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SATS Transient Fission Gas Release Test with Irradiated Fuel under LOCA Conditions

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SUMMARY

The transient fission gas release (tFGR) during the temperature ramp associated with a loss-of-coolant accident (LOCA) in light-water reactors (LWRs) is likely a significant contribution to the total pressure in a fuel rod and may cause an unexpected rod burst. The lack of data related to tFGR continues to be a key gap in understanding LWR cladding burst behavior under LOCA conditions. To fully characterize this behavior, tFGR data must be collected from several different systems that can capture all relevant testing conditions. Oak Ridge National Laboratory (ORNL) has developed a system to measure the integral tFGR from irradiated fuel segments. This system was designed to integrate with the existing Severe Accident Test Station (SATS) and to build upon decades of experience capturing fission gas to characterize fuel behavior. The tFGR system consists of a sweep gas system to transport gases from the in-cell SATS apparatus to an out-of-cell fission gas detection system composed of a series of cold traps to capture the off-gas from the heating tests and a gamma spectrometry system to detect and measure ^{85}Kr. Initial system testing operations were completed during which ^{85}Kr collection and measurement were verified along with the ability to detect stable inert gases. A tFGR test with a high-burnup fuel specimen was successfully conducted by the in-cell SATS-tFGR system at ORNL. The post-test examination is under way, the result of which will be reported in FY24.

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ABBREVIATIONS

CCCTF	Core Conduction Cooldown Test Facility
CT	cold trap
FFRD	fuel fragmentation relocation and dispersal
HBFF	high-burnup fuel fragmentation
IFEL	Irradiation Fuel Examination Laboratory
LOCA	loss-of-coolant accident
LWR	light-water reactor
MT	moisture trap
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
RIL	research information letter
RPV	reactor primary vessel
SATS	Severe Accident Test Station
SCCM	standard cubic centimeters per minute
tFGR	transient fission gas release

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SATS TRANSIENT FISSION GAS RELEASE TEST WITH IRRADIATED FUEL UNDER LOSS-OF-COOLANT ACCIDENT CONDITIONS

1. INTRODUCTION

The US nuclear industry is renewing efforts to extend peak rod average burnup limits beyond the current regulatory burnup limit of 62 GWd/tU rod average [1-2]. However, the US Nuclear Regulatory Commission (NRC) will likely require a new technical basis or modification to the existing technical bases. The greatest challenges to overcome are primarily related to burnup extension and the associated measures required to ensure public safety. Fuel fragmentation relocation and dispersal (FFRD) is the primary technical challenge [3]. FFRD was first observed during an integral loss-of-coolant accident (LOCA) test performed at the Halden reactor and later in semi-integral tests at Studsvik. The Halden and Studsvik tests assessed high-burnup fuel (>67 GWd/tU), showing that fuel pellets could pulverize into a sand-like consistency. In a postulated LOCA event, a significant fraction of these particles could axially relocate within the balloon region and become susceptible to ejection through cladding rupture openings into the reactor primary vessel (RPV). This postulated series of events is now collectively known as FFRD, and fuel pulverization has been termed high-burnup fuel fragmentation (HBFF).

The NRC published a research information letter (RIL) [3] to provide their interpretation of FFRD experimental data and to highlight important elements for consideration in subsequent safety cases. The RIL highlights five elements and provides a technical basis for each element. The elements are as follows: (1) threshold for fine fragmentation, (2) cladding strain threshold for fuel relocation, (3) mass considered dispersible, (4) transient fission gas release (tFGR) and its effect on cladding balloon-burst behavior, and (5) packing fraction in balloon region. Although limited data are available [4-10], accurately predicting tFGR from high-burnup UO_2 fuel remains very difficult. Furthermore, tFGR data are generally lacking, as is the consensus on the appropriate experimental approach and interpretation of the data. Therefore, an R&D program has been conducted by the Advanced Fuels Campaign to develop a tFGR system that can be assessed across a broad range of conditions, including pressure, heating rate, temperature, and other conditions.

