THE USE OF IMMERSION RIGS FOR HIGH TEMPERATURE HYDROGEN EXPOSURE TESTING WITHIN THE NUCLEAR THERMAL ROCKET ELEMENT ENVIRONMENTAL SIMULATOR (NTREES): THERMAL SOAK RIG (TSR)

Jacob Ondeck, James Post

NASA Marshall Space Flight Center (MSFC), Propulsion Research and Technology Branch, Huntsville, AL

ABSTRACT

The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) facility was purpose constructed to perform non-nuclear evaluations of nuclear thermal propulsion (NTP) system fuel materials and structures within prototypic thermochemical environments. This system has been utilized steadily in its ability to subject test specimens to thermochemical and thermohydraulic environments simulating that of an operating nuclear rocket engine. Fission heat is simulated by induction power and experiments are conducted within a ~1000 psi pressure vessel. Hydrogen is conventionally passed through the heated fuel surrogate test specimen while pressure, temperature, and gas species data are collected at various points along the experiment. In order to test fuel and material coupon samples, a class of test apparatus named "immersion rigs" are being developed and employed to more rapidly test these smaller and more technically challenging test specimen.

One example of a promising potential fuel structure, Tristructural-isotropic (TRISO) particles, presents unique challenges for testing of this type. TRISO fuel micro-particles are spheroids typically on the order of 500 – 1000 μm in diameter, and exposing a batch sample to hot hydrogen requires purpose-built special test equipment. Thusly, an immersion rig was developed and successfully demonstrated to expose ~1 g of micro-particles to hydrogen gas at temperatures and pressures relevant to NTP systems for the purpose of fuel evaluation. The rig, comprised primarily of graphite and pure tungsten, houses in its core a batch of micro-particles between pucks of porous silicon carbide (SiC). This approach permits gas flow while simultaneously retaining the particles in place. Herein is a discussion of the design, analysis, fabrication, and testing of the NTREES Thermal Soak Rig (TSR).

INTRODUCTION

The NTREES facility at NASA MSFC is a hot hydrogen furnace capable of providing the necessary pressures and temperatures required for testing of NTP fuel and components. Leveraging this national capability provides nuclear systems technology developers with the opportunity to characterize and test material samples, component concepts, and fuel designs early within the design lifecycle without requiring nuclear heating. The facility's 1.2MW of AC power proves the foundation for inductively heating fuel samples and components within an inert pressure vessel, while subjecting test specimen to pressurized hydrogen gas. Figure 1 displays the typical configuration of an NTREES test, in which the test article is placed within an energized induction coil as described. This "non-nuclear" approach to testing has provided meaningful data for NTP fuel and moderator development as well as significant Space Nuclear Propulsion technology maturation [1].

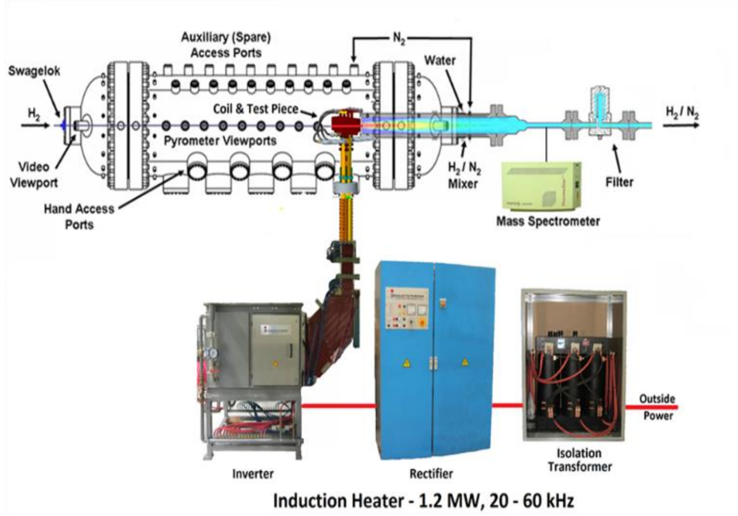

Figure 1: Standard NTREES Testing Configuration

Out of a desire to support characterization and testing of smaller material coupons, a broader selection of fuel forms, and more technically challenging system subcomponents, a class of hardware named “Immersion Rigs” were conceived for use within NTREES. Immersion rigs are devices in which test samples are not directly heated by facility power, yet are still subjected to prototypic conditions via heated gas immersion or thermal soak [2]. This concept of operations allows NTREES to be utilized earlier in the design process and permits more rapid test campaigns of material samples that could otherwise not be inductively heated within NTREES. This paper is a discussion of the first iteration of a Thermal Soak Rig (TSR-01), a rig designed to subject ~1g of TRISO fuel particles to temperatures relevant to NTP systems.

