

Use of the Carbon Ceramic Experimental Test Apparatus to Validate the HTTF Design

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Abstract

Oregon State University is building an experimental test facility, which will provide data for the validation of very high temperature gas reactor codes. This facility has been designed to represent a 1:4 length and radial scale representation of VHTR. The thermal conductivity and diffusivity scaling shows that a low thermal conductivity ceramic material is needed to provide the appropriate temperature profile through the core region. To ensure that the thermal stresses induced from heating the blocks will not cause cracking and failure, work has been done to determine the ceramics' ability to endure the thermal and structural loading.

Introduction

The High Temperature Test Facility (HTTF) is being constructed at the Nuclear Engineering Department at Oregon State University. The purpose of this facility is to provide code validation data about the safety characteristics of Very High Temperature Gas Reactor (VHTR) designs. The HTTF is designed to represent a 1:4 height and radial scale model of the Modular High Temperature Gas Reactor (MHTGR) design, which is designed by General Atomics. An in-depth discussion of the facility scaling can be found in the paper written by Woods and Jackson (1). In the MHTGR design, the core is comprised of a hexagonal array of fueled graphite blocks. The array is composed of ten layers with 66 blocks in each layer. Within each of the 66 blocks, there is an array of fuel pins and coolant channels. In designing the HTTF, it was decided to build each of the ten levels of the core in one large slab, instead of many individual blocks. This simplification in construction also removed the problem of needing to quantify the coolant that bypasses the flow channels. The scaled monolithic core slab measures 1.17 m across the flat of the overall hexagon and 0.198 m in thickness. A render of a HTTF core block can be seen in Figure 1. In this render, roughly 700 channels are shown represented by three different colors. The blue channels represent the coolant flow paths, the red channels represent the voids where the heater rods are placed, and the green channels represent the flow paths that are added to simulate the core bypass within the prototype. The HTTF will be electrically heated using custom designed graphite heating elements.

Even though the HTTF is of reduced physical size, the facility is designed to achieve full VHTR temperatures to investigate the thermal behavior of anticipated transients in the VHTR. This requires that the facility be designed to achieve core center line temperatures of 1600 °C. The facility is designed to model normal operations and multiple accident scenarios such as the hot leg break, cold leg break, control rod port break, and the quadruple guillotine break (when the concentric hot and cold crossover vessel separate from the steam generator simultaneously).

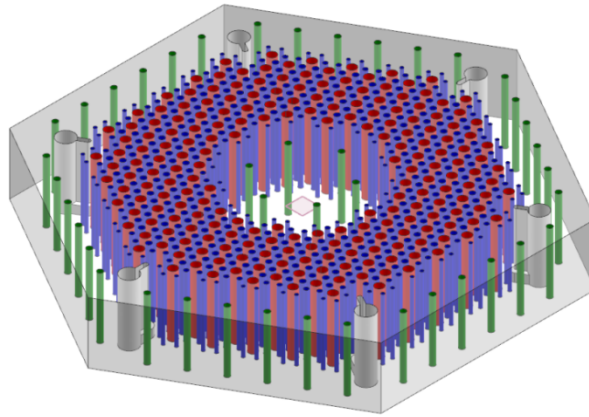


Figure 1: Render of the HTTF core block, where the bypass channels are shown in green (quantity 42), the coolant channels shown in blue (quantity 516), and the heater rod voids are shown in red (quantity 210).

During the simulation of normal operations, 2.2 MW of thermal energy will be input into the core region using graphite heater rods. The heat will be removed using downward flowing forced convection of helium or nitrogen gas. Similar to the MHTGR design parameters, the HTTF will have a coolant inlet temperature of 259 °C and a bulk core outlet temperature of 687 °C, with a helium mass flow rate of 1.0 kg/s. During the depressurized conduction cooldown accident scenario, the forced convection will be terminated and the core will be cooled through natural circulation, radial heat conduction, and radiation heat transfer to the reactor pressure vessel walls. During the initiation of an accident, the down flowing forced convection will stagnate and begin to flow upwards as natural circulation begins to drive the fluid movement through the core. During this time of flow reversal, it is expected that the core may achieve the temperature of 1600 °C.

To minimize the distortion of the thermal profile during the scaling process, the thermal properties of the core material need to be reduced, where the core material thermal conductivity is scaled by 1:8 and the thermal diffusivity is scaled by 1:8. Using a typical carbon for the core material of the HTTF does not provide the appropriate scaled thermal transfer capabilities and thus a custom low binding agent ceramic is utilized. The desired thermal conductivity for the HTTF core is 4.0 W/m²-k at room temperature. No ceramics with high working temperatures, 1600 °C and the desired thermal and mechanical properties, are available for purchase. The Missouri Refractory Company (MORCO) is being contracted to develop a custom ceramic to meet the HTTF's material requirements. The expected material will be a silicon carbide ceramic doped with mullite. This material will provide the thermal characteristics desired but the mechanical properties are lower than desired and thermally induced cracking may potentially be a problem with the material.

