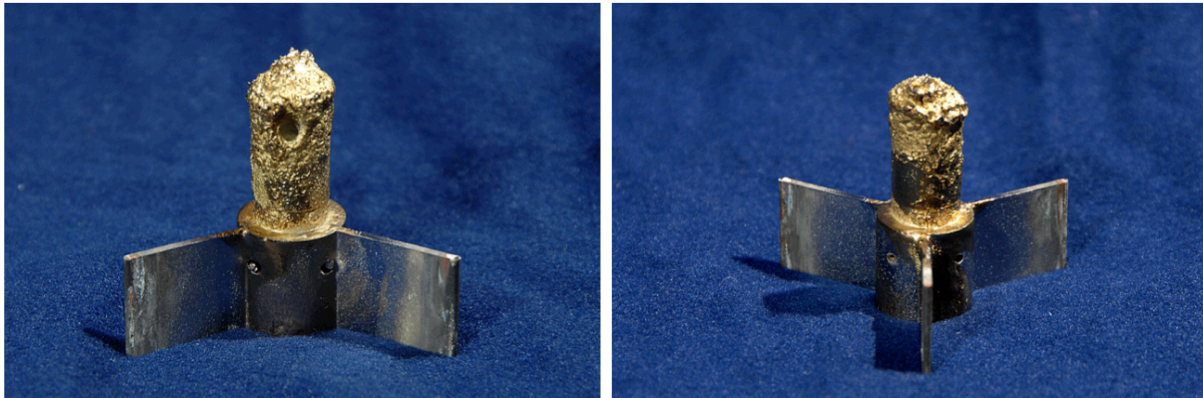

FIGURE 6. Effects of long duration W-5%Re/40%HfN CERMET exposure to hyperthermal hydrogen flow.

CONCLUSIONS AND RECOMMENDATIONS

Demonstration testing of an arc-heated hyperthermal environments simulator capable of generating hot hydrogen flows directly traceable to nuclear rocket reactor core conditions represents a new and valuable national asset to the inventory of non-nuclear testing capabilities and an important option for low-cost exposure and screening of candidate fissile fuels and reactor materials. These efforts bring to fruition years of dedicated work and effort by numerous participants and mark full readiness for supporting future nuclear rocket engine development programs.

The baseline design is far from being fully evolved to its ultimate potential, however, and preliminary engineering design studies have been undertaken for various evolutionary design modifications that could greatly expand usefulness and impact. Strategies for integrating this non-nuclear testing technology into materials development programs have been formulated, based on critical consultations with high temperature materials experts.

The resulting reactor environments simulation capability is expected to have a real and lasting impact on emerging nuclear rocket development activities. However, the baseline design is far from being fully evolved to its ultimate potential, and preliminary engineering design studies have been undertaken for evolutionary design modifications that could greatly expand usefulness and impact. Along these lines, it is recommended that these design improvements for performance and operational enhancement be implemented and that follow-on efforts be devoted to the strategic integration of this non-nuclear testing technology into future nuclear rocket material development programs.

ACKNOWLEDGMENTS

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