The US Department of Energy's Oak Ridge National Laboratory (ORNL) has developed a system to measure the integral tFGR from irradiated fuel segments. The system design, testing capabilities, and construction were reported in FY 2022 [11]. This milestone report summarizes the first in-cell tFGR test with the irradiated high-burnup fuel.

2. EXPERIMENTAL SECTION

A high-burnup pressurized water reactor North Anna M5 fuel segment irradiated to approximately 70 GWd/tU [12, 13] was used for tFGR testing. The ^{235}U initial enrichment was 4.20 wt %. The parent rod for this test is known as B16 (A/G 651). The segment of fuel (651F3) was cut approximately 292 cm from the bottom of the fuel pin [14]. The tested specimen is 31.7 mm long.

The test train used to conduct these in-cell tFGR tests is shown in Figure 1. Two Type S thermocouples are strapped 180° apart onto the X-nickel alloy (similar to Inconel HX or Hastelloy X) sample holder above the sample. One of these thermocouples controls the SATS furnace power to achieve the desired hold temperature. The other one monitors circumferential temperature distribution. Before conducting the in-cell tests, out-of-cell thermal benchmark tests were conducted with thermocouples attached directly onto the sample outer surface. For in-cell testing, no thermocouple was attached on the sample surface. The irradiated sample temperature was deduced from the out-of-cell thermal benchmark tests. This approach has been used for short specimens in high-temperature steam oxidation tests [13,15].

The new tFGR system is located in the ORNL Irradiation Fuel Examination Laboratory (IFEL) and is built on previous ORNL experience with the Core Conduction Cooldown Test Facility (CCCTF) [16]. Figure 2 shows a schematic diagram of Severe Accident Test Station (SATS) tFGR facility. This facility was designed to integrate with the existing SATS [17,18]. Figure 3 shows a flow diagram overview of some of the tFGR system's major components and indicates how they connect and interact with each other. The tFGR system consists of a sweep gas system to transport gases from the in-cell SATS apparatus (Figure 4) to an out-of-cell fission gas detection system (Figure 5) that is composed of a series of cold traps to capture the off-gas from the heating tests and a gamma spectrometry system to detect and measure ^{85}Kr. The SATS LOCA furnace is used to heat an irradiated fuel sample under conditions that mimic heating experienced by irradiated fuel in a LOCA. This releases a portion of the fission gas inventory trapped in the fuel following irradiation. The released gases are retrieved by a low flow rate sweep gas (helium) that transports the fission gas to the cold trap system for analysis.