DESIGN AND ANALYSIS

Due to the extreme operating temperature of the devise, TSR-01 is comprised of graphite, pure tungsten, boron nitride (BN), and silicon carbide (SiC). TSR-01 (Figure 3) is approximately 20.5” long, including the cold and hot clamp adaptors, and 1.5” in diameter. A 0.125” axial through hole permits gas leakage through the rig for two reasons; (1) such that any trapped gas cannot pressurize during thermal cycling and (2) so that the rig can be actively “trickle” purged of any oxygen or impurities from off-gassing of constitute materials during heating. This trickle purge is achieved operationally by leaving this inner volume open to the pressure vessel’s argon atmosphere. A tungsten tube is located around the body of TSR-01. This tube acts both (1) as a susceptor for inductive heating and (2) mitigates thermal losses due to its lower emissivity. This approach traded most favorably in thermal analysis against a pure graphite design.

Figure 2: Sample Holder Designed for 1g of TRISO Fuel Particles

A graphite sample holder (Figure 2) is embedded within the body of TSR-01. This cylindrical, two-piece sample holder is comprised of a body – in which the sample are retained – and a screw-on cap. Both components of the sample holder are drilled and plugged with SiC foam such that they (1) retain all particles and (2) permit the trickling of purge gas as described above. Additional SiC foam is inserted into the body of the sample holder for particle packing and locating.

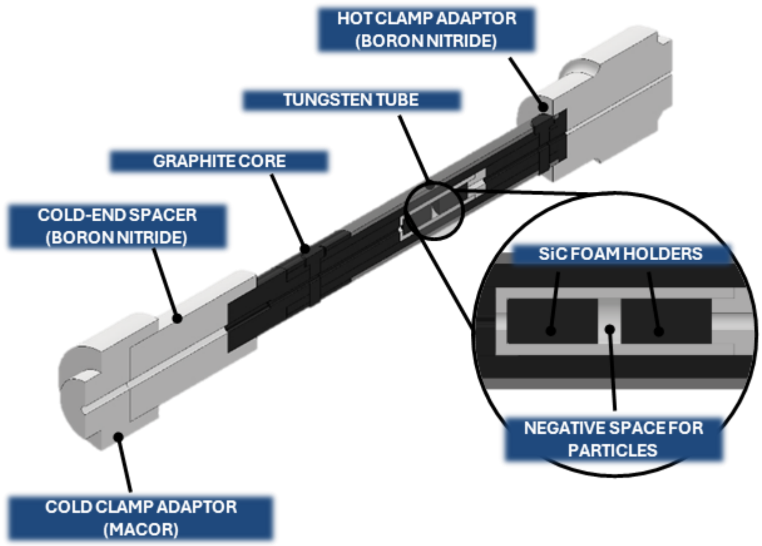

Figure 3: TSR-01 Cross Section View in CAD Software

Thermal modeling was performed for all design iterations of TSR-01, with a 2D thermal model of the final design being shown by Figure 4. A significant number of cases (~30) were performed, each iterating the design with modifications to subcomponent geometries and material selections. These cases were traded with consideration to maximizing achievable temperature of the sample region without exceeding temperature limits of TRS-01's constitute materials and minimizing the thermal losses to the environment.

