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P. G. MEDVEDEV, D. L. PORTER,
B. A. HILTON

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Idaho National Laboratory

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D.A. SELL[1], C.E. BAILY[1], T.J. MALEWITZ[1], P.G. MEDVEDEV[1], D.L. PORTER[1], B.A. HILTON[2]

[1]Idaho National Laboratory
1765 North Yellowstone Hwy, Idaho Falls, ID 83415 – USA

[2]TerraPower
330 120th Ave NE, Suite 100
Bellevue, WA 98005 - USA

ABSTRACT

A system has been developed to perform measurements on irradiated, sodium bonded-metallic fuel elements to determine the amount of fission gas retained in the fuel material after release of the gas to the element plenum. During irradiation of metallic fuel elements, most of the fission gas developed is released from the fuel and captured in the gas plenums of the fuel elements. A significant amount of fission gas, however, remains captured in closed porosities, which develop in the fuel during irradiation. Additionally, some gas is trapped in open porosity but sealed off from the plenum by frozen bond sodium after the element has cooled in the hot cell.

The Retained Fission Gas (RFG) system has been designed, tested and implemented to capture and measure the quantity of retained fission gas in characterized cut pieces of sodium bonded metallic fuel. Fuel pieces are loaded into the apparatus along with a prescribed amount of iron powder, which is used to create a relatively low melting, eutectic composition as the iron diffuses into the fuel. The apparatus is sealed, evacuated, and then heated to temperatures in excess of the eutectic melting point. Retained fission gas release is monitored by pressure transducers during the heating phase, thus monitoring for release of fission gas as first the bond sodium melts and then the fuel. A separate hot cell system is used to sample the gas in the apparatus and also characterize the volume of the apparatus thus permitting the calculation of the total fission gas release from the fuel element samples along with analysis of the gas composition.

1. Introduction

A new sustainable and economic nuclear energy system is being developed which may use metallic fuel elements. Post irradiation examination of metallic fuel elements is being performed to understand their behavior with respect to fuel design and operating parameters. One aspect of metallic fuel element behavior for which a greater understanding is needed, is the amount of fission gas that is retained in the fuel material after release of the gas to the element plenum. This may influence the stress that the fuel applies to the cladding wall.

During irradiation of fast reactor metallic fuel elements, most of the fission gas developed is released from the fuel and captured in the gas plenums of the fuel elements [1]. A significant amount of fission gas, however, remains captured in porosities, which develop in the fuel during irradiation. The bond sodium may also retain some dissolved gas once the fuel is removed from the reactor and the sodium has cooled and solidified. Additionally, some gas is trapped in open porosity but sealed off from the plenum by the frozen bond sodium while the fuel element is still pressurized.

2. General System Description

A fission gas volumetric determination system was designed to collect and measure gas released from melted small samples of metallic fuel. This system was used in conjunction with an existing system in the hot cell, which was used to puncture fuel element plenums and extract fission gas samples from the fuel elements.

The main components of the fission gas volumetric determination system are the test assembly, furnace, and data acquisition system. Figure 1 shows an overview of the test system in the furnace.