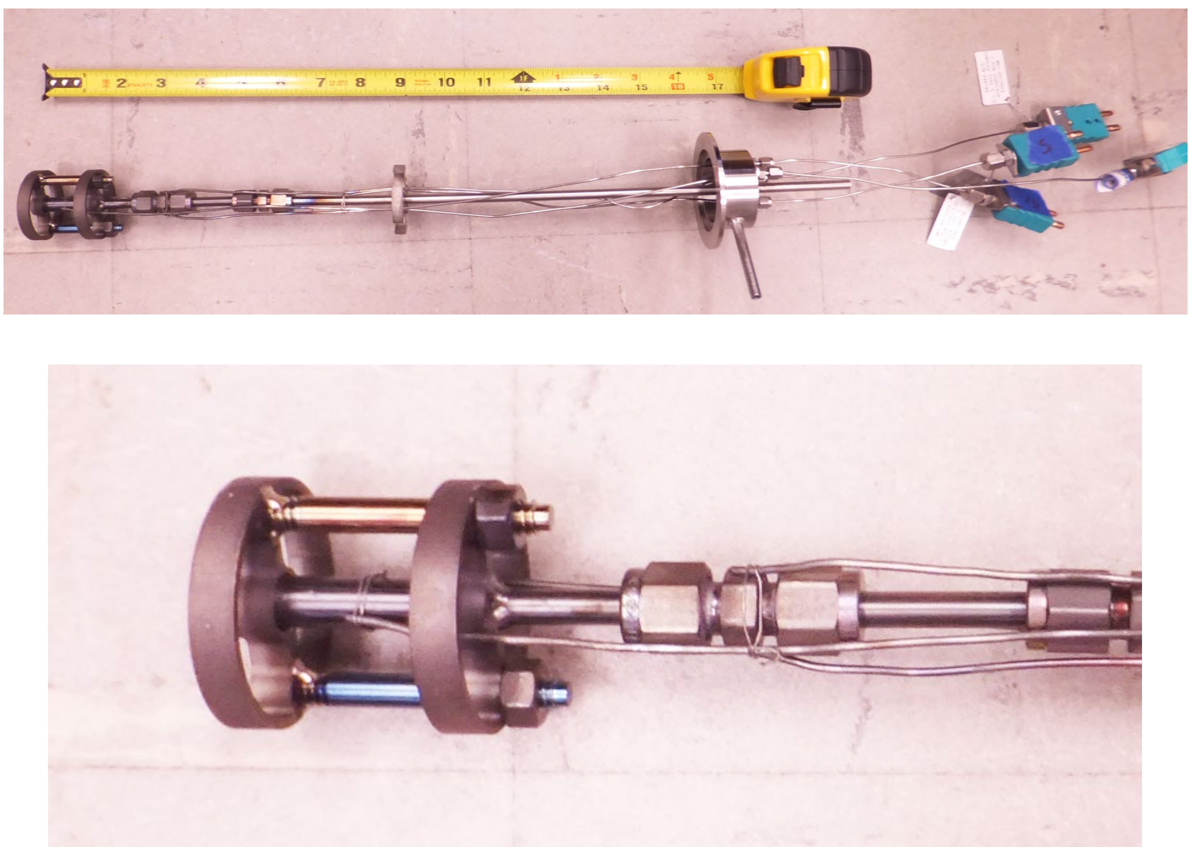

Figure 1. Test train (top) and sample holder (bottom) for in-cell SATS tFGR testing.