To provide 2.2 MW of thermal energy, an electrically heated isostatic graphite rod was chosen. This material was selected over the typical cartridge heaters because of the needed power density and operating temperature. The graphite chosen is graphitized in a furnace held at 3000 °C. Having a graphitization temperature this high will ensure that the material properties will not change during operation. This is not to say that the material properties are constant over the

operating temperatures, but more that the properties do not vary in an unknown manner due to a crystalline structure change at operating temperatures. One important characteristic of the isostatic graphite is that the material properties do not vary with the crystalline alignment and thus the material can be treated like an isotropic material simplifying the determination of the heater resistance. The HTTF core will be heated by 210 graphite elements that are individually 1.98 m in heated length and 0.0254 m outer diameter. These heaters are connected in groups of seven in series where three groups will be connected together to form a Wye configuration for the 480 VAC 3Phase power supply. Many electrical junctions are needed to provide a complete current flow path. Typical metal clamping devices will not reliably survive the maximum operating temperature and thus graphite-graphite connections are needed inside the pressure boundary. Using the chosen graphite further study is needed to determine the junction resistance as a function of applied pressure.

1. Background

Questions about the thermal induced stresses within the core blocks were raised as the HTTF design progressed. In conducting a literature survey two fundamental texts and a multitude of journal articles have been found testing very specific materials and shapes. In Kingery's paper *Factors Affecting Thermal Stress Resistance of Ceramic Materials*, he defines Thermal Stress as "a stress arising from a temperature gradient" and Thermal Stress Resistance as "Resistance to weakening or to fracture from thermal stresses" [2]. In the loading case of a ceramic material such as the HTTF core slab, it will experience compression forces on the periphery and tension forces at the block center. The thermal resistance factor is defined as:

$$R = St \frac{(1 - \mu)}{E * \alpha}, \quad (1.1)$$

where St is the shape factor of the material, μ is the Poisson's ratio, E is the modulus of elasticity, and α is the coefficient of thermal expansion. The resistance factor is the total temperature change allowable for a steady flow of heat, beyond which thermally induced cracks will begin to develop. It should be noted the shape factor is a function of the material geometry and the material's tensile strength. One difficulty in applying this formulation is that a shape factor value for the HTTF geometry is not given. A reformulation of the thermal stress can be written as:

$$\sigma_{th} = \frac{E * \alpha * \Delta T}{1 - \mu} \quad (1.2)$$

where σ_{th} is the thermally induced stress [3]. As long as the thermal stress remains below the tensile stress of the material, thermally induced fractures, spalling, and shock should not occur [4]. Again this formulation of the equation brings problems because the determination of the material's tensile strength is uncommon by manufacturers. To work around this problem experimental tests can be conducted to determine the affects of the thermal stresses [2, 5, 6].

To determine the temperature profile and thermal gradients through-out the core region, a numerical model of the HTTF core was constructed in the Thermal Analysis package included in Siemens NX 7.5. The core is comprised of hexagonal unit cells, and can be reduced to a 30 degree section when axial symmetry is assumed. A 2D model of the core block was then meshed with 324,243 nodes and had a maximum node size of 0.2 mm. The block with the largest expected thermal gradient would occur where the greatest difference between the coolant and the

heaters exists, which is the core inlet. Heat flux and convection boundary conditions typical for normal operations were applied to the mesh. The solution results can be seen in Figure 2. From these figures it can be seen that the maximum thermal gradient is expected to occur at the heater channel walls, with a maximum value of 16 °C/mm, which could cause a concern for thermal spalling. Another area of concern is the webs between the coolant channels where the gradient is 8 °C/mm, which could cause thermal fracture across one or more of the webs. To determine if the ceramic chosen for the core block will survive the applied thermal gradients, a benchtop experiment is needed to apply the predicted thermal gradients to a sample of the material.