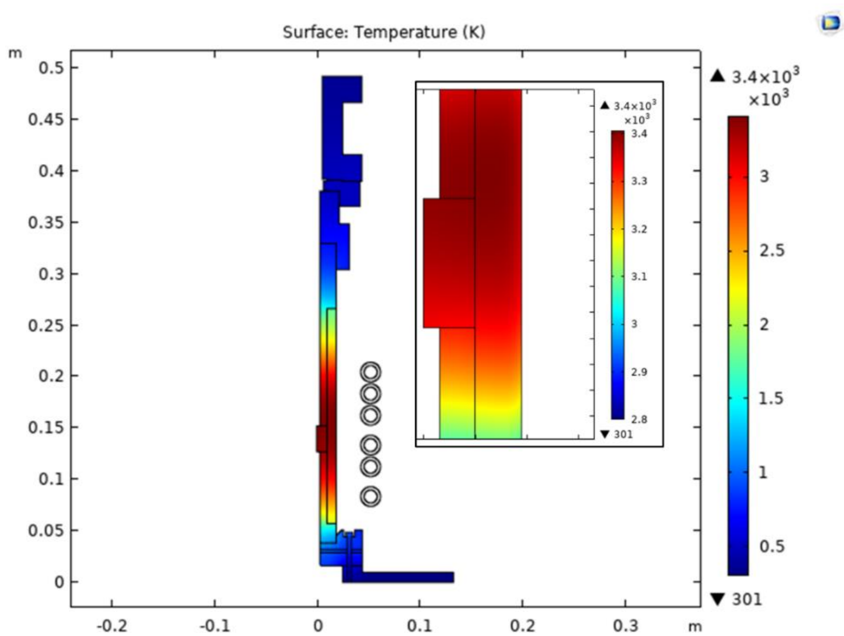

Figure 4: Thermal Model of TSR-01 with Particle Region Emphasized

EXPERIMENTAL APPROACH

TSR-01 was installed within the NTREES pressure vessel, suspended centrally within an induction coil as shown by a modeling software cross-section view in Figure 5 and a photo of the installed hardware in Figure 6. The fixtures of TSR-01, specifically the boron nitride cold clamp adaptor and hot clamp adaptor (Figure 3), provide electrical isolation from adjacent components. On the upstream end of this configuration TSR-01 mates to a standard NTREES “cold clamp” and adjoining components provide axial alignment and compressive load to encourage gas sealing. On the downstream end of this configuration the rig mates to NTREES’ exhaust gas handling system via a standard NTREES “hot clamp”. This directly flowing gas into the NTREES “mixer”, a water-cooled volume in which exhausting gas from NTREES experiments is diluted by gaseous nitrogen before being exhausted to the atmosphere. As mentioned in the previous section, the inner volume of TSR-01 is open to the pressure vessel’s argon atmosphere and this permits gas to trickle through the rig during experiments.

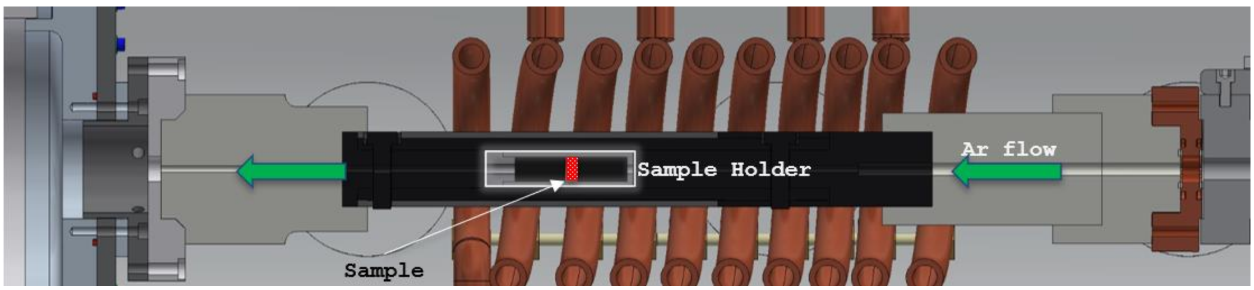

Figure 5: TSR-01 Layout within the NTREES Pressure Vessel

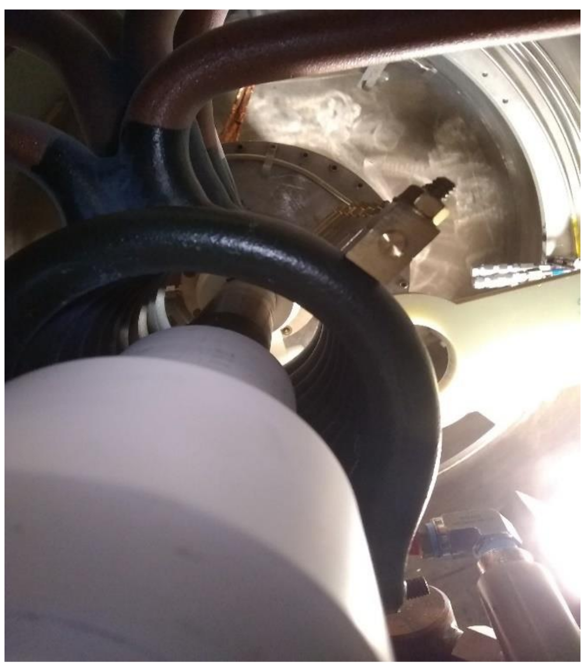

Figure 6: TSR-01 Installed within the NTREES Pressure Vessel (Looking Downstream)

To capture testing parameters several instrument types were used. The NTREES pyrometer suite was utilized for gathering real-time surface temperature of TSR-01 during testing, with a distribution of focal points shown in Figure 7. Additionally, an infrared camera was set up perpendicular to the chamber axis and was utilized for viewing the thermal gradients along the rig.

