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Ceramography of irradiated TRISO fuel from the AGR-2 experiment

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ABSTRACT

Ceramography was performed on cross sections from four tristructural isotropic (TRISO) coated particle fuel compacts selected from the AGR-2 experiment, which was irradiated between June 2010 and October 2013 in the Advanced Test Reactor (ATR). The individual fuel specimens examined in this study contained coated particles with either uranium oxide (UO_2) kernels or uranium oxide/uranium carbide (UCO) kernels that were irradiated to final burnup values between 9.0 and 11.5% FIMA. These examinations were intended to explore kernel and coating morphology evolution during irradiation. This included observations of kernel porosity, kernel swelling, and irradiation-induced TRISO coating layer fracture and separation. Variations in behavior within a specific cross section, which could be related to temperature or burnup gradients within the fuel compact, were also explored. Results were compared with similar investigations performed as part of the earlier AGR-1 irradiation experiment. The criteria for categorizing AGR-1 particle post-irradiation morphologies during ceramographic exams were applied to the AGR-2 compact particles examined. This paper presents the results of the AGR-2 examinations and discusses the key implications for fuel irradiation performance.

1. Introduction

The AGR-2 experiment, the second in a series of test irradiations for the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program (Petti et al., 2010), contained both uranium oxide (UO_2) and uranium oxide/uranium carbide (UCO) tristructural isotropic (TRISO) fuel. The experiment was implemented with the following three objectives (Collin, 2011):

1. Irradiate UCO and UO_2 fuel produced in a large (150 mm diameter) coater in an engineering-scale pilot line.
2. Provide irradiated fuel samples for post-irradiation examination and safety testing.
3. Support the development of an understanding of the relationship between fuel-fabrication processes, fuel-product properties, and irradiation performance.

The purpose of performing ceramographic post-irradiation examinations (PIE) on AGR-2 compacts is to provide fuel-performance data to help fulfill Objective 3 of the AGR-2 experiment. Specifically, this was to assess the kernel and coating morphology evolution during irradiation. This includes kernel swelling, kernel porosity, and coating fracture. Examination of fuel compact cross sections enabled particles to be examined in their original locations within the fuel compacts. In this manner, any trends in particle behavior relative to location in the compact which may have been influenced by local gradients in burnup and temperature, could be identified. Similar examinations were performed previously on fuel from the AGR-1 irradiation experiment (Ploger et al., 2014), and AGR-1 results are compared to the AGR-2 results presented here.

2. AGR-2 experiment background

The AGR-2 fuel and irradiation have been described by Harp et al. (2017). AGR-2 coatings were applied at BWX Technologies (BWXT) using an engineering-scale (150 mm diameter) coater, compared to the lab-scale (50 mm diameter) coater used for AGR-1 (Collin, 2011). Thus, AGR-2 served as a demonstration of the performance of TRISO fuel with coatings fabricated at an industrial vendor. While the coating layers were deposited with process parameters similar to those used for the AGR-1 Variant 3 fuel, other minor process variations were introduced. Among these was a longer fluidization time between the end of buffer deposition and the beginning of inner-pyrolytic carbon (IPyC) layer application. The TRISO particles were over-coated and pressed into fuel compacts that were nominally 12.3 mm in diameter and 25.1 mm long. UCO compacts had a particle packing fraction of 37% and contained approximately 3180 particles each. UO_2 compacts had a particle packing fraction of 23% and contained approximately 1540 particles each.

The AGR-2 experiment was irradiated in the B-12 position of the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL)

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and contained six independently controlled and monitored capsules. Capsules 2, 3, 5, and 6 contained fuel fabricated in the US, while the remaining two capsules contained fuel supplied by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, France) and Pebble Bed Modular Reactor Limited (PBMR, South Africa). Each US capsule contained twelve fuel compacts of a specific type (UO_2 or UCO). The irradiation capsule configuration is discussed by Collin (2011) and Harp et al. (2017). Compacts were identified with a numbering scheme based on their location in each capsule during irradiation (Harp et al., 2017).

The experiment was irradiated for 559.2 effective full-power days. Compact-average burnups in the US capsules ranged from 7.3 to 13.2% fissions per initial metal atom (FIMA) for UCO, and 9.0 to 10.7% FIMA for UO_2. The time-averaged, volume averaged (TAVA) temperature for UCO fuel ranged from 987 °C to 1296 °C and for UO_2 fuel from 996 °C to 1062 °C (Collin, 2014). Capsule 2 was deliberately operated at a very high temperature (the capsule time-averaged peak temperature was 1360 °C) in order to explore the high temperature performance margin with the UCO fuel. A summary of test train configurations, diagrams, and fuel irradiation parameters (e.g. neutronics and thermal analyses, including fuel temperature gradients) for all US Capsules in the AGR-2 experiment is available (Collin, 2014; Hawkes, 2014; Hawkes et al., 2015; Sterbentz, 2014).