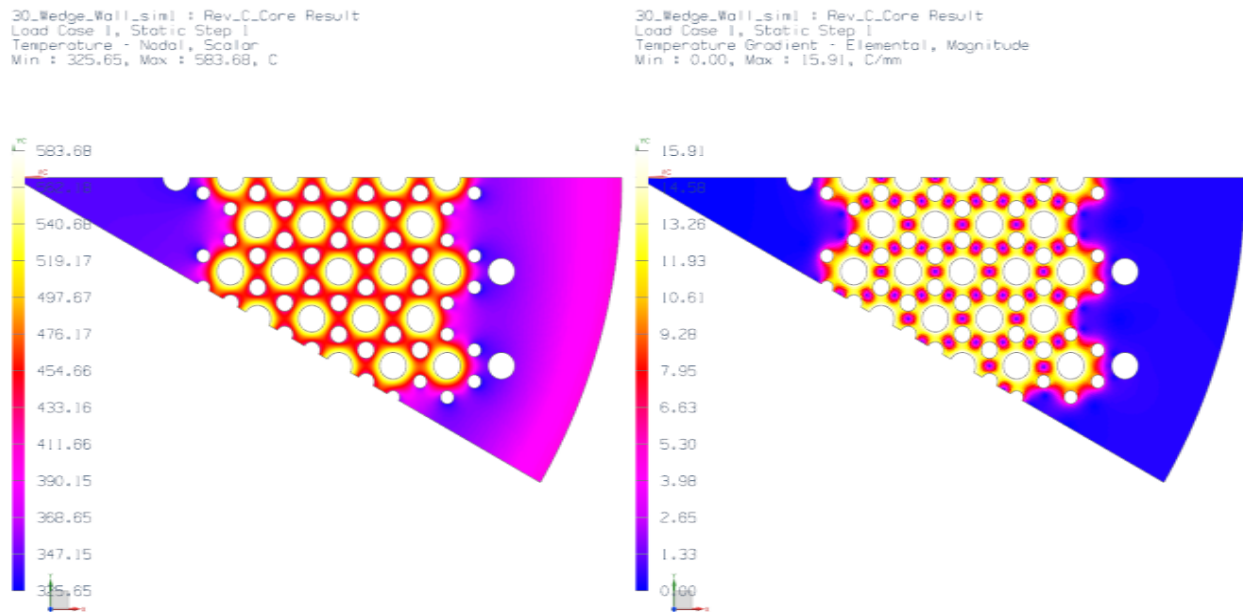


Figure 2: Numerical results of the core block temperature distribution (left image) and the thermal gradient (right image) analysis, across a 30° symmetry section.

2. CCETA Overview

Obtaining a material and heating source to repeatedly operate at the needed temperatures has provided the HTTF design team challenges because no “off-the-shelf” options are available. To meet their needs, a custom ceramic is being developed and graphite heater rods are being designed specifically for this facility. Experimental data is needed to reduce the number of unknowns in designing the heaters and ceramic materials. The Carbon Ceramic Experimental Test Apparatus (CCETA) has been designed, built, and operated to gain knowledge about the chosen materials. This apparatus has two primary functions: 1) determine the resistance and junction characteristics of the graphite heater rods, and 2) determine a set of cracking criteria to ensure the longevity of the HTTF ceramic core.

As shown in equation 1.2, the thermal resistance is a function of temperature gradient and is independent of overall shape of the material. Using this relationship, a smaller block can be utilized to test the thermal resistance of a material. This allows the size of the CCETA to be reduced from the full size of the core block to the general shape of a rectangular-piped

containing two unit hexagons that are present in the core block layout. The CCETA is comprised of a stack of ceramic test blocks, a steel support frame, graphite heater rods and instrumentation to measure the data required. A render of the apparatus can be seen in the left frame of Figure 3. The ceramic test-block stack measures 0.20 m x 0.20 m x 0.56 m and is cast with 28 voids (25.4 mm, 15.88mm, 12.7 mm, and 6.35 mm diameters). These voids are for instruments, coolant pathways, and heater rods, which can be seen in Figure 4. In addition to the instrument pathways cast into the block, six 3 mm diameter thermocouples are permanently cast into the block, which can be seen in the detail view presented in Figure 3. The junctions of these thermocouples are placed in one of the webs between coolant channels in order to directly measure the thermal gradient in that region. The size of the thermocouple sheath was minimized to limit the disturbance the measurement caused.

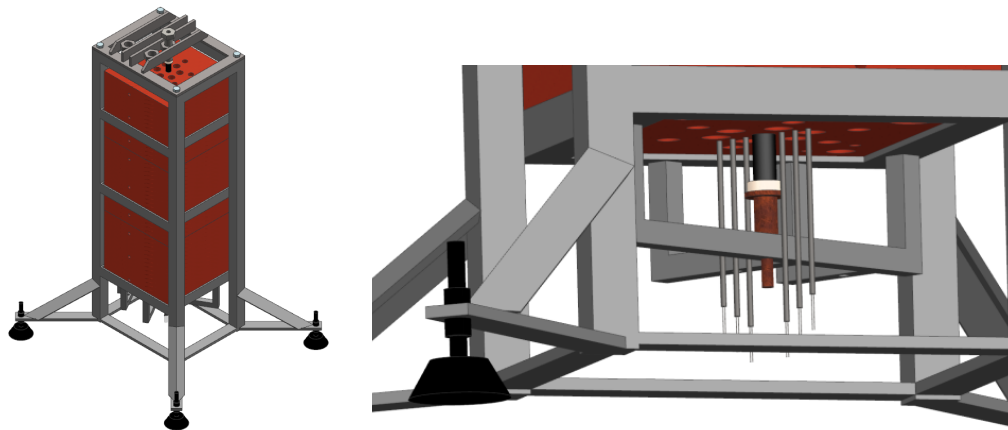


Figure 3: Render of the completed CCETA (left) and a detail image of the embedded thermocouples (right). The test ceramic block is colored in red.