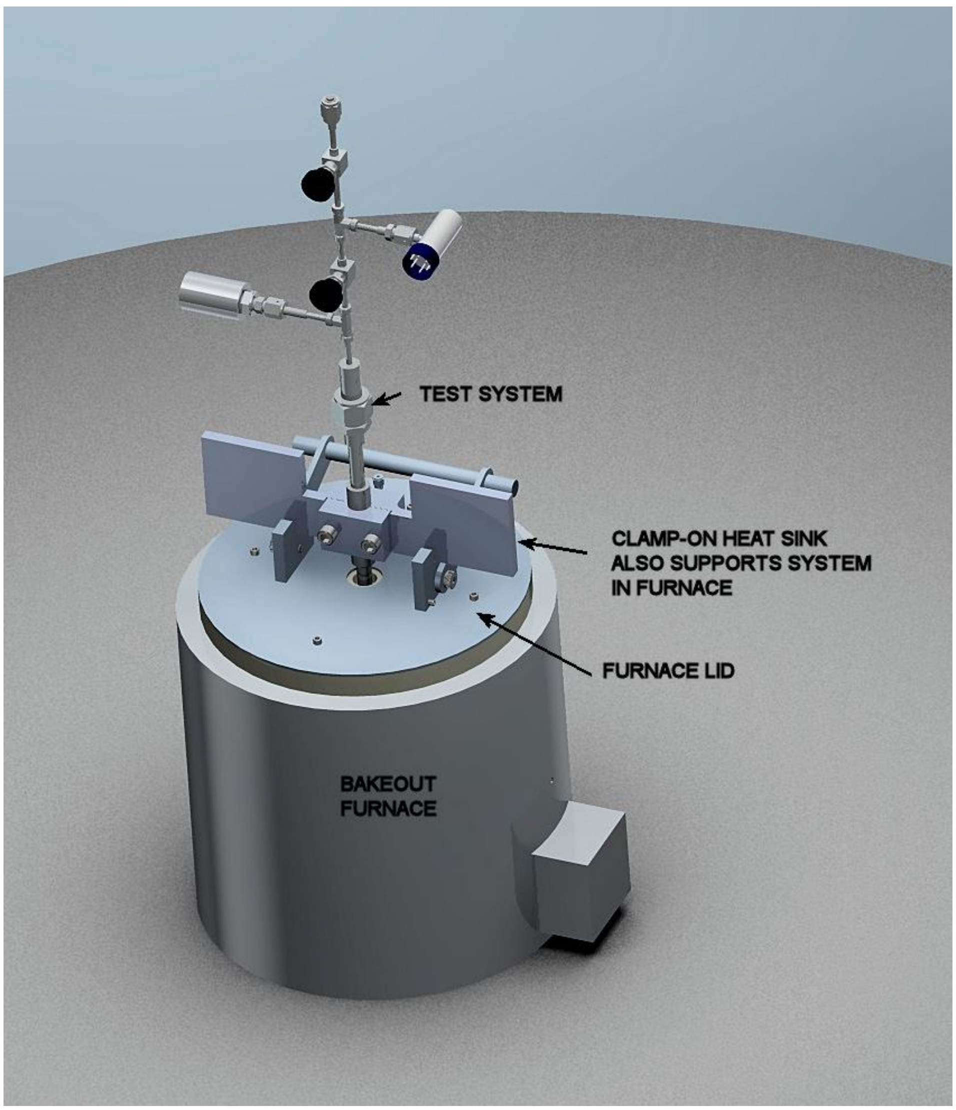

Figure 1, Retained Fission Gas System

The test assembly consists of two main sub-components. The first is the furnace tube, which is the part of the test assembly that contains the fuel element sample during the test. The furnace tube is only used for one test and then is discarded. The furnace tube also has a sodium condenser section whose purpose is to prevent sodium vapor migration into the instrument assembly and avoid damage to the vacuum and pressure transducers. The furnace tube is connected to the instrument assembly using a Swagelok VCR fitting with a metal gasket. The instrument assembly contains a vacuum transducer and a pressure transducer. The vacuum transducer is used to leak check the final in-cell assembly of the test apparatus and verify the initial vacuum conditions in the test apparatus prior to heating. The pressure transducer monitors the pressure increase in the test apparatus during the heat up as the fuel is melting. The instrument assembly also has a vacuum connection, which is used to connect the test assembly to a vacuum pump. The instrument assembly is designed to be reusable once it is removed from the furnace tube following a test run. A heat sink clamp is attached near the middle of the test assembly to reduce heat transfer between the furnace tube and the instrument assembly. The heat sink also supports the test assembly in the tube furnace.

Once the test assembly is loaded with a fuel specimen, the test assembly is then loaded into a tube furnace. The test assembly is supported by the heat sink clamp on the top of an insulated plate which rests on top of the furnace. A dual element thermocouple is installed through the insulated plate and is located adjacent to the fuel sample in the furnace tube. One element of the thermocouple is connected to the furnace control module and is used to control the temperature of the furnace. The other element of the thermocouple is connected to the data acquisition system. The data acquisition system is used to record the temperature of the furnace and the signals from the vacuum and pressure transducers.

The furnace temperature is raised to 1000 °C and held for approximately 1 hour to melt the fuel sample and release the retained fission gas. After this process is complete, the furnace and test assembly are allowed to cool to ambient temperature.

The furnace tube is then removed from the test apparatus and moved to another apparatus in the hot cell where a gas sample is extracted from the test assembly. The gas sample is sent to an analytical laboratory for gas analysis. The gas sampling apparatus is next used to perform volumetric measurements of the test assembly. Knowing the volume of the test assembly permits calculation of the total moles of gas released from the fuel sample.

3. Pre-Test Development

Several tests were performed during the development of the RFG to verify the equipment and process would perform as required. The first test investigated the melting of the uranium fuel with iron at 1000 °C. Unirradiated uranium was cast into stainless steel cladding to simulate the test specimens. They were then contacted with iron or manganese powder and heated in a sealed furnace in an argon glovebox. Post-test examination of the samples showed that a eutectic formed and the surrogate fuel melted. Iron powder was ultimately chosen as the metal to be used in the actual tests.

The next test involved the testing of a RFG prototype in an out-of-cell mockup. The first portion of the test evaluated remote loading of surrogate fuel samples and iron powder into the crucible and assembly of the test system. The second portion of the test simulated operation of the system in the hot cell and heating of the furnace tube portion of the system to 1200ºC after evacuation of gas. This portion also verified operation of test instrumentation and evaluated system response. The system design performed as expected with little modification needed. Mockup testing then continued in the Hot Fuel Examination Facility (HFEF) argon atmosphere hot cell, which repeated the scope of work for the out-of-cell testing. The results of this testing were also as expected and no system modifications were required.

A final test was performed to verify the performance of the integral sodium trap in the RFG. A small amount of sodium was loaded into a zirconia crucible and then loaded into the test assembly. The test assembly was then heated in excess of sodium boiling point (852 °C). The test apparatus was then cooled. The sections were separated and allowed to sit in the cell atmosphere for a day to allow the Na to react to form NaOH. Phenolphthalein solution was used after the test to note what sections of the apparatus were contaminated with sodium during the testing. NaOH turns a bright red when contacted with the phenolphthalein solution (See Figure 2). This test showed that the cold trap worked as planned and none of the parts on the cold side of the trap such as the pressure and vacuum transducers were contaminated with sodium. However, it was discovered that the zirconia crucible used during this testing, reacted with some of the sodium and crumbled. A tantalum crucible was selected as a substitute for the RFG apparatus design.