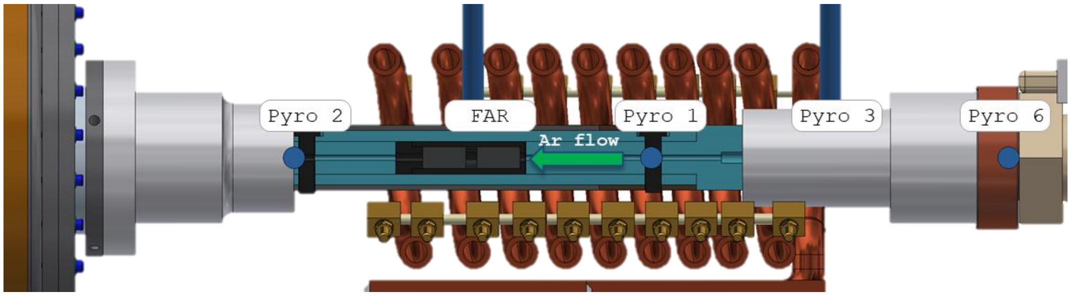

Figure 7: NTREES Pyrometer Suite Focal Locations Along TSR-01

Pressure transducers were utilized to record gas pressure at various points within the system. For the purposes of this experiment, the most significant of these are chamber pressure (denoted as P3), pressure at the inlet to the article (recorded as P7), and TSR-01's back pressure (titled T/A BACK PRESS and denoted as P4). Throughout testing, the existence of flowing purge gas can be inferred by P3 and P7 tracking closely, and a low back pressure can confirm minimization of nitrogen contamination backflowing from the mixer section.

The goal of the experiment was to heat TRISO fuel samples to >2600K within a ~650psig argon environment for a dwell time of ~30 minutes. For the experiment discussed here, ~1g of TRISO fuel particles was loaded into the sample holder of TSR-01. The characterization of fuel particles and specific test results are outside the scope of this paper. The results and conclusion are instead focused on the viability of TSR-01 and the approach to testing fuel particles.

RESULTS AND CONCLUSION

During this inaugural trial of TSR-01, NTREES instrumentation performed as expected and data collected was well in line with both prescribed parameters and thermal predictions. Figure 8 shows the pressure data collected. In this plot chamber pressure and the TSR-01's cold clamp pressure track closely at ~650psig as expected, indicating that argon gas was flowing through the rig as desired. The back pressure (P4) is significantly low and remains less than 25psig throughout the test, informing that nitrogen contamination via migration from the mixer was kept at a minimum.

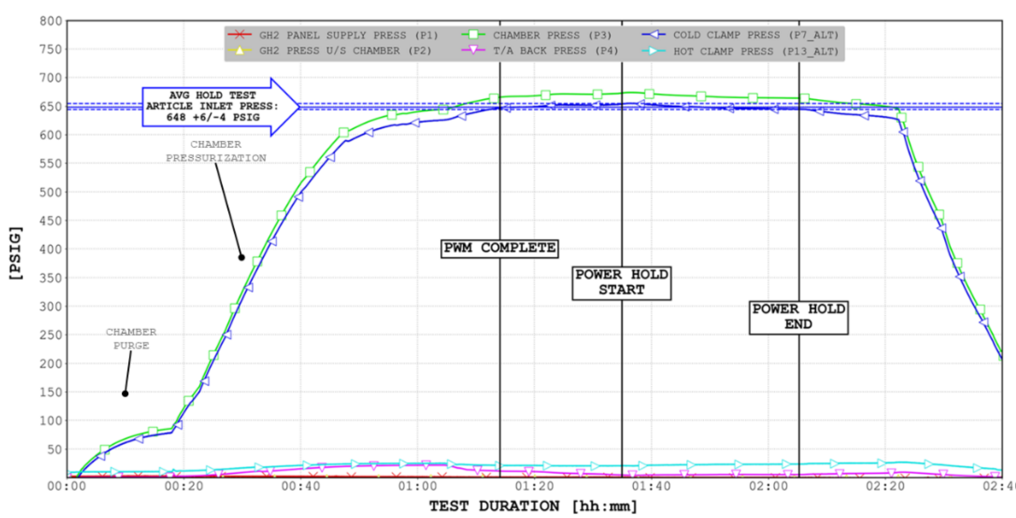

Figure 8: Pressures as Measured by NTREES Transducers During Initial TSR-01 Testing