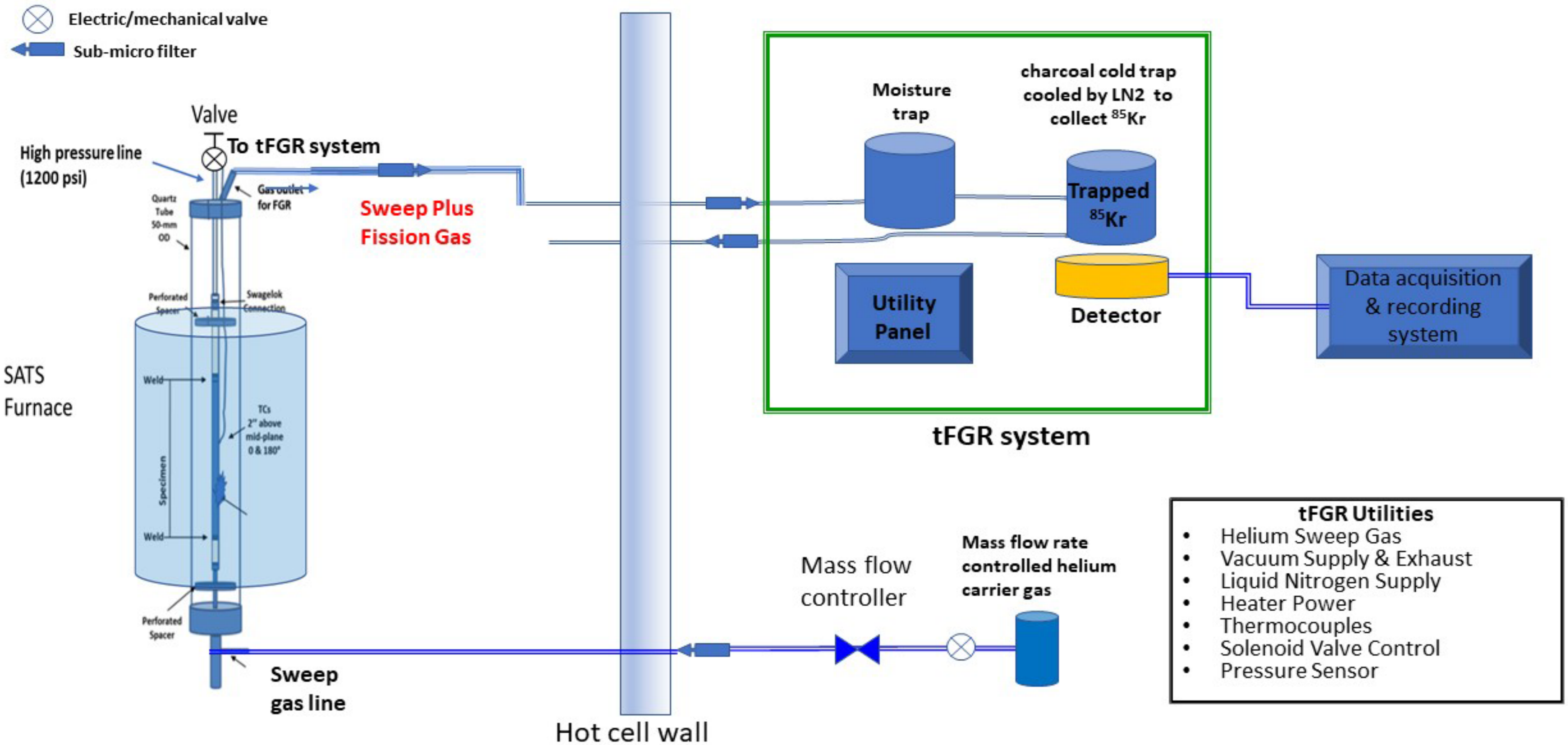

Figure 2. Schematic diagram of SATS tFGR facility for real-time tFGR measurement.

