THE USE OF IMMERSION RIGS FOR HIGH TEMPERATURE HYDROGEN EXPOSURE TESTING WITHIN THE NUCLEAR THERMAL ROCKET ELEMENT ENVIRONMENTAL SIMULATOR (NTREES): NTREES-5 HYDROGEN HEAT EXCHANGER (N5HHX-01)

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ABSTRACT

The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) facility at NASA's Marshall Space Flight Center (MSFC) subjects materials and components typically found on nuclear thermal propulsion (NTP) systems to non-nuclear simulations of prototypic NTP reactor thermohydraulic environments. With 1.2 MW of inductive power available, the currently employed methods to simulate nuclear heating in NTREES consist of 1) inductively heating a test specimen, which typically cannot be performed on ceramic materials, or 2) heating gas that envelops the test specimen. The latter of these has provided a basis for developing so-called "immersion rigs" to be used in NTREES. Furthermore, immersion rigs are especially useful in the case of smaller, technically challenging test specimens

One such device, the "NTREES-5 Hydrogen Heat Exchanger" (N5HHX-01), designed and deployed to test small material coupons to ~0.5 g/s of 2800 K, 500 psi Hydrogen, is discussed herein. To achieve this desired delivery temperature level, the most suitable material for the N5HHX's construction was pure tungsten, which imposed budgetary and manufacturing challenges. Also discussed in this paper is the design of the N5HHX rig's sample container, which became the first iteration of improving NTREES small material coupon test operations by permitting rapid changeout of different material samples.

INTRODUCTION

NTREES, the Nuclear Thermal Rocket Environmental Simulator, was designed c. 2005 to experimentally simulate the environment of a Nuclear Thermal Propulsion (NTP) system for the purpose of reactor fuel development. The facility has been utilized heavily in the last decade with the recent reemphasis of Space Nuclear Propulsion technology. Testing and experimentation have largely consisted of fuel and moderator development with test articles mostly constituting sub-length high temperature fuel elements and occasionally heated tests of adjacent system components such as tie tubes. During testing of this type a fuel article is inductively heated to high temperatures (~2500 K) as shown in Figure 1, while high pressure hydrogen gas (<1100 psig) is through-flown [1].

Although the NTREES facility's natural trajectory is to be utilized for high temperature testing of full length elements – development of which is underway – testing of smaller material samples and more discrete system subcomponents at SNP relevant temperatures and pressures must also be possible. To this end the development of specialty rigs in which gas is heated upstream of immersed test samples, or "immersion rigs", is underway. Such rigs permit testing of subcomponents such as a fuel element flow channel liners [2] or more technically challenging fuel forms such as particles (as discussed in a separate submission). Herein is a discussion of the development of an immersion rig designed to expose material coupons (~1.5" Ø x 2" long) to high temperature (>2500 K), high pressure (~500 psig) hydrogen gas (~0.5 g/s).