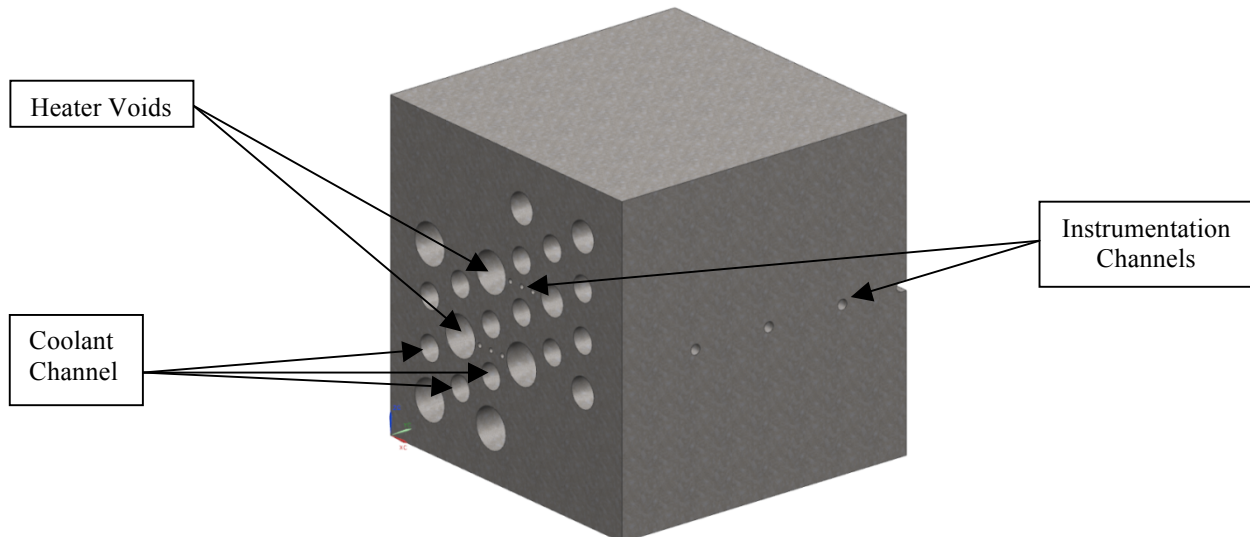


Figure 4: Isometric view of the CCETA test block. Note three of these blocks are used to create the full stack shown in Figure 3.

The initial test block is made from a ceramic that is similar to the desired custom ceramics, where the thermal conductivity is 3.4 W/m-K as opposed to the desired 4.0 W/m-K of the custom material. Choosing a material with a lower thermal conductivity will provide more conservative results because the lower thermal conductivity will decrease the thermal resistance [2].

To determine the junction characteristics of the heaters, voids are cast into the test-block where custom ordered graphite rods were placed. The graphite rods are vertically oriented where a compression bolt applies a force at the top of the rod and a load cell measures the force applied to the heater. Over the 0.558 m of the heated length, multiple junctions were made in the heater rod. The test-block walls are used to restrain the heaters and provide a prototypical intracore heater connection.

Electrical power supplies power the graphite heaters. To accurately determine the energy being emitted from the heaters, the voltage drop across the heaters was measured as well as the current flowing through the heating loop, using a Hall Effect sensor. These two measurements provide power measurements that will omit the power distribution losses that occur in connecting the heater to the power supply.

To measure the ceramic block temperatures, ten K-Type thermocouples were attached in the various holes within the block. In addition to the block temperature measurements, K-Type air probes were utilized to measure the bulk coolant temperature as the flow passes through the channels during operation. All data was collected, processed, and stored using a custom VI built in LabVIEW.

3. CCETA Results

The following two subsections will discuss the specific findings for the CCETA experiments that were conducted during January through May of 2011. All of the tests were conducted in a building that was at 70 m above sea level in a climate controlled laboratory space that was maintained between 15 and 20° C during the experiments. All tests were conducted in the open air.

3.1 Ceramic Work

During the CCETA tests, many heated graphite tests were conducted. None of these tests were capable of producing the desired thermal gradients because the heater temperature necessary to produce the necessary thermal gradient would be above the oxidation threshold. Instead Inconel sheathed heater cartridges were utilized to provide the necessary thermal input. While the heater cartridges will not meet the HTTF's design temperature, the CCETA was designed to produce the desired thermal gradients at a reduced temperature to allow the use of alternate heating methods.

During the heater cartridge operation an infrared camera was used to measure the temperature profile of two of the block faces: one face without thermocouple ports and one face with thermocouple ports. These images can be seen in Figure 5, where the face with thermocouple

ports is shown in the left frame and the face without thermocouple ports is shown in the right frame. Two interesting observations were made using this measurement technique. The first was that there is a significant thermal resistance at the seams of the core blocks. In looking at the infrared images, there is a sharp color change between the bottom and center blocks. Three lines were drawn over the image where the temperatures profiles were then plotted, as shown in Figure 6 and Figure 7. In the first plot the red line is drawn over the thermocouple ports, which explains the spikes in the red profile because the gas leaving the ports is hotter than the block itself. In looking at the plot of the profiles of the no-port face, Figure 7, a step at the position of $x = 0.18$ m shows a $10\text{ }^{\circ}\text{C}$ rise at the block interfaces.