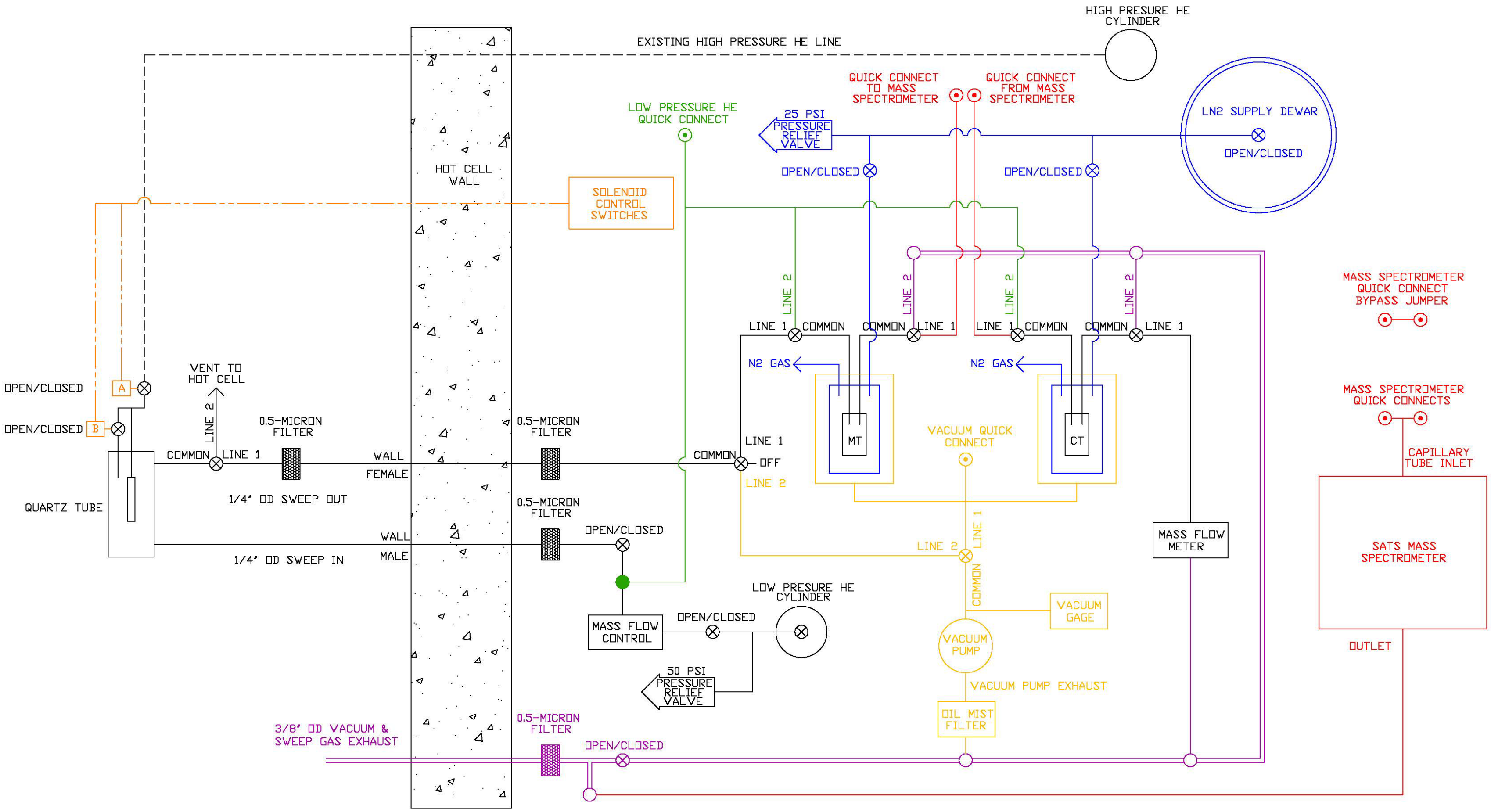

Figure 3. Flow diagram of the tFGR system.

During normal low-pressure operation, helium sweep gas is metered through a mass flow controller. The helium then passes through the hot-cell wall and enters the bottom of the quartz tube that contains the test specimen. As fission gas including stable Kr and Xe isotopes as well as radioactive ^{85}Kr is released from the test specimen during heating, it mixes with the sweep gas and exits the quartz tube at the top. The mixed gases then pass back through the hot-cell wall and on to the moisture trap assembly located on the tFGR table. When the mixed gases pass through the moisture trap, any water vapor present in the sweep gas stream is removed, and fission gases and helium will pass on to the cold trap assembly. The cold trap assembly contains a column of activated charcoal are submerged in liquid nitrogen cooling. As the fission gas (^{85}Kr) encounters the charcoal, it is absorbed and trapped in place while the helium sweep gas passes through and returns to the hot cell through an exit mass flow meter and integrated exhaust system. The released gases transferred to the tFGR table are analyzed online by a gamma spectrometry station under the cold trap.

The test conditions used for this first test are not fully representative of LOCA conditions because the fuel segment was not pressurized. This initial test was still a confirmation of the ability of the system to generate, transport, capture, and evaluate tFGR. The fuel segment cut from 651F3 was suspended in the center of the LOCA furnace with the fixture shown in Figure 1. No end-caps were applied to the fuel segment so that gas from the test could freely flow from the sample to the tFGR table. The furnace was ramped at 1°C/s to 500°C and held for 30 minutes. The furnace was ramped again at 1°C/s to 700°C and held for 30 minutes before being shut down. Following this the same sample was ramped at 1°C/s to 800°C and held for 1 hour then ramped at 1°C/s to 1000°C and held for 15 minutes. This second ramping is not shown in this report and represents conditions beyond LOCA burst conditions. There is nonetheless scientific interest in tFGR at these temperatures. Going beyond 1000°C would move the fuel from burst fission gas release range into diffusion driven fission gas release which is not relevant to LOCA fuel performance.