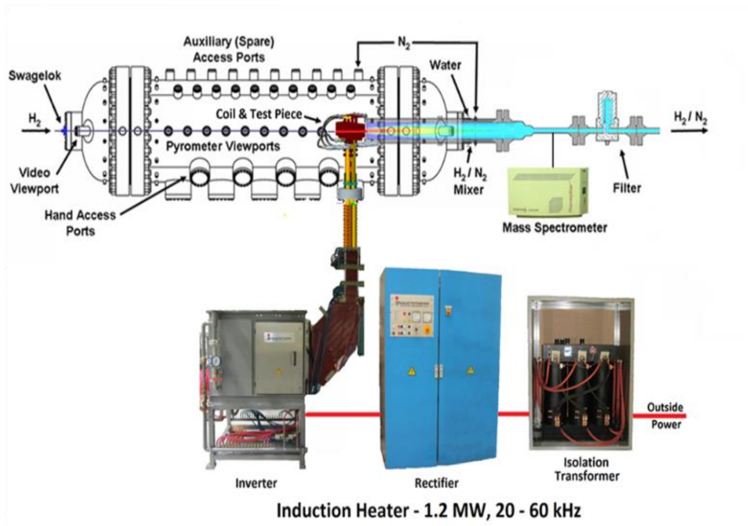

Figure 1: Standard NTREES Testing Configuration

DESIGN AND ANALYSIS

The immersion rig, dubbed the NTREES 5 Hydrogen Heat Exchange (N5HHX-01), is a pure tungsten (99.95%) design (all apart from a single rubber O-ring and a stack of Belville washers for axial spring retention force), 22.5" in length and 2" Ø. The rig design, as shown in Figure 1, consists of an upstream heat exchanger section and a downstream sample volume. As shown in Figure 3, Hydrogen gas enters the inductively heated rig and is directed through a spiral gas path against the hot outer wall of the assembly. The pathway is specifically designed to prolong the dwell time of the hydrogen gas within the heated zone. Exiting the heated zone gas is further directed into the sample volume where test specimen is bathed in the hot gas. The design accommodates relatively low flow rates (<~3 g/s) and the design intent is to deliver heated high pressure hydrogen to the sample volume for sustained exposure experiments.

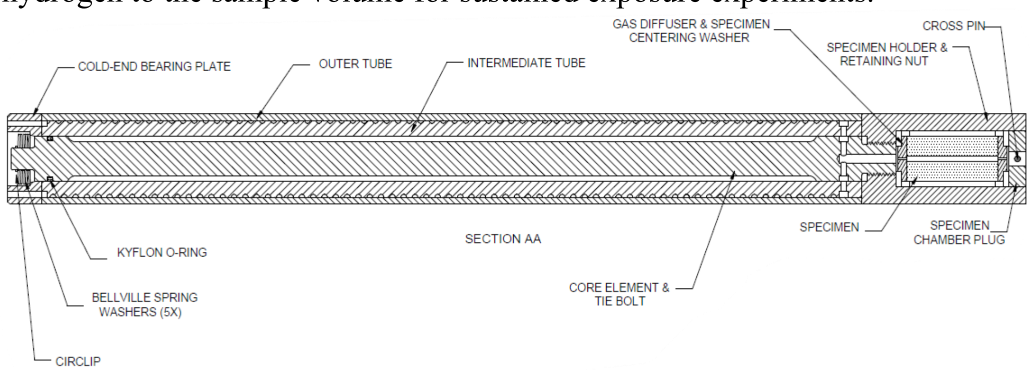

Figure 2: N5HHX-01 Design (Cross Section)

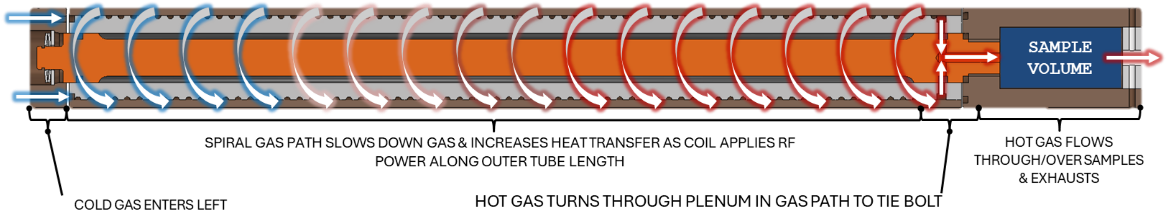

Figure 3: N5HHX-01 Diagramed Gas Routing (Cross Section)

Due to the pure tungsten design, manufacturing rig components presents challenges. Tungsten is hard, requiring much consideration during machining, and brittle, yielding a highly likelihood of chipping during most common operations. Additionally, raw stock is typically expensive and dense making procurement and shipping challenging. The manufacturing process for N5HHX-01 required cutting of spiral grooves and threads, which proved to benefit from slower operations and carbide machining bits. Despite this, in-house machining was a success, with the rig's subcomponents being shown in Figure 4.

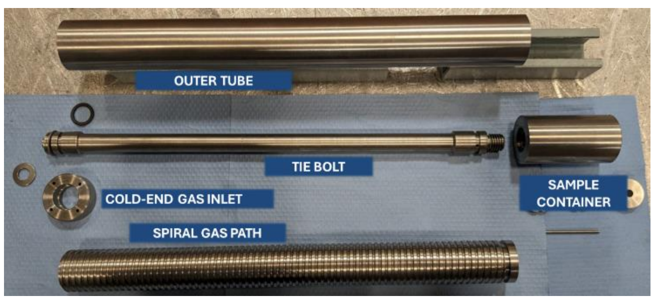

Figure 4: Tungsten (99.95%) Subcomponents of N5HHX-01 Alongside Rubber O-Ring and Stainless Steel Washer

Additionally, for the first trial of this hardware, SiC crucibles were used to retain particle fuel samples. Although the design is flexible and could be used for a variety of material samples within the sample retention volume, the need to retain particle fuel while permitting gas flow drove the selection of foam. This SiC foam was assumed to be hydrogen resistant at test temperatures while permitting flow and particle retention.