The heater cartridge was operated for a total of 598 hours, where the block was allowed to cool down every 60 hours. This provided ten thermal cycles of the block. The center channel of the block was heated, with an applied heat flux of 70 W/m^2 . This heat flux provided the necessary $16\text{ }^{\circ}\text{C/mm}$ wall thermal gradient and a measured web thermal gradient in excess of $8\text{ }^{\circ}\text{C/mm}$. During this extended operation, no crack growth or thermal spalling was observed. Figure 8 displays a crack in the test block that originated during the casting process. This crack was measured during each thermal cycle and no measureable creep or growth was noted.

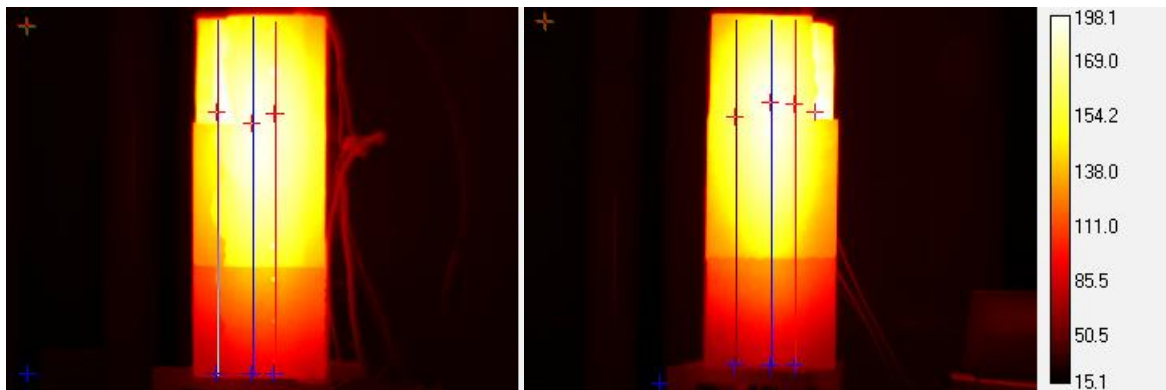


Figure 5: Infrared images of the test block under heating, TC Port (left) and No Port (right).

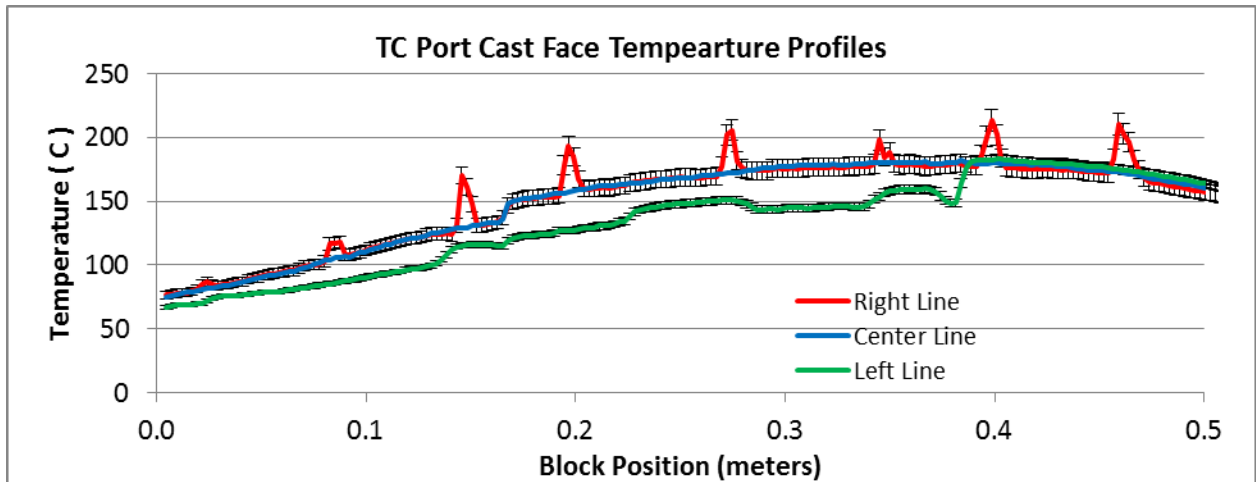


Figure 6: Plot of the temperature profiles along the front of the test block, where the lines correspond to the lines plotted on the left image of figure 5.