Surface temperatures of TSR-01 were recorded by the pyrometer suite as expected, with temperatures tracking well alongside power delivered to the coil and in good agreement with thermal prediction models. Recorded temperatures and emissivity values as measured by the NTREES pyrometer suite can be seen in Figure 9. As seen in the temperature plot, the average surface temperature about the sample holder is 2623K over the duration of the power hold, as recorded by the FAR pyrometer. As mentioned in the previous section, Figure 7 displays the distribution of pyrometer focal points along the outer body of TSR-01.

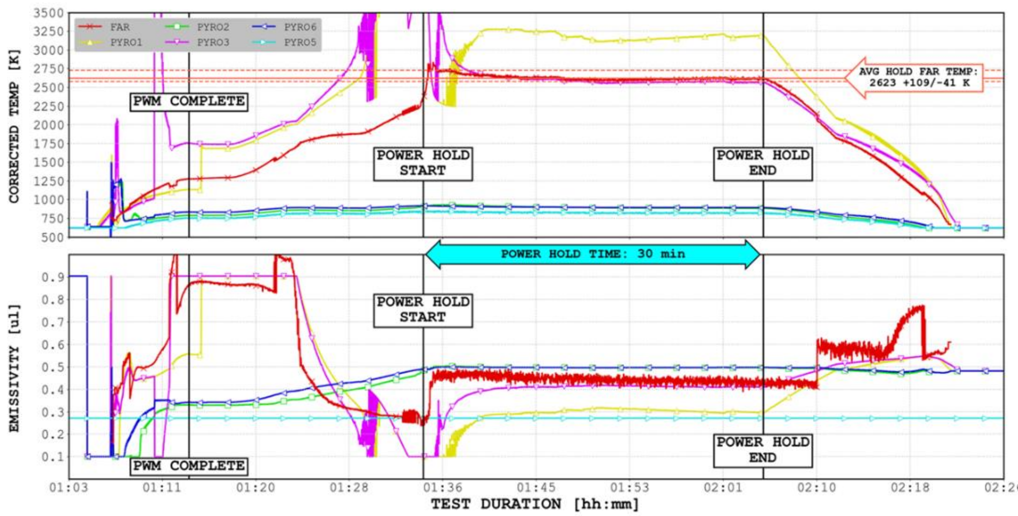

Figure 9: Temperatures and Emissivity as Measured by NTREES Pyrometers During Initial TSR-01 Testing

Additionally, the NTREES infrared camera captured images displaying thermal gradients and heating signatures of TSR-01 structures and performed as expected. The NTREES infrared camera is primarily utilized for imaging thermal gradients and monitoring hardware health and is not intended to perform as a tool for gathering specific temperature data. The side IR camera view in Figure 10 shows a snapshot at the conclusion of the 30 minute high temperature dwell. In this image coil turns can be discerned and partially obscure the axially central, heated TSR-01. Apparent deformation can be seen on the surface of the rig in zone 3 and zone 5.