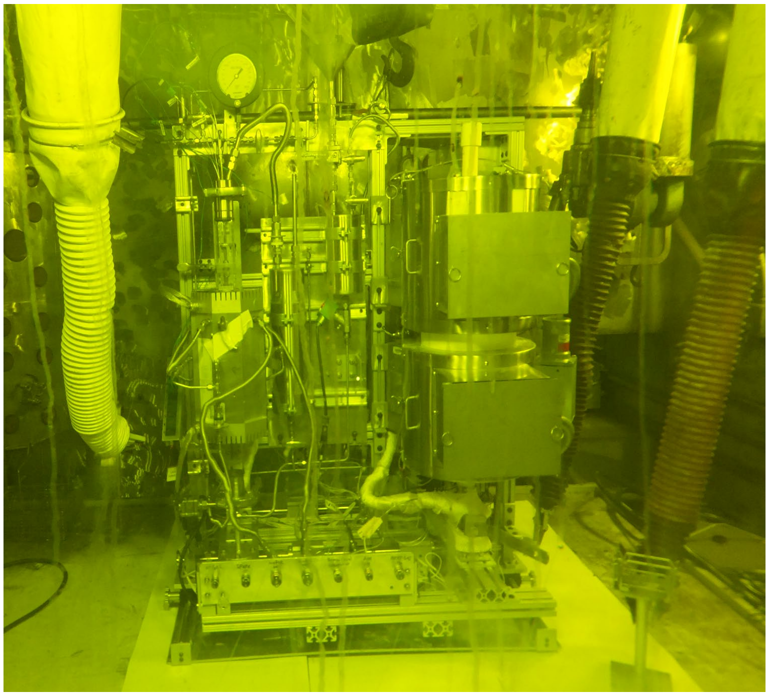

Figure 4. SATS installed in ORNL hot cell.