Figure 2, Phenolphthalein solution rinse of displacement rod (internal component of test assembly) contaminated with Na

4. Test Procedure

The first step in the test procedure is to characterize the irradiated fuel specimen to be melted. The length and weight of the fuel specimen are measured, and are used to calculate the quantity of fuel in the test specimen. Next, the tantalum crucible is loaded with a bottom charge of iron powder, then the fuel specimen, and finally a top charge of iron powder. A sample is often cut into multiple subsections to allow layering of fuel and iron powder to encourage iron/fuel reaction and melting. The iron powder is used to reduce the overall melting temperature of the fuel due to the eutectic reaction between the iron and uranium. A stainless steel mesh screen is then installed on the top of the crucible to reduce the possibility of the material from falling out of the crucible during handling. Figure 3 shows the configuration of the loaded crucible.

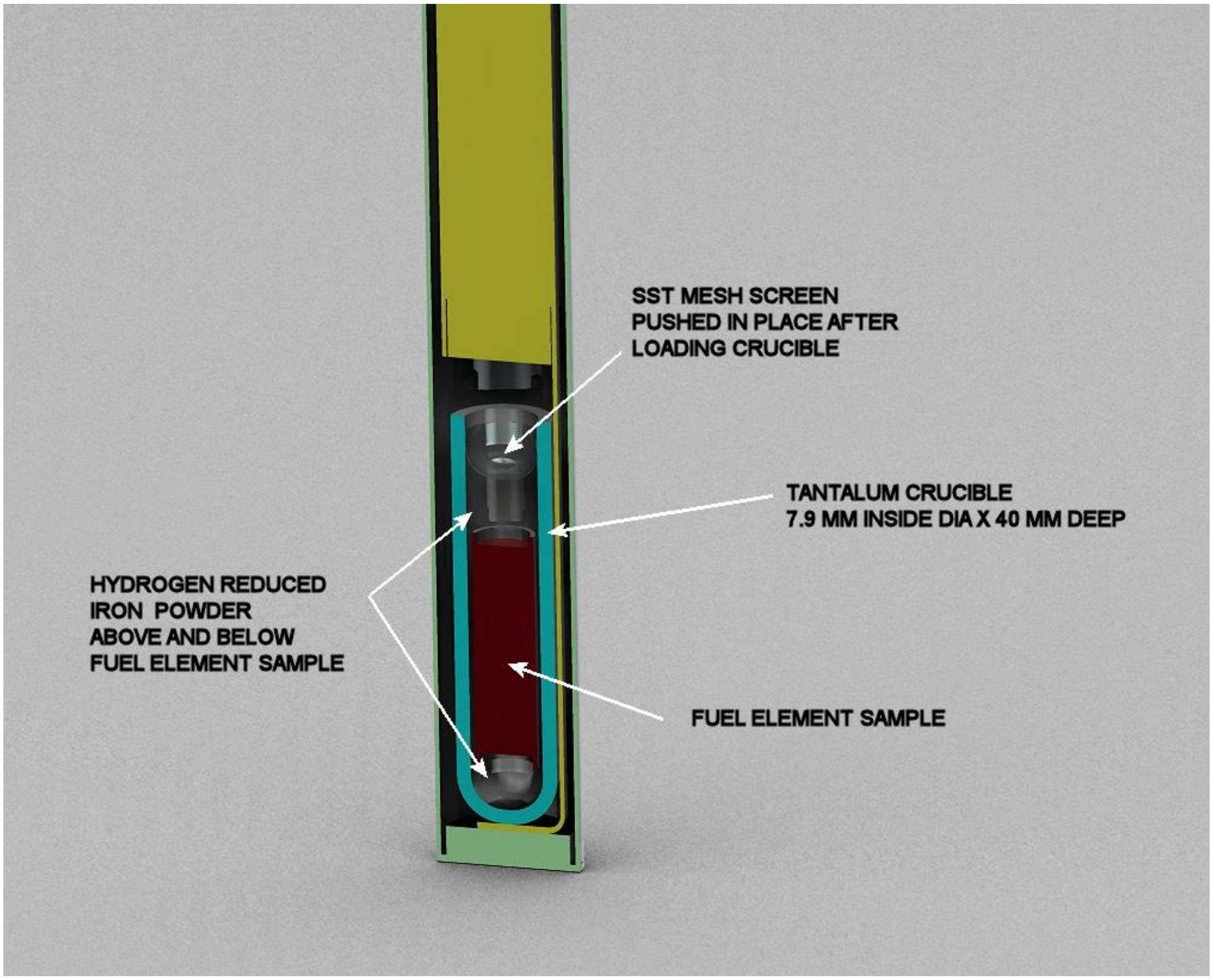

Figure 3, Loaded Crucible

Next, the crucible is attached to the stainless steel displacement rod using a crucible clip (Figure 4). The displacement rod is used to install the crucible in the furnace tube and is also used to reduce the overall internal volume of the test assembly. The furnace tube also has a sodium condenser section whose purpose is to eliminate sodium vapors from migrating into the instrument assembly and damaging the vacuum and pressure transducers. Its effectiveness was described in a previous section.