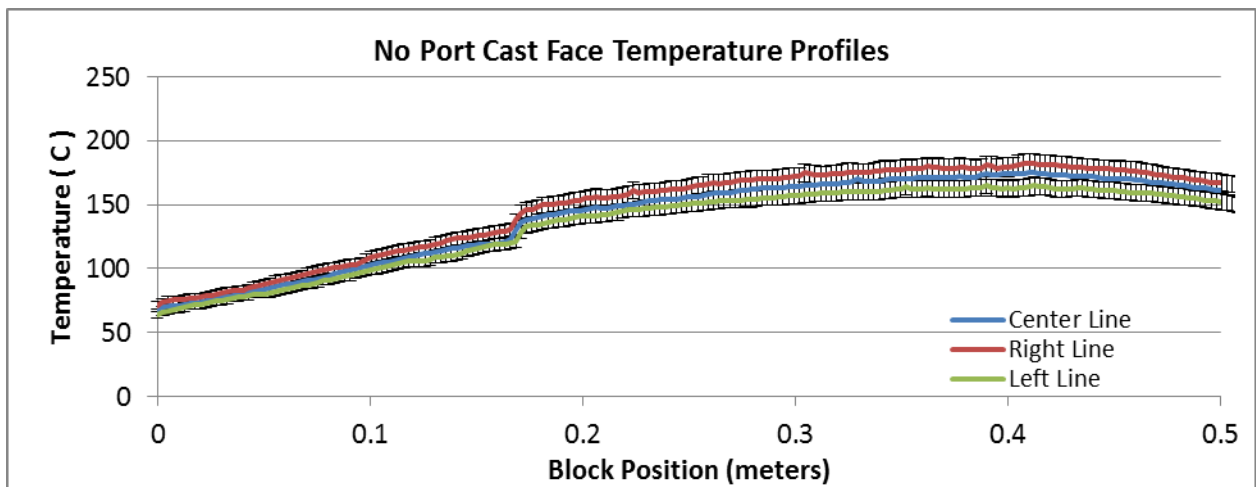


Figure 7: Plot for the temperature profiles of the along the side of the test block, where the lines correspond to the lines plotted on the right image of figure 5.



Figure 8: Image of the crack that occurred during the 820 °C curing process of the ceramic.

3.2 Graphite Work

An ideal heating element would be a tube that is 2.0 m in length with an outer diameter of 25 mm and composed of isostatic graphite. The inner diameter of this tube would be set to provide the appropriate electrical properties for the heating element, which is about 20 mm. A heating element in this aspect ratio is difficult to machine and handle because of its fragility and thus it was decided to break the heating element into multiple sections. Assembling the heating element out of many smaller sections provides a more robust item, which is less expensive to replace if dropped. The down side to this change is that the junctions between the heating elements need quantification, because each junction contributes to the electrical resistance of the complete heating element. Experimental data was needed to determine the shape, quantity, and electrical characteristics of junctions used in each heating element.

A test rod using the chosen graphite was procured having an outer diameter of 15.8 mm and inner diameter of 6.35 mm. Tests were conducted varying the number of junctions and current applied to the graphite rods, and a plot of the resultant data can be seen in Figure 9. In all tests the total length of the element was 0.304 m, with a force of 22 N being applied to the junctions, and the temperature was measured along the centerline of the graphite tube traversing the pathway in both directions. In the first test with one junction the two elements were equal length and a significant spike at the junction is measured. With the five junction tests, the left graphite remained 0.152 m in length while the right half was cut into five separate pieces. The data shows an increase in the overall rod temperature, but along the area with an increase in junction quantity the peak was reduced. In the nine junction tests the left graphite rod was cut into five pieces as well as the right rod. These measurements showed the flattest temperature profile. It should be noted that the ends of the graphite lengths were exposed to the ambient environment, which is why there is a temperature increase at measurement location 0 and 24. Using this data and further scoping tests it was determined that individual heating sections of 0.101 m in length would provide the flattest temperature profile while minimizing the number of individual components in the heating system.