A two-dimensional, axisymmetric, steady-state, Multiphysics model was generated incorporating coupled inductive heating and heat transfer of N5HHX-01. Although the rig was originally designed to have a 16" long heated section, a 10" induction coil was ultimately used in the experiment discussed, therefore the thermal analysis reflecting that will be discussed here. The experimental layout utilities in the model can be seen in Figure 5, depicting the rig in NTREES.

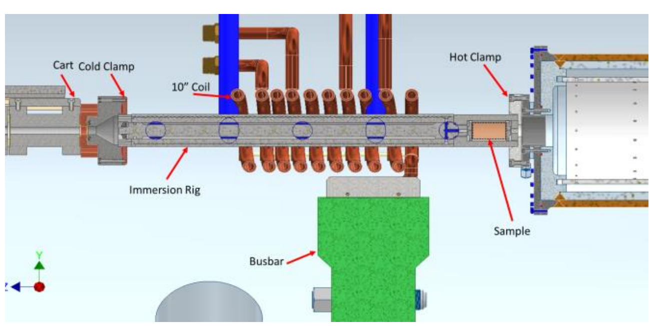

Figure 5: Layout of N5HHX-01 within the NTREES Chamber

A number of thermal model cases were trialed to characterize the rig's anticipated performance ahead of testing. This discussion will focus on a high temperature case in which the targeted temperature of the gas entering the sample volume region is set at 2900 K, the results of which are displayed in Table I. Hydrogen gas pressure was taken to be 1000 psig for this model, and a targeted flow rate of 0.5 g/s was used. This lower flow rate allows the exhausting gas temperature to be driven high due to the increased dwell time of gas within the heated zone. Resultant power required of the system is well within the capability of the NTREES facility, and material temperatures are kept below limits, although significant. Lastly, a trade was made to include silicone carbide (SiC) around the sample container volume for thermal insulation. It was decided not to include this addition in that it decreased material temperature and power required only marginally, and implementation was challenging.

Table I: Thermal Modeling Tabulated Results for N5HHX-01 High Temperature Case

	P_{inlet}	H_2 outlet T	mass flow	Tungsten max T	Tungsten max T location	RMS coil current	RMS coil voltage	coil power	phase angle	thermocouple H_2 T	power deposited into Tungsten	power transferred to H_2	H_2 exit Mach number	pressure drop
	(psi)	(K)	(g/s)	(K)	(in)	(A)	(V)	(kW)	(degrees)	(K)	(kW)	(kW)		(psi)
Without	1,000	2,900	0.5	3,069	15.89	1,719	772	51	87.81	2,242	35	22	0.08	233
SiC Foam	1,000	2,600	0.5	2,717	16.07	1,566	702	40	87.93	1,982	27	19	0.07	199
With SiC Foam	1,000	2,900	0.5	2,999	15.94	1,686	757	48	87.84	2,476	33	22	0.08	233

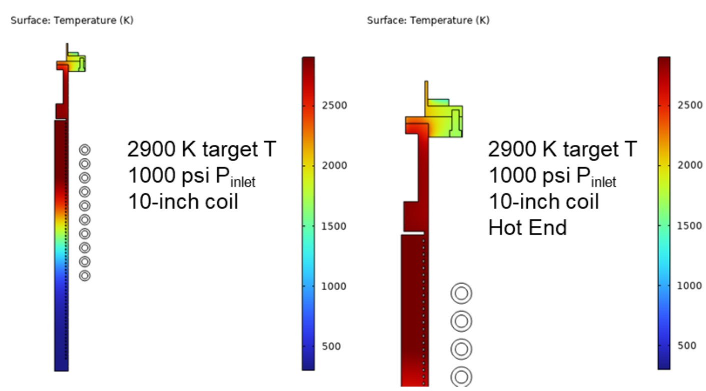

Figure 6: Thermal Modeling Mapped Results for N5HHX-01 High Temperature Case

EXPERIMENTAL APPROACH

As mentioned above the hardware was installed within the NTREES facility pressure vessel and supported axially within an induction coil. N5HHX-01 was supported via a boron nitride hot clamp at the downstream end, proving electrical isolation. This hot clamp is part of an instrumented stack-up that is designed to measure the temperature and pressure of the exhausting hot hydrogen gas while routing it to the water cooled mixer section where it is mixed with nitrogen prior to being exhausted from the facility. A custom cold clamp was used on the upstream end of the assembly and provided gas to the rig. The cold clamp was supported by the NTREES cart assembly which provided electrical isolation and an axially compressive spring force to aid seals.