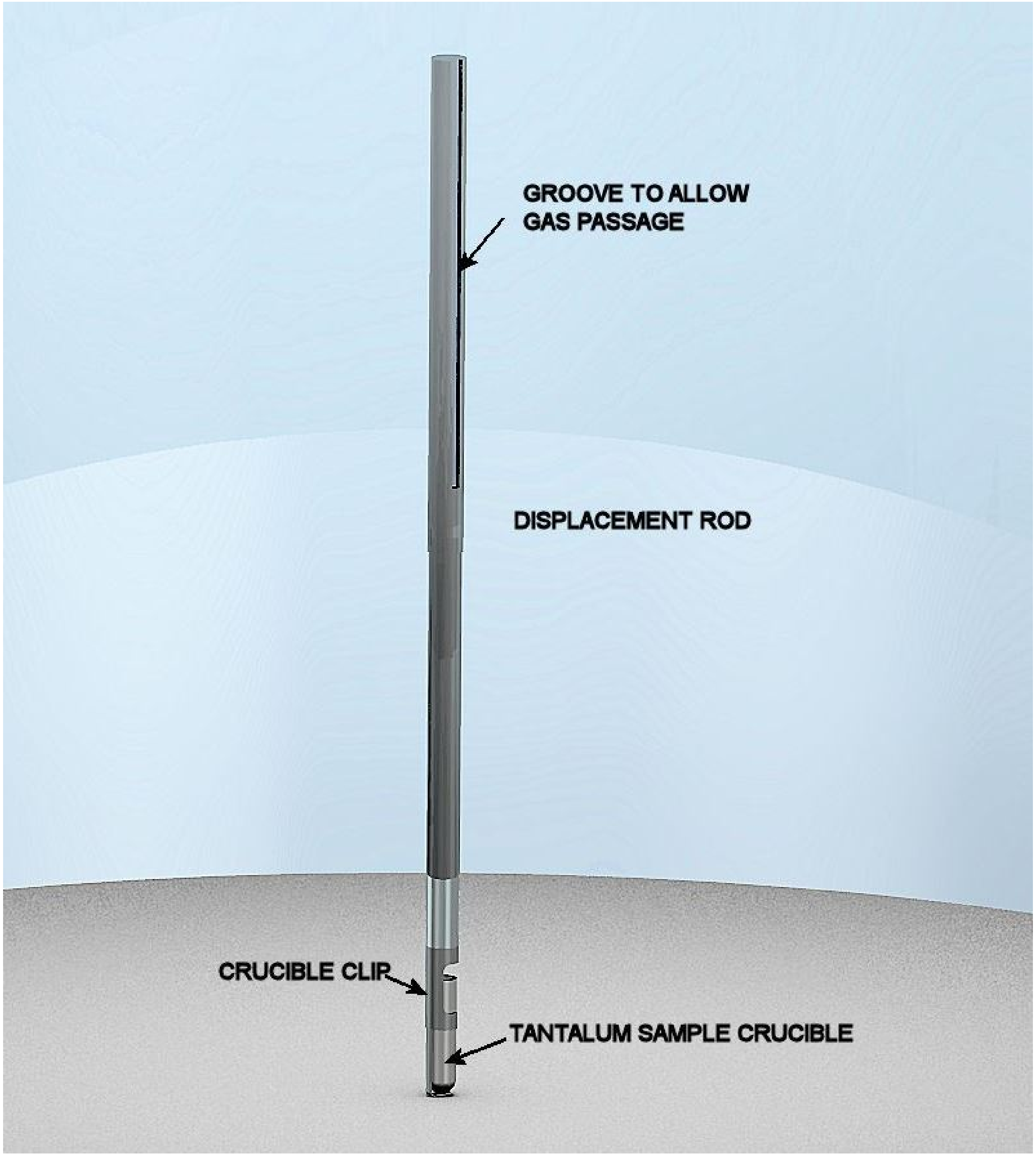

Figure 4, Loaded Furnace Tube

The instrument assembly is next installed on the top of the furnace tube and the two sections are connected with a Swagelok VRC fitting and metal gasket. The assembled test apparatus is shown in Figure 5. The instrument assembly is then connected to a vacuum pump and a leak check of the assembled system is performed by evacuating it to less than 50 millitorr. A decay test is also performed to ensure the leak rate is less than 10 millitorr in 10 minutes.