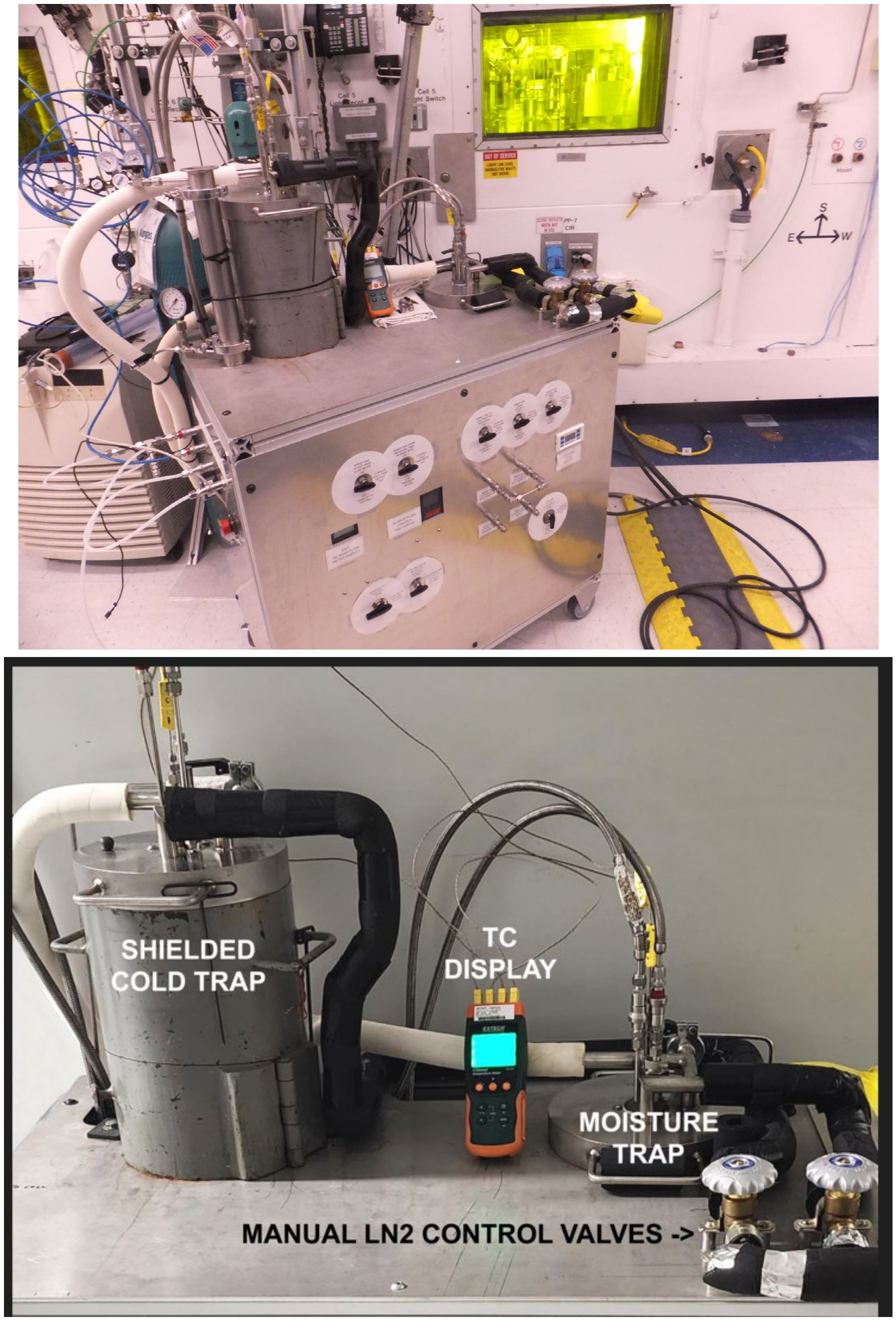

Figure 5. The SATS tFGR system (top) and the moisture & shieled cold traps (bottom).

3. RESULTS

Figure 6 shows temperature and cumulative ^{85}Kr release histories for the SATS LOCA relevant transients up to 500°C and 700°C. Both instantaneous ratemeter measurements (qualitative and averaged over 3 seconds) and interval counted (quantitative with a 300 second count time) values were collected; after test completion the ratemeter values were scaled to the final interval values for a more complete picture of the release behavior as a function of time. Note that as the Kr-85 inventory increased, the detector to trap distance was changed (increased) to avoid overloading the detector. The following temperature history was applied to the fuel sample:

1. Increase temperature to 500°C at 1°C/s.
2. Hold for 30 min.
3. Increase temperature to 700°C at 1°C/s.
4. Hold at 700°C for 30 min.
5. Rapid natural cooling.

Considering a delayed time of 4–5 min for the specimen internal regions to reach temperature and the gas to transfer from the SATS test chamber to the tFGR system's ^{85}Kr detector, the ^{85}Kr release transients were judged to be near instantaneous release.

Figure 6 reveals two characteristic releases of this type of transient:

1. On the temperature transient from room temperature to 500°C, the ^{85}Kr gas release increased with increasing temperature. During the plateau at 500°C, cumulative activity is approximately 3,300 µCi. Additional gas release was not observed during the dwell at 500°C. This release is equivalent to a tFGR of 5.3% which is in-line with expectations from literature [3, 19-25] and is likely somewhat elevated compared to release if the fuel was tested under end of life pin pressure.
2. More releases were measured during the temperature increase from 500°C to 700°C. Cumulative activity is approximately 5,400 µCi. This is equivalent to a tFGR of 8.6%. There is a small amount of additional fission gas release observed during the dwell at 700°C, but this may also be statistical variations in the counts.