Surface temperatures of the N5HHX-01 were captures by the NTREES facility's suite of pyrometers, with their focal points distributed along the length of the rig as shown by Figure 7. In addition, two IR cameras were used to capture a side view and a view of the exhaust plenum during testing. Pressures, flow rates, and temperatures of flowing gas are collected across the test bed including pressure chamber gas (argon), mixer volume gas (nitrogen), and axially through-flowing hydrogen.

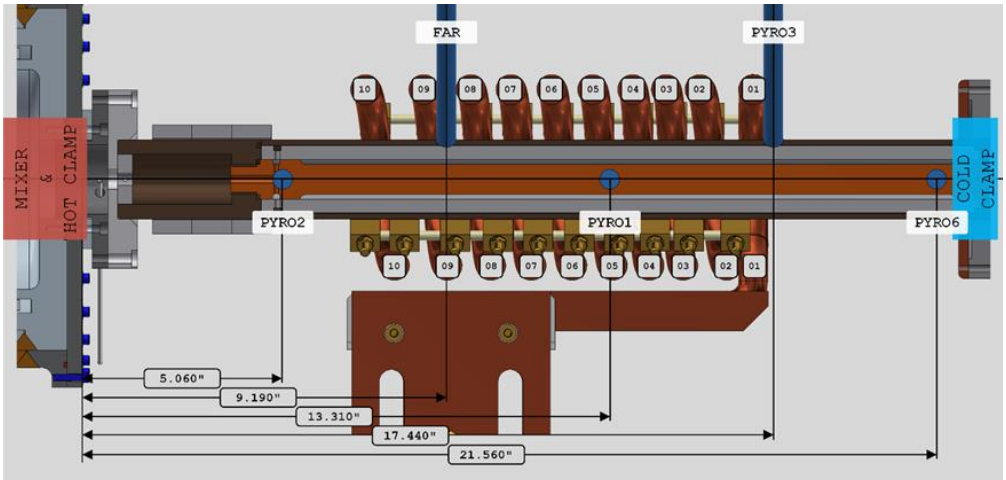

Figure 7: NTREES Pyrometer Suite Focal Point Distribution

Initial installation and checkout tests were performed with a 16" coil and the as-designed hardware, however checkout tests uncovered issues with the rigs performance in this configuration. Gas sealing was a significant challenge, as hydrogen was leaking from interfaces within the rig (tungsten-tungsten) and between the rig and the hot clamp (tungsten-boron nitride). To mitigate leaks, gaskets were added to these interfaces. A groove was cut into the inlet face of the sample container to accommodate graphite packing (seen in Figure 8), greatly improving the sealing at this interface. Similarly, a flat graphite gasket was added to the boron nitride hot clamp, shown in Figure 9. This, along with increasing the compressive load imparted on the assembly, increased the gas seal at this boundary.

Figure 8: Sample Container with Graphite Packing

Figure 9: Hot Clamp Interface with Addition of Graphite Gasket

During these checkout tests, it was also observed that the coil was occasionally arcing to the outer surface of the rig (seen in Figure 10), as recognized by the safety interlock system as an electrical fault, causing it to trip. Despite attempts to mitigate this, it was concluded that the physical gap between the coil's inner bore and the outer surface of N5HHX-01 was too small, and a coil with a larger bore was required. Thus, the switch to a 10 inch coil was made as that specific hardware met this requirement, and ultimately proved to resolve the issue. Further thermal modeling was performed to address the shorter heated length, the results of which were discussed in the previous section.

