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First high temperature safety tests of AGR-1 TRISO fuel with the Fuel Accident Condition Simulator (FACS) furnace

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HIGHLIGHTS

- Three high-temperature fuel performance tests were performed on US TRISO coated particle fuel.
- Release of fission products Ag, Cs, Eu, Sr, and Kr from fuel specimens was measured at 1600 and 1800 °C.
- Behavior of fission products provides information on the integrity of specific coating layers.

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ABSTRACT

Three TRISO fuel compacts from the AGR-1 irradiation experiment were subjected to safety tests at 1600 and 1800 °C for approximately 300 h to evaluate the fission product retention characteristics. Silver behavior was dominated by rapid release of an appreciable fraction of the compact inventory (3–34%) at the beginning of the tests, believed to be from inventory residing in the compact matrix and outer pyrocarbon (OPyC) prior to the safety test. Measurable release of silver from intact particles appears to become apparent only after ~60 h at 1800 °C. The release rate for europium and strontium was nearly constant for 300 h at 1600 °C (reaching maximum values of approximately 2×10^{-3} and 8×10^{-4} respectively), and at this temperature the release may be mostly limited to inventory in the compact matrix and OPyC prior to the safety test. The release rate for both elements increased after approximately 120 h at 1800 °C, possibly indicating additional measurable release through the intact particle coatings. Cesium fractional release from particles with intact coatings was $<10^{-6}$ after 300 h at 1600 °C or 100 h at 1800 °C, but release from the rare particles that experienced SiC failure during the test could be significant. However, Kr release was still very low for 300 h 1600 °C ($<2 \times 10^{-6}$). At 1800 °C, krypton release increased noticeably after SiC failure, reflecting transport through the intact outer pyrocarbon layer. Nonetheless, the krypton and cesium release fractions remained less than approximately 10^{-3} after 277 h at 1800 °C.

1. Introduction

Tristructural isotropic (TRISO) coated particle fuel is a robust fuel form designed for use in high temperature gas-cooled reactors (HTGRs) [1,2]. The fuel provides a high degree of fission product retention during reactor operation and during depressurized loss of forced cooling, allowing for high reactor core and coolant temperatures. US TRISO fuel development was re-initiated in the early 2000s as part of the US Department of Energy Advanced Gas Reactor (AGR) Fuel Development and Qualification Program [3]. The objective of the program is to perform the requisite research and development needed to qualify TRISO fuel for use in an HTGR. As part of this program, a series of fuel irradiation experiments is being conducted in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). These experiments are intended to provide data on fuel performance under irradiation, support fuel process development, qualify the fuel for normal operating conditions, provide irradiated fuel for safety testing, and support the development of fuel performance and fission product transport models. The first of these irradiation tests, designated AGR-1, began in the ATR in December of 2006 and ended in November 2009.

Post-irradiation examination (PIE) of the AGR-1 fuel is currently in progress at INL and Oak Ridge National Laboratory (ORNL). The PIE focuses on assessing the fuel performance during the

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irradiation, primarily by quantifying the level of fission product release from particles and fuel compacts and characterizing irradiation-induced changes to the fuel kernel and coating microstructures in order to better understand potential causes of coating failures [4–9].

A key component of TRISO fuel performance evaluations is post-irradiation safety testing, in which fuel specimens (either intact fuel elements or loose particles) are heated to elevated temperatures representative of reactor accident scenarios and the release of fission products is measured [10–17]. The tests can provide information on fission product diffusion through intact coating layers, failure rates for various coating layers, and the total fraction of fission products released at high temperatures. These data comprise a vital part of reactor design and safety assessments.

Safety testing of the AGR-1 fuel is in progress at INL and ORNL, involving a number of AGR-1 compacts spanning a range of irradiation conditions (burnup, fast neutron fluence, and irradiation temperature) and safety test temperatures between 1600 and 1800 °C [18]. While peak core temperatures are generally not expected to exceed approximately 1600 °C during a loss of forced coolant flow incident, temperatures as high as 1800 °C are used as margin tests and to accelerate thermally driven phenomena (e.g., fission product diffusion and coating failure) to aid in determining their temperature dependence. The results of the first three AGR-1 safety tests using the recently commissioned Fuel Accident Condition Simulator (FACS) furnace at INL are presented here.

2. Experimental

2.1. AGR-1 fuel and irradiation

The AGR-1 fuel particles consist of 350 μm diameter spherical kernels comprised of a heterogeneous mixture of uranium oxide and uranium carbide (denoted UCO), with 19.7% uranium enrichment [19]. The kernels were coated with porous carbon buffer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC) layers. The coated particles were pressed into right cylindrical compacts nominally 25 mm in length and 12.3 mm in diameter containing approximately 4100 coated particles each. The final compact consists of a uniform distribution of coated particles in a carbonaceous matrix. A Baseline fuel and three fuel variants were included in the AGR-1 irradiation, with each variant fabricated by varying one step of the coating process to produce slightly different IPyC or SiC coating properties [20]. One key goal of the experiment is to identify any fuel performance differences between the fuel types, either during the irradiation or during post-irradiation high temperature safety testing, in order to support optimization of the fuel fabrication process and eventual selection of a reference fuel for qualification.