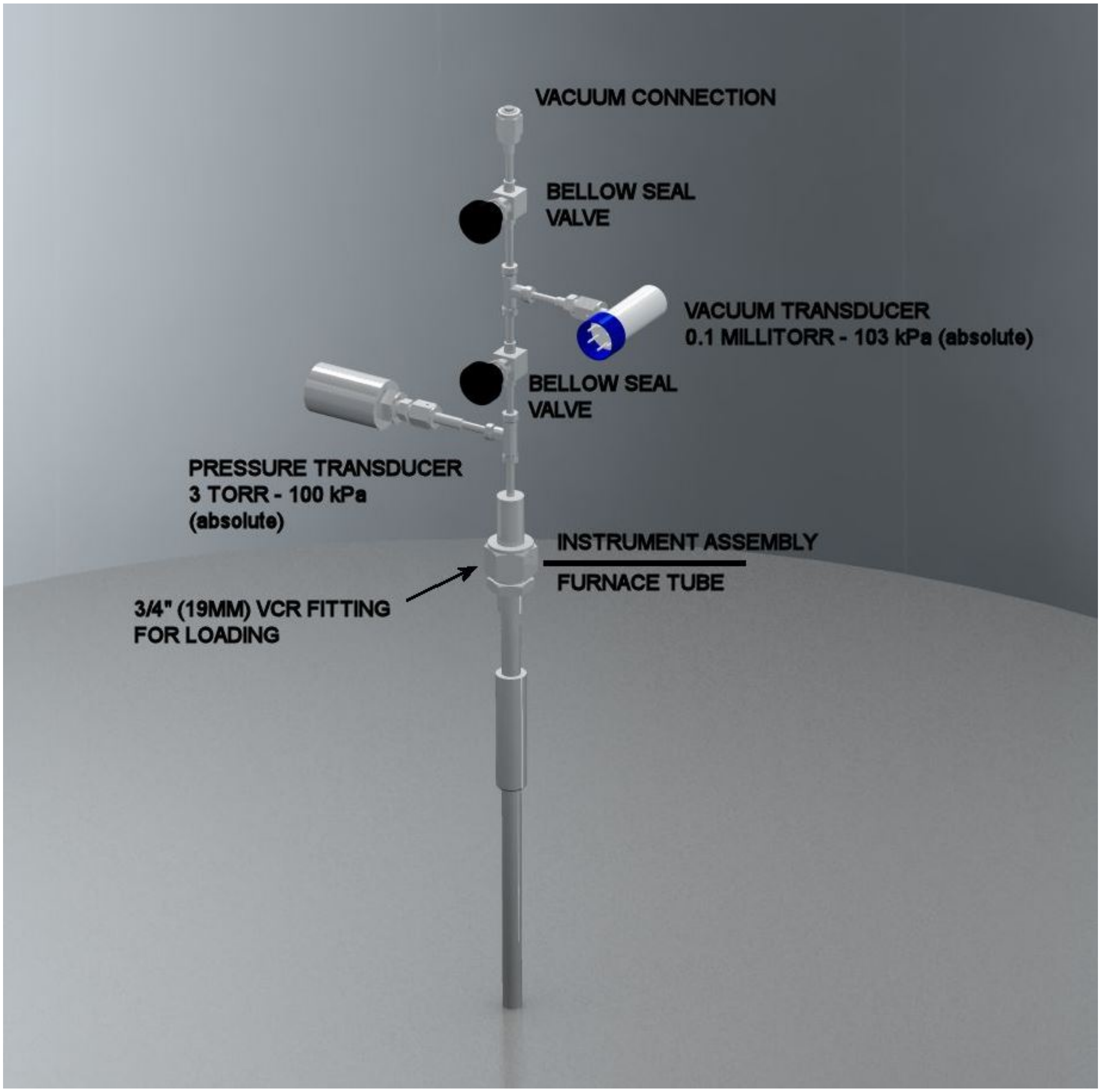

Figure 5, Assembled Test Apparatus

Finally, the assembly is installed in the clamp on support/heat sink, which rests on the insulated support plate on top of the tube furnace. Figure 6 shows a section view of the test assembly in the furnace. The heat sink clamp is then tightened. Figure 7 shows the setup of the equipment in the HFEF argon hot cell.