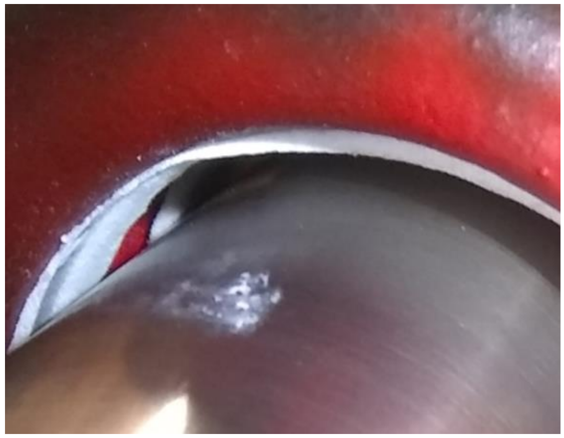

Figure 10: Arc Strike on the Installed N5HHX-01

RESULTS AND CONCLUSION

The results of a specific trial of this hardware, a significant temperature test conducted with fuel samples contained within N5HHX-01, are shared here. Firstly a pressure graph is presented in Figure 11 showing that the hydrogen pressure at the inlet to N5HHX-01 was maintained at approximately 516 psig, chamber pressure (argon) was maintained at 850 psig, and the test rig's back pressure (mixer volume) was held to less than 25 psig, minimizing the migration of nitrogen from the mixer. Pressure at the hot clamp was also very low and tracked very closely with back pressure. This is coupled largely with pressure drop differential across N5HHX-01.

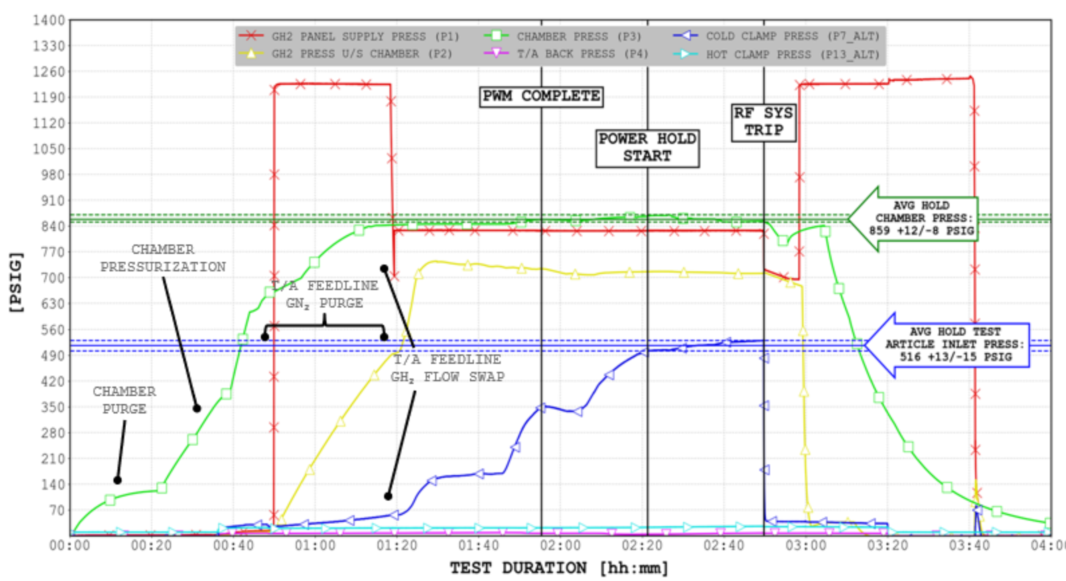

Figure 11: Gas Pressures During Testing of N5HHX-01 Sample Case

Figure 12 presents the flow rates through and pressure drop across the N5HHX-01 during this test trial. Pressure drop across NTREES-5 HX is measured to peak at ~500 psid, having increased by ~50 psi throughout the run. Flow rate is relatively steady and is maintained at ~0.3 g/s. It is speculated that the SiC foam further restricted the assembly. Pressure differential across the article does seem to correlate to temperature (plotted in **Error! Reference source not found.**), likely correlating to components physically shifting within the thermal environment.