3. Specimen selection and preparation

In light of the objectives outlined in Section 1, four AGR-2 compacts (3 UCO and 1 UO_2) were selected for ceramographic examination and comparison. Table 1 lists the specific compacts with their fuel properties and irradiation conditions. Temperature gradients existed in the compacts during irradiation, and may have affected observed particle morphologies discussed later in this article. Table 1 includes the TAVA compact irradiation temperature, the time-averaged (TA) minimum temperature, and the TA maximum temperature. Taking Compact 2-1-3 as an example, on average, the hottest location within that compact was at 1305 °C and the coldest location within that compact was at 1034 °C. Table 1 also includes the TA particle power within each compact. Note that while the average UO_2 particle power is higher than the UCO particle power, UCO compacts have more than twice as many particles as UO_2 compacts so that the UCO compact power is higher than the UO_2 compact power.

Table 1 also lists the identification numbers given to each compact and the ceramographic mounts from each compact. In the irradiation test train, capsules were numbered from bottom to top; thus, Capsule 1 was at the bottom of the test train and Capsule 6 was at the top. Compacts were given unique identifiers in the irradiation test train according to the capsule number, axial level within the capsule, and stack within the capsule. Each capsule had three stacks of four compacts, with stacks 1 and 2 nearest to the center of the reactor core (Harp et al., 2017). Compact 2-1-3, for example, was in Capsule 2, at level 1 (the bottom of the stack), in stack 3.

Methods applied for the specimen preparation and examination were those developed during the AGR-1 ceramography campaign and have been presented by Ploger et al. (2012). A major challenge in the preparation of these mounts was avoiding pull-out of particles during grinding and polishing. A brief summary of the steps to track compact segments, mount, remove regions with damage and particle pullout, and achieve the final polish are as follows:

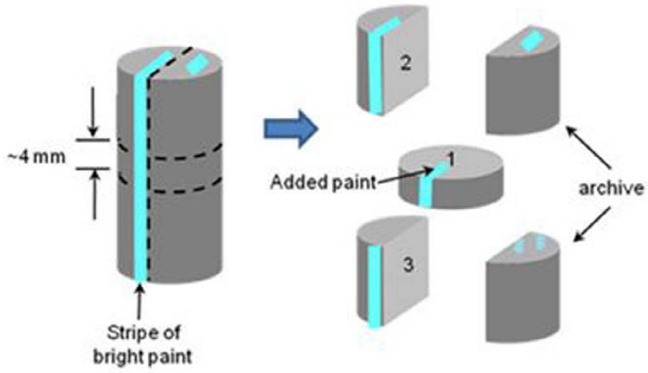

Fig. 1. Cutting diagram for AGR-2 compacts, illustrating use of bright paint to preserve orientations of the discrete sections for alignment relative to the mount's reference markers. Relative to mount IDs from Table 1, 67X would be surface #1, 68X, #2 and 69X, #3 and so on with each compact sectioning.

- Section each compact with a low-speed saw per diagram in Fig. 1. The orientation of each compact section relative to the intact compact was maintained; however, compact azimuthal orientation relative to the reactor core could not be maintained during disassembly (i.e., information on which part of the compact faced the reactor core during irradiation was not available).
- Each of the numbered cross sections in Fig. 1 was placed into a resin compound mount with orientation relative to the paint.
- Each cross-section was potted using Buehler Epoheat® epoxy, aided with vacuum impregnation prior to heat curing.
- Each met mount was ground using 220 grit, then 500 grit Struers MD-Piano® grinding discs, and then 1200 grit Struers MD-Piano® grinding discs to remove the thick layer of epoxy covering the mount and to remove the layer with saw damage. A back-pot (addition of epoxy to the ground mount surface) was applied between each grit-coarseness reduction using a thin layer of Buehler Epoheat® epoxy aided with vacuum impregnation prior to heat curing. This helped retain particles as well as kernel and coating fragments on the mount during grinding and polishing. The objective was to grind sufficiently beyond the initial region of saw damage and thus characterize freshly exposed particles with minimal sample processing damage. Each mount was carefully examined through the hot-cell periscope to monitor loss of particles and to anticipate regions likely to lose particles.
- Once the epoxy from the initial potting of the specimen was removed, in-process measurements were performed to monitor material removal. This provided a means to determine when a thickness approximately equal to a particle radius has been removed, thus revealing fresh particles without saw damage and a minimal number of void spaces in locations where a particle had been pulled

Table 1
AGR-2 compacts used for cross-section analysis along with selected compact properties.

Compact	Fuel Type	Packing Fraction (%)	Compact Temperature[a] TAVA/TA Min/TA Max (°C)	Average burnup[b] (% FIMA)	Average fast fluence[b] (10^{25} n/m^2)	TA Particle Power (mW)[b]	Ceramography Mount IDs
2-1-3	UCO	37	1194/1034/1305	10.95	2.88	66.6	67X/68X/69X
2-4-3	UCO	37	1216/1054/1324	11.52	3.08	70.1	58X/59X/60X
3-2-3	UO_2	23	1045/980/1092	9.01	3.09	91.1	61X/62X/63X
5-1-3	UCO	37	1078/936/1177	11.09	3.03	67.4	64X/65X/66X

[a] Temperatures calculated in Hawkes (2014).
[b] Burnup, particle power, and fast fluence (E > 0.18 MeV) calculated in Sterbentz (2014).