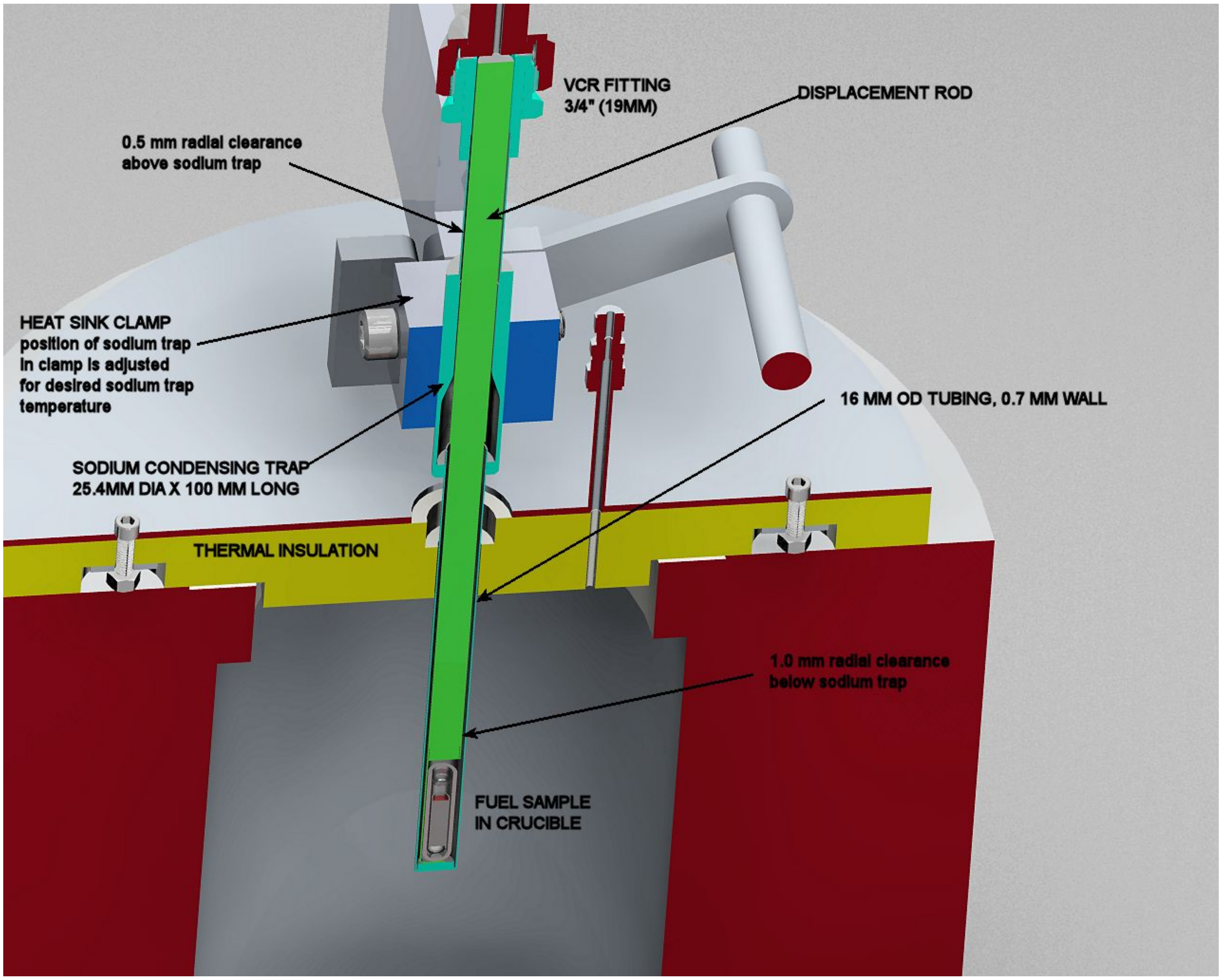

Figure 6, Section View of Test Assembly

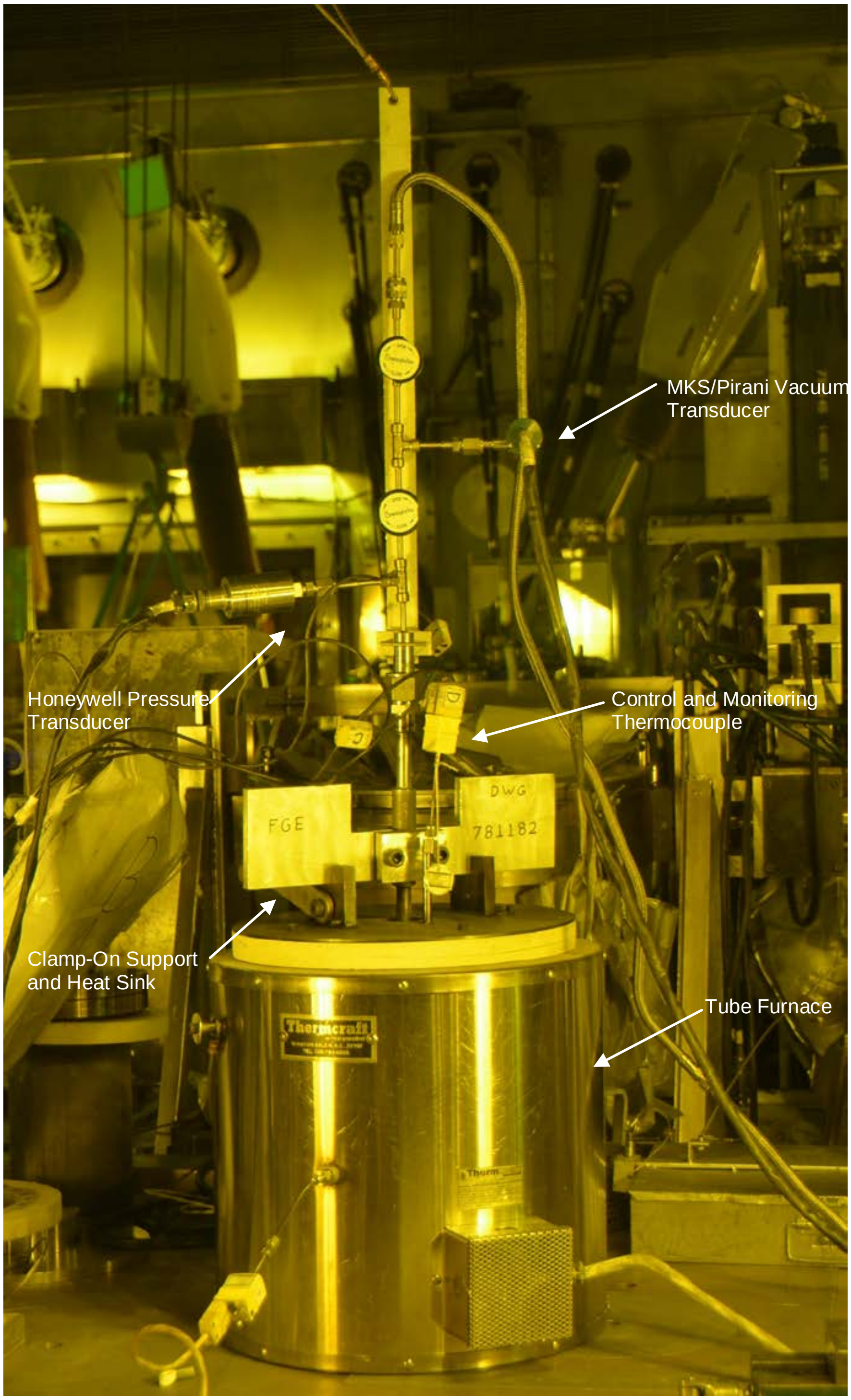

Figure 7, Test Setup in the HFEF Hot Cell

Prior to furnace heat up, all system instrumentation is verified to be operating and data is being recorded. The system pressure is also verified to be < 100 millitorr. The furnace is then heated to 1000°C and held at that temperature for one hour. Figure 8 shows a typical temperature – pressure plot for a test. Figure 9 show pressure versus temperature data for the same test. The initial pressure increase between 400°C and 500°C was unexpected and additional testing will to be performed to further evaluate this behavior.