These burst releases at 500°C and 700°C are similar to the burst releases observed by Hiernaut [25] in small scale laboratory annealing tests of irradiated UO_2. An image of the fuel after the heating test is shown in Figure 7.

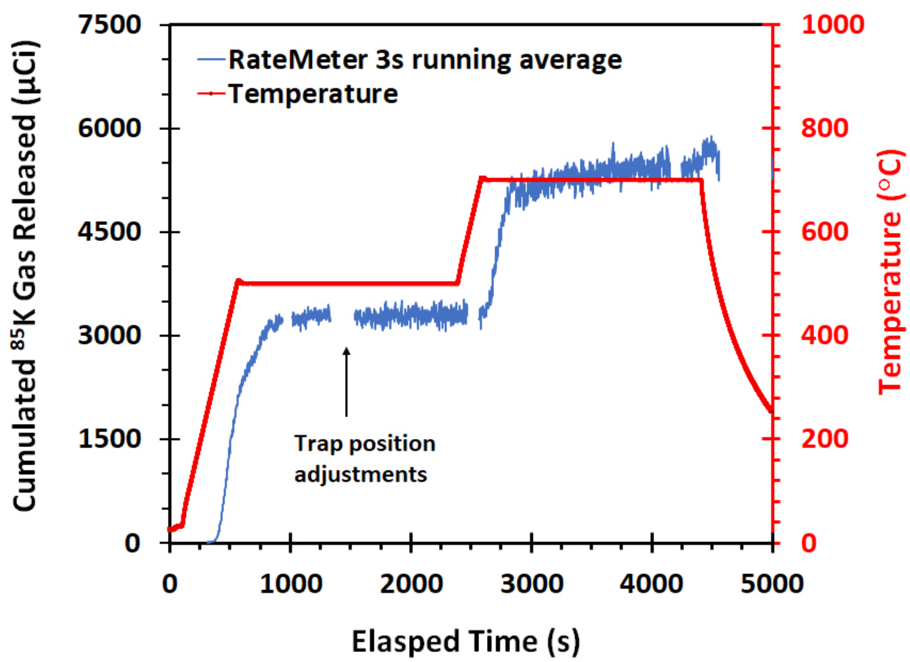

Figure 6. Temperature and cumulated ^{85}Kr release histories for the SATS LOCA-type transients.

Figure 7. Images of the post-test tFGR sample tested under LOCA conditions.

4. CONCLUSION

To address the lack of data related to tFGR and its impact on Light Water Reactor cladding burst behavior under LOCA conditions, a system to measure the integral tFGR from irradiated fuel segments was designed and integrated with the existing SATS. The base of this new capability was built upon decades of experience capturing fission gas to characterize fuel behavior developed by other ORNL programs. The tFGR addition consists of a sweep gas system to transport gases from the in-cell SATS apparatus to an out-of-cell fission gas detection system composed of two cold traps to first capture tramp moisture and then the off-gas from the heating tests; a gamma spectrometry system is used to detect and measure the ^{85}Kr in the second trap. Initial system testing operations have been completed; ^{85}Kr collection and measurement were verified along with the ability to detect and quantify stable inert gas fractions. A tFGR test with a high-burnup fuel specimen was successfully conducted by the in-cell SATS-tFGR system at the ORNL IFEL hot cell facility. As expected for high burnup fuel, the gas release was a function of temperature, and the release rapidly followed the temperature changes. Thus, it is postulated that this rapid release will add to the pressure loading during a LOCA. The likely clad stress magnitude and its importance are yet to be determined. The post-test examinations are under way and the results will be reported in FY24. Future tests will implement the study of tFGR under more prototypic pressure conditions to better evaluate the impact of rod pressure on tFGR.

5. ACKNOWLEDGMENT

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