A total of 72 compacts were irradiated in the AGR-1 experiment in six separate capsules. Each capsule contained 12 compacts of a specific fuel type [21]. Each compact has a unique identifier in the format X–Y–Z that denotes the original position in the irradiation experiment. X indicates the capsule, Y indicates the vertical level within the capsule, and Z indicates the stack as described in Ref. [5]. The experiment completed 620 effective full power days in the reactor and achieved a compact-average peak burnup of 19.6% fissions per initial heavy metal atom (FIMA) with zero TRISO coating failures observed based on the measured fission gas release-to-birth ratios during the irradiation [22,23].

2.2. Safety testing fuel specimens

The three AGR-1 fuel compacts selected for these tests are listed in Table 1 along with selected fuel properties and irradiation conditions. Note that Compact 6-4-1 was AGR-1 Baseline fuel, while Compacts 4-3-3 and 4-3-2 were Variant 3 fuel, which was fabricated to have a smaller SiC grain size relative to the Baseline fuel.

Table 1
Properties [24] and irradiation conditions [25,26] for the safety test fuel specimens.

Compact ID	AGR-1 6-4-1	AGR-1 4-3-3	AGR-1 4-3-2
AGR-1 fuel type	Baseline	Variant 3	
^{235}U enrichment (%)	19.74 (±0.05)	19.74 (±0.05)	
Kernel diameter (μm)	349.7 (±9.0)	349.7 (±9.0)	
Buffer (μm)	103.5 (±8.2)	104.2 (±7.8)	
IPyC (μm)	39.4 (±2.3)	38.8 (±2.1)	
SiC (μm)	35.3 (±1.3)	35.9 (±2.1)	
OPyC (μm)	41.0 (±2.1)	39.3 (±2.1)	
Particles/compact	4145	4126	
Particle packing fraction (%)	36.9	36.0	
Burnup (%FIMA)	13.4	18.6	16.4
Fast fluence × 10^{25} (n/m^2)	2.43	4.16	3.68
Irradiation temperature[a] (°C)	1041	1094	1057

[a] Time-average, volume-average irradiation temperature.

2.3. Safety testing

The fuel compacts were heated in the FACS furnace located at the Materials and Fuels Complex (MFC) at INL. The FACS furnace utilizes a graphite resistance-heating element and has a refractory metal hot zone (Fig. 1). Fuel specimens are supported on a tantalum holder inside a tantalum flow tube. High purity helium is injected into the flow tube from the bottom, sweeps past the fuel specimen and out the top of the flow tube, and then flows out of the furnace to the Fission Gas Monitoring System (FGMS). A water-cooled cold finger is used to position a steel condensation plate immediately above the hot zone and in the path of helium flow as it exits the flow tube. Condensation plates are used to collect condensable fission products during a test, and can be exchanged during furnace operation so that time-dependent data on fission product release from the fuel can be obtained. The furnace is capable of heating specimens as high as 2000 °C. The main furnace chamber is installed in the shielded hot cells of the Hot Fuel Examination Facility (HFEF) at MFC, and is controlled from a user workstation located adjacent to the hot cell window. The atmosphere inside of the HFEF main hot cell is argon with O_2 and H_2O impurities controlled below approximately 100 ppm.

The FGMS consists of two lead-shielded, cryogenically-cooled charcoal traps used to retain fission gases (primarily ^{85}Kr) that may be released from the fuel during a test and carried to the traps along with the helium sweep gas. Each cold trap is continuously monitored with a high purity germanium gamma detector during a test to provide real-time data on the buildup of radioactive fission gases. During initial testing and calibration of the FGMS system, it was observed that a radioactive gas source injected into the FACS furnace in a helium carrier gas flow of 1 L/min was first detected in the FGMS cold traps in approximately 4 min, with 99% of the activity collected in the traps within approximately 30 min.

Both the FACS furnace and FGMS have been described in further detail previously [27]. The tests presented in this paper mark the first use of these systems with irradiated fuel. In addition to providing important data on AGR-1 fuel performance at elevated temperatures, the tests were also used as a performance evaluation of the equipment and methods used at INL. Although destructive analysis of the AGR-1 compacts is often performed following safety tests [28], this will not be discussed in this paper.

The compacts were heated in ultra-pure helium flowing at 1 L/min. The peak temperatures for the tests were 1600 °C (6-4-1