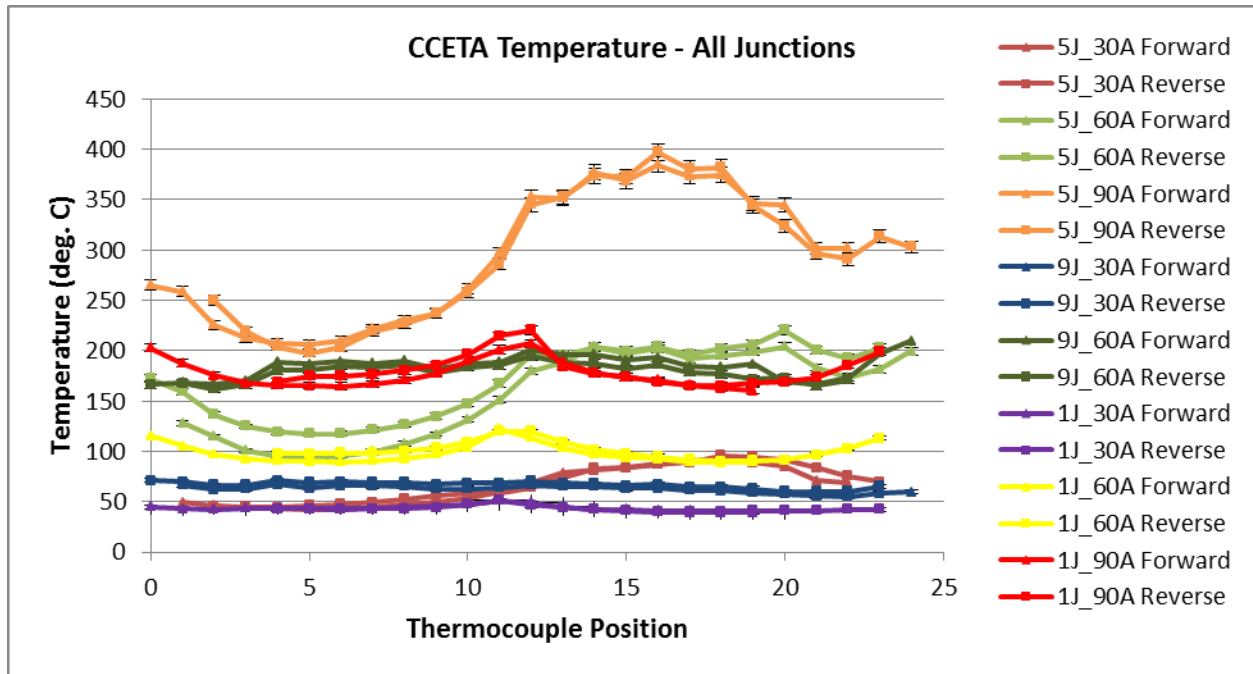


Figure 9: Plot of the temperature along the length of a tubular heating element.

Further work was conducted to determine the most repeatable junction interface. The criterion of repeatability was determining the junction shape that produced the least variance in the electrical resistance across the junction itself. Ten equal length graphite sections measuring 12.7 mm in diameter were randomly stacked in different voids that were cast in the test block, which measure 13 mm and 16 mm in diameter, which correspond to the $\frac{1}{2}$ and $\frac{5}{8}$ labels in the figures respectively. Plots of some of the data can be found in Figure 10 and Figure 11. Each set was machined to have a different junction shape, from a flat rough sawn face to a polished steep conical face. Each test was repeated ten times with the average overall ten tests being shown in the eleventh column. For the sake of space, only the flat junction and 88 degree cone angle tests are shown, but 6 other junction styles were also tested. The flat and 88 degree tests are reported because they are most significant, because the flat junction is the simplest but provided the worst repeatability and the 88 degree cone contains the most surface area but is the most repeatable. The extensive junction testing informed the decision to machine nesting conical faces on each graphite section. This work also informed the final block design, which shows the designers that the heater sections should closely fit the void cast into the core block.

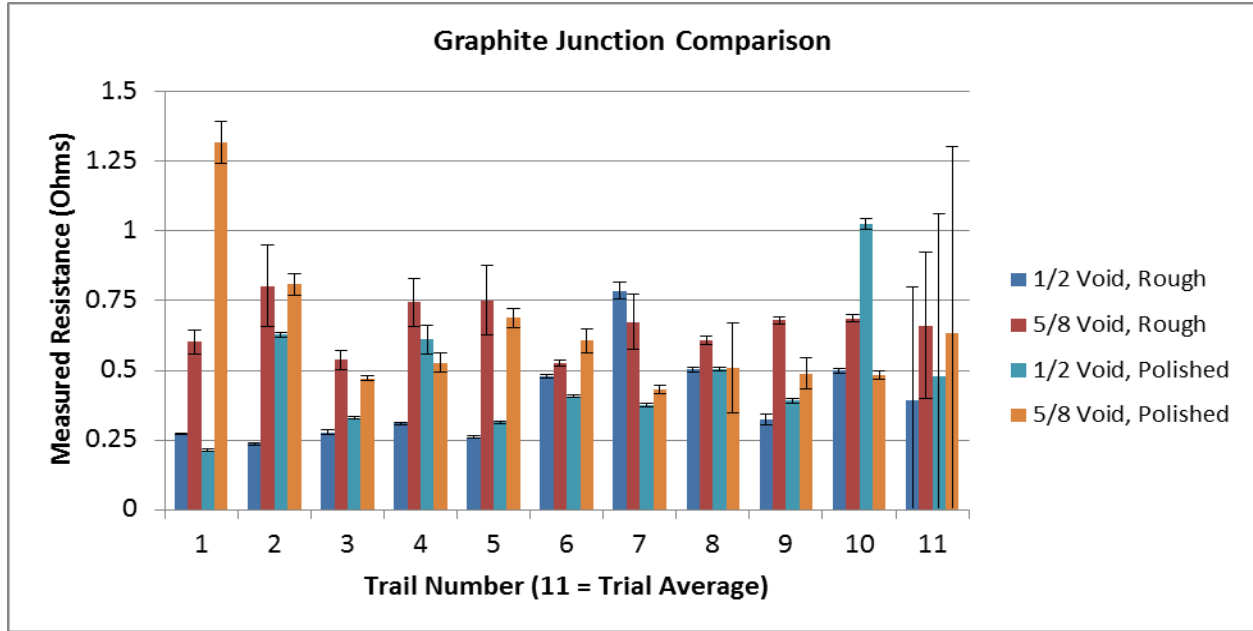


Figure 10: Plot of the heater junction tests using planar junctions.