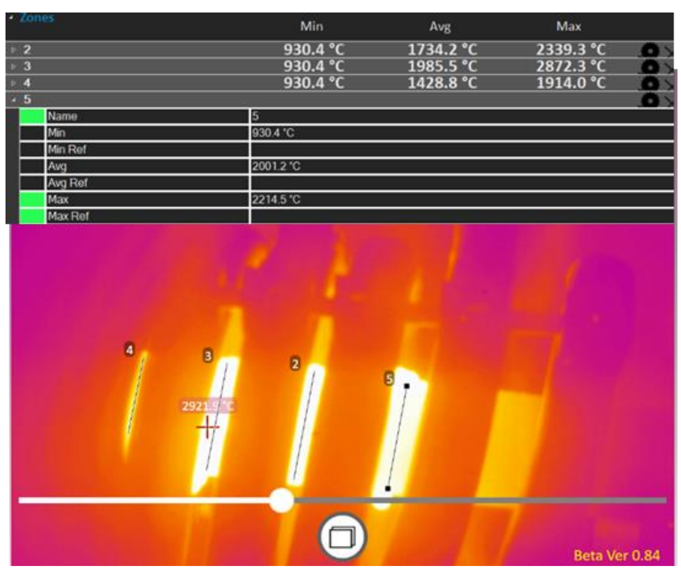

Figure 10: Side IR Camera Capture During TSR-01 Testing within NTREES

Post-test inspection of the TSR-01 hardware indicates significant deformation of the outer surface of the outer tungsten tube. The rig, shown in Figure 11 after the test, shows deformation consistent with melting, despite temperatures being maintained below tungsten's melting temperature (3695K). Upon a deeper inspection, the melt pool appears to originate at the tungsten graphite interface. All other components of TSR-01 appear unaffected, including the undamaged sample holder.

Figure 11: Partially Deconstructed TSR-01 Post-Test with Melted Tungsten Outer Sleeve

Laser-induced breakdown spectroscopy (LIBS) was performed on select locations along TSR-01's melt pool and surrounding regions. Results confirm that the tube was of pure tungsten construction, with indication that some tungsten-carbon compounds had formed during the test. The phase diagram of tungsten carbide (Figure 12) is consistent with observations, displaying that the compound is expected to be liquid at test temperatures [2]. The likely conclusion is that a tungsten-carbide eutectic formed at the tungsten to graphite interface and melted. Considerations to electrical arcing have also been made, however this appears less likely due to (1) that phenomenon being recognizable to the testing team during test and (2) the NTREES electrical system tripping due to off nominal loading. It is further likely that some small arc pathways were created during the melting process, but are not attributable to the overall deformation of the tungsten tube.

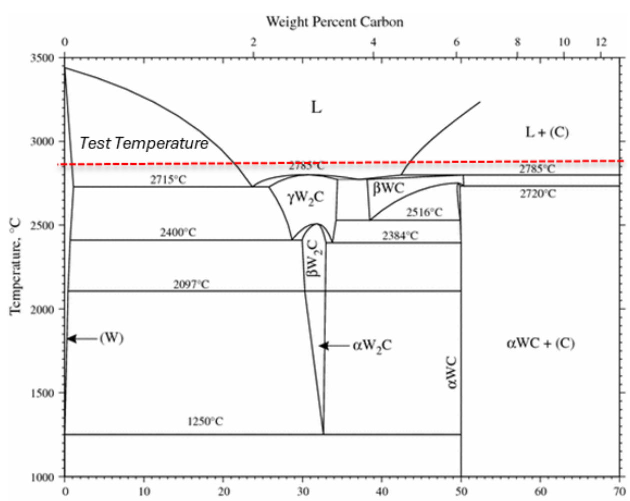

Figure 12: W-C Phase Diagram with Test Temperature Roughly Demarcated [3]

Despite the observed deformation of TSR-01's outer tungsten tube, the sample holder remained intact and functional, and can be seen in Figure 13 having been removed from the rig immediately following test conclusion. All particles were retained within the holder as designed.

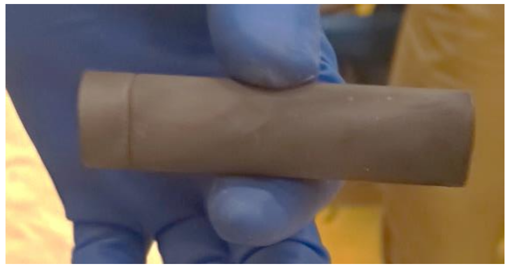

Figure 13: TSR-01 Sample Holder Post-Test

SUMMARY AND FUTURE WORK

As designed, TSR-01 permitted high temperature testing of TRISO fuel particles while exposing them to gas pressures relevant to NTP. Further, when consulting thermal predictions, the hold temperature achieved within the sample holder was ~2700K. TSR-01 is therefore considered a success by the authors. However, in future iterations of this hardware further considerations must be made to the formation of tungsten-carbide at test temperatures. One potential solution is to incorporate tantalum in place of tungsten.

Additionally, due to TSR-01 being largely constructed of graphite, it is not suitable for use with hot hydrogen gas due to the high likelihood of chemical erosion. This problem is resolved by another iteration of an NTREES immersion rig, the NTREES-5 Hydrogen Heat Exchanger (N5HHX-01), the design and implementation of which is discussed in a separate paper.

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