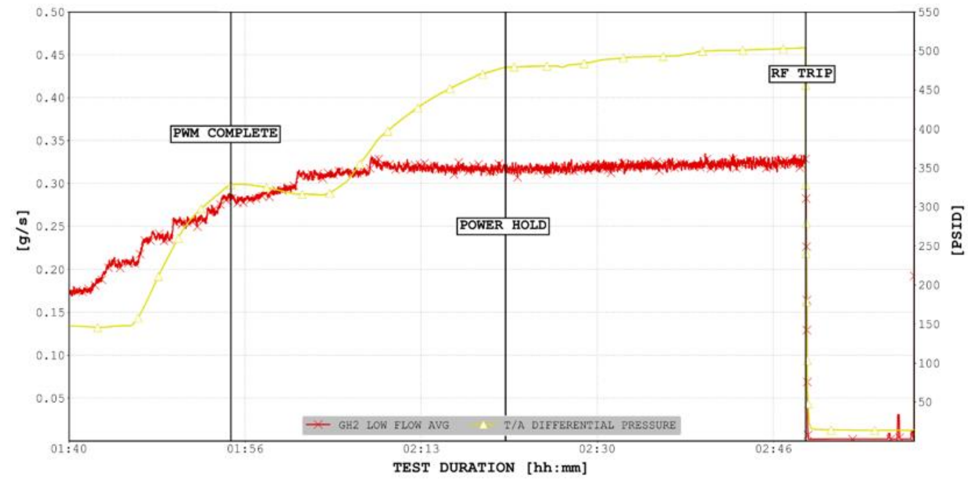

Figure 12: Gas Flow Rate and N5HHX-01 Pressure Differential

Power was held at 110 kW throughout the test's high temperature dwell for approximately 28 minutes before the trial was prematurely ended due to a system trip consistent with arc flashing. This trip was likely caused by suspected chamber effluent (noted during post-test inspection) producing an arc path between coil mount plates. During the test, power ramp rates, as shown in Figure 13, were smooth overall, maintained at roughly 6 kW/min during ramping windows.

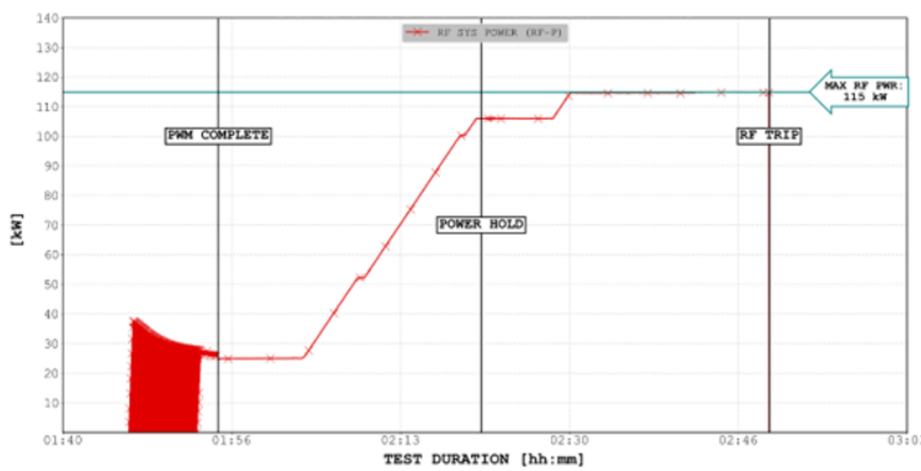

Figure 13: System Power During N5HHX-01 Testing

Temperatures as recorded by the NTREES pyrometer suite are presented in Figure 14. At the high-temperature dwell, the peak surface temperature was held to ~2976 K. Peak temperatures recorded by each pyrometers and IR cameras and their corresponding observation location is presented in Table II, with IR cameras assuming a target surface emissivity of 1.0 and pyrometer emissivities calculated and presented also in Figure 14. Pyrometer 2, located at approximately the inlet to the sample container (Figure 7), informs hydrogen bath (sample volume) inlet temperatures as co-located surface temperature and gas temperatures track closely as represented by thermal models.

Similarly, the exhaust IR camera can inform hydrogen bath exit temperatures. The derivation of this yields that samples were bathed in hot gaseous hydrogen at 1776 K +0/-176K for the ~28mins.