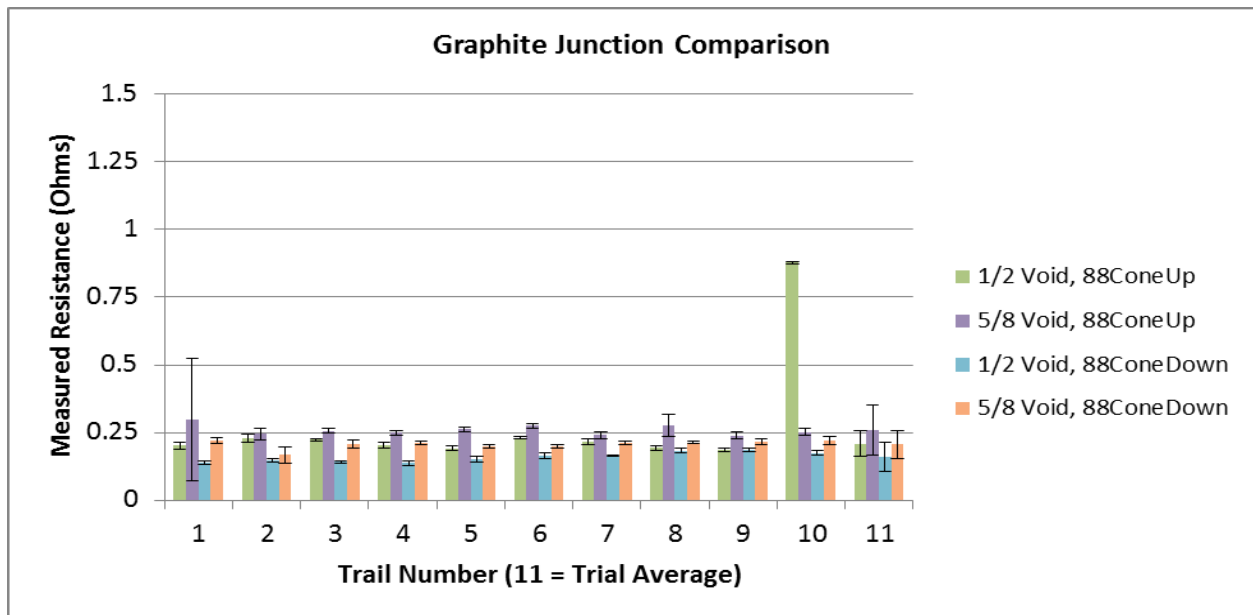


Figure 11: Plot of the heater junction tests using conical junctions.

4. Conclusions and Future Work

In designing a test facility to validate VHTR system codes, questions arose about the test facilities material integrity both with regard to the heater materials and the core materials. A small benchtop test apparatus, named the CCETA, was constructed and operated to produce experimental data that will inform the overall test facility design. During the construction and

operation of the test blocks the ceramic material showed to be resilient to thermal cracking and thermal spalling while being subjected to heat fluxes 120% of those expected. While cracks did develop during the block fabrication process, no crack growth or propagation was measured during the 500 hours of heater operation. In addition to the ceramic testing, many experiments were conducted to determine the size, length and junction characteristics for the graphite heater rods that will provide the power for the facility. Large diameter heating elements provide a reduced surface heat flux to the core block, which reduces the thermal stresses that often result in thermal spalling. To provide the appropriate heater element resistance a wall thickness was determined using the experimental data. Lastly, it was determined that the most repeatable junction characteristic was machining the tubular heater elements with nesting cones at an 88° angle. An image of the final heating element can be seen in Figure 12, where the graphite elements are 25 mm outer diameter, 18 mm inner diameter, and 100 mm in length.



Figure 12: Image of the final heater element shape, composed of Tokai A348 Isostatic Graphite.

Similar experiments will be conducted in the near future if the final materials are different from the materials initially studied in this work. This additional work will be used to ensure the long term survivability of the HTTF and its internal components.

5. Acknowledgments

This presentation was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission.

6. Nomenclature

CCETA Carbon Ceramic Experimental Test Apparatus
HTTF High Temperature Test Facility
MHTGR Modular High Temperature Gas Reactor
VHTR Very High Temperature Gas Reactor

E modulus of elasticity
R thermal resistance
St shape factor of the material
 α coefficient of thermal expansion
 μ Poisson's ratio
 σ_{th} thermally induced stress

7. References

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