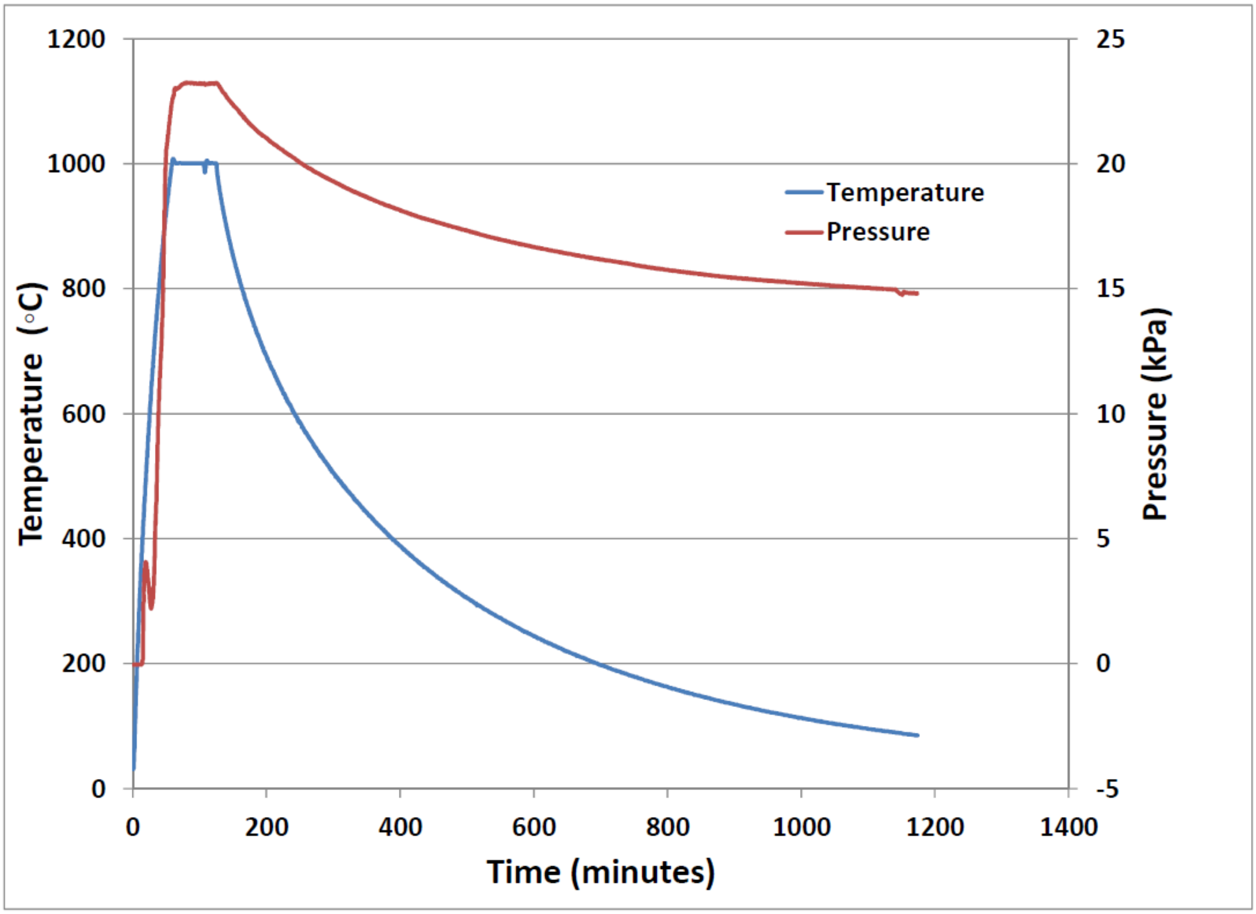

Figure 8, Typical Temperature – Pressure Test Plot

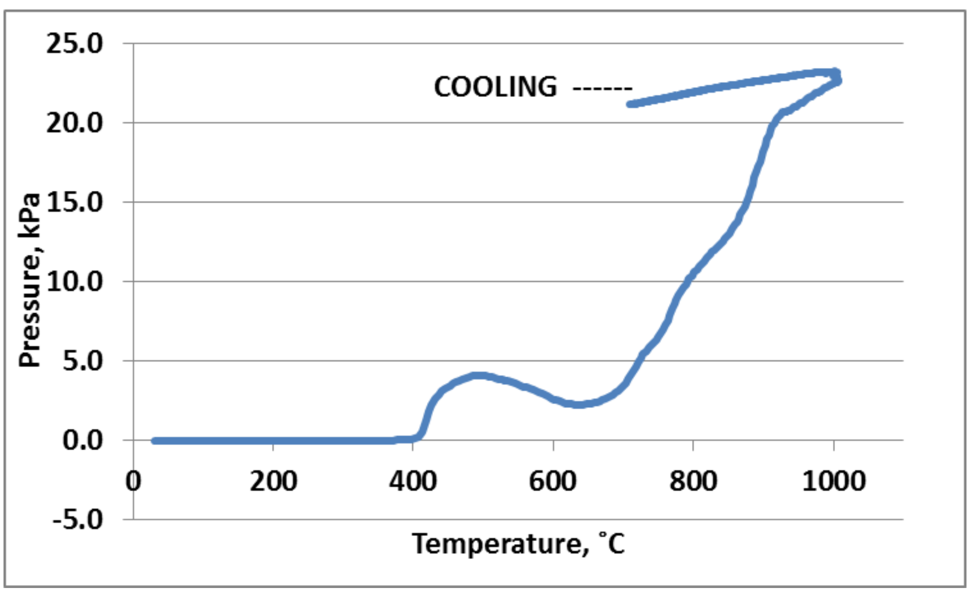

Figure 9, Test Pressure-Temperature Diagram

Following cooldown, the test apparatus was removed from the tube furnace and transferred to the Gas Assay Sample and Recharge (GASR) system. The GASR uses a laser to drill a hole into the furnace tube on the test assembly and recover a gas sample. The gas sample is sent to another facility for gas composition analysis. The results from the gas composition analysis obtained from the RFG system confirm that a fission gas sample (Xe + Kr) was recovered from the fuel matrix. The GASR is also used to measure the volume of the test assembly. Using the pressure of the test assembly measured at various points during the heat up portion of the test or the final pressure measured using the GASR system, and the volume determined with the GASR, the moles of gas that were released from the test specimen were calculated.