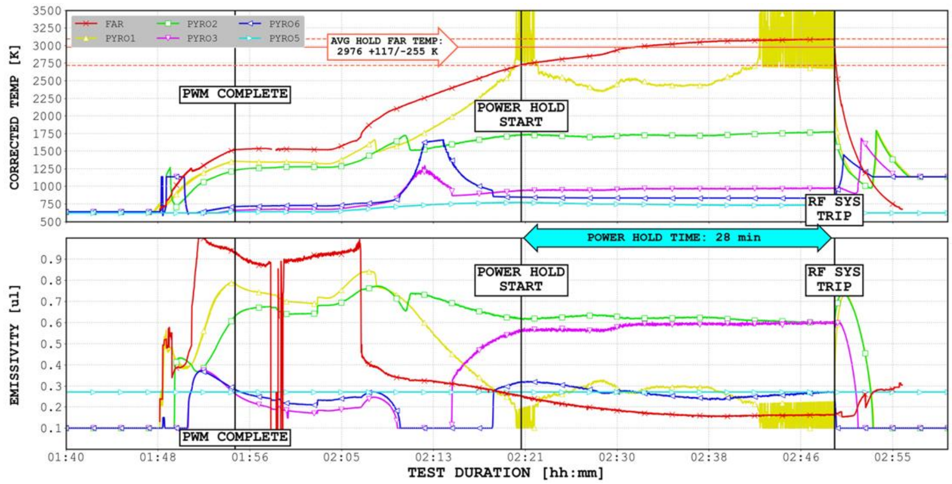

Figure 14: N5HHX-01 Surface Temperatures Reported by Pyrometer Suite

Table II: Peak Surface Temperatures Reported by Pyrometer Suite

Location	Peak Temp (K)
Downstream Cold Clamp	846 (Pyro6)
Before Coil Turn 1	978 (Pyro3)
Between Turns 4-5	--- (Pyro1)
Between Turns 8-9	3093 (Far)
Downstream Coil Turn 10	1776 (Pyro2)
Side IR Temp (Turns 5-10)**	~2873 (Turns 7-9)
Exhaust IR Temp**	1776

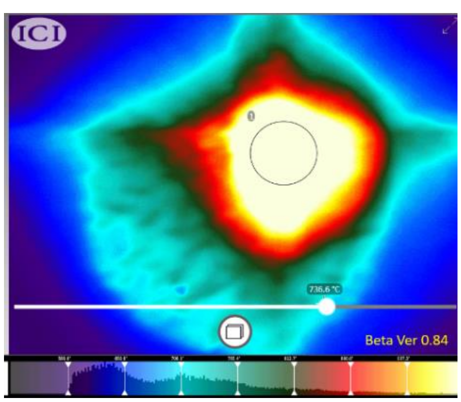

Figure 15: Exhaust IR Camera During N5HHX-01 Testing

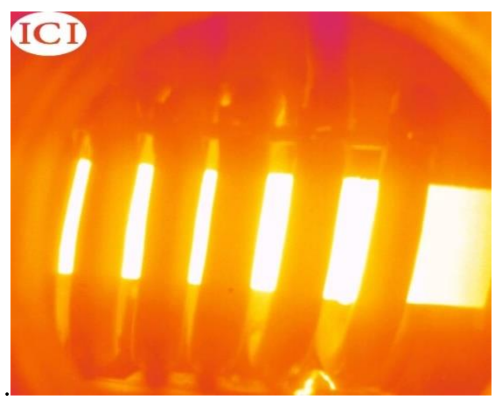

Figure 16: Side IR Camera View Showing Arc Flash

After testing was concluded, particle samples were removed from N5HHX-01 for post-test inspection. Although the results of material testing are not discussed here, evaluation of SiC components showed significant erosion and deformation of the supporting foam structures. The sample volume assembly was disassembled inside a glovebox, with the container split using discrete applications of force and intentionally cracked cleanly down middle, as shown in Figure 17. It was observed that the SiC components had been reshaped significantly during test conduct, shown in Figure 18. The SiC stopper showed erosion but did not provide path for particles out of sample container, meaning particle fuel was retained. The sample container inner walls were coated with residue, brown and white in appearance. Fuel particle samples had left imprints on SiC inner walls, and SiC "pucks" were similarly marred with residue on surfaces in contact with the container walls.

Figure 17: Sectioned Sample Volume Assembly

Figure 18: SiC Components Post-Test

SUMMARY AND FUTURE WORK

Overall the specific high-temperature test discussed here was successful as it exposed fuel samples to hydrogen gas at temperatures and pressures relevant to NTP systems and permitted the necessary prototypic environment compatibility experiment for prospective fuel. Additionally, the N5HHX-01 effort yielded many valuable lessons to the team.

N5HHX-01 proved challenging and will likely need a complete redesign. As the majority of power is deposited onto outer tube during inductive heating, it can be inferred that the outer component grows away from middle tube, decreasing the conductive heat transfer effectiveness and impacting performance. The pressure drop across the immersion rig was significant, and leak paths were impossible to entirely resolve. Graphite gaskets and graphite packing were proven to be well-performing approaches to hot gas seals for hydrogen under pressure when not exposed to a high flow. However, these require significant preloads that are likely impractical for most testing configurations. Lastly, SiC eroded significantly and is likely not a viable choice for this approach.

ACKOWLEDGMENTS

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