In order to ensure all the fuel had completely melted, optical metallography was performed on the fuel/iron ingot in the crucible for the first few tests. The ingot of fuel and iron was removed from the furnace tube. The crucible was first cut lengthwise using a slow speed saw and then one of the longitudinal halves was cut into three approximately equal-length segments. The middle and bottom sections were then mounted and polished. Figure 10 shows a typical cross section of one of the samples. The metallography confirmed that all the fuel melted during heat up.

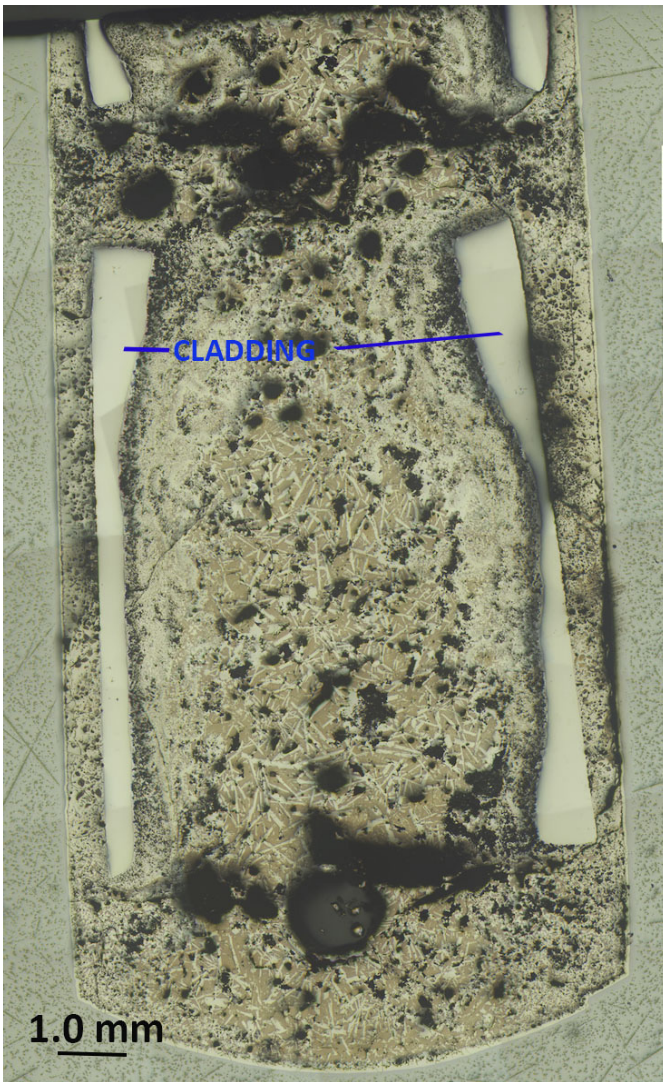

Figure 10, Bottom section of split Ta crucible

5. Summary

A RFG system has been built to recover retained fission gases from metal fuel specimens. The system is located in an argon filled hot cell and is operated remotely. The system as designed, fabricated, and tested has proven to perform its function of melting metallic fast reactor fuel to capture the fission gases, which have been released from the fuel matrix. The RFG System became operational in the HFEF argon hot cell in April 2016. To date, three tests have been performed using the fission gas retention equipment.

6. References

1. G. L. Hofman, L. C. Walters, and T. H. Bauer, “Metallic Fast reactor Fuels,” Progress in Nuclear Energy, Vol.31, No.1 / 2 (1997) p.83-110