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Gray S. Chang
Misti A. Lillo
John T. Maki
David A. Petti

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Gray S. Chang, Misti A. Lillo, John T. Maki, and David A. Petti
IDAHO NATIONAL LABORATORY
2525 N. Fremont Ave.
Idaho Falls, Idaho, USA

Gray.Chang@inl.gov, Misti.Lillo@inl.gov, John.Maki@inl.gov, and David.Petti@inl.gov

Abstract – The Very High Temperature gas-cooled Reactor (VHTR), which is currently being developed, achieves simplification of safety through reliance on ceramic-coated fuel particles. Each TRISO-coated fuel particle has its own containment which serves as the principal barrier against radionuclide release under normal operating and accident conditions. These fuel particles, in the form of graphite fuel compacts, are currently undergoing a series of irradiation tests in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) to support the Advanced Gas-Cooled Reactor (AGR) fuel qualification program.

A representative coated fuel particle with an ^{235}U enrichment of 19.8 wt% was used in this analysis. The fuel burnup analysis tool used to perform the neutronics study reported herein, couples the Monte Carlo transport code MCNP, with the radioactive decay and burnup code ORIGEN2. The fuel burnup methodology known as Monte-Carlo with ORIGEN2 (MCWO) was used to evaluate the AGR experiment assembly and demonstrate compliance with ATR safety requirements. For the AGR graphite fuel compacts, the MCWO-calculated fission power density (FPD) due to neutron fission in ^{235}U is an important design parameter.

One of the more important AGR fuel testing requirements is to maintain the peak fuel compact temperature close to 1250°C throughout the proposed irradiation campaign of 550 effective full power days (EFPDs). Based on the MCWO-calculated FPD, a fixed gas gap size was designed to allow regulation of the fuel compact temperatures throughout the entire fuel irradiation campaign by filling the gap with a mixture of helium and neon gases. The chosen fixed gas gap can only regulate the peak fuel compact temperature in the desired range during the irradiation test if the ratio of the peak power density to the time-dependent low power density (P/T) at 550 EFPDs is less than 2.5. However, given the near constant neutron flux within the ATR driver core and the depletion of ^{235}U in the graphite fuel compacts versus EFPD, the P/T ratio was calculated to be 5.3, which is unacceptable given the fuel compact temperature control requirement. To flatten the FPD profile versus EFPDs, two proposed options are – (a) add fertile (^{232}Th) particles to the fuel compact and (b) add burnable absorber (B_4C) to the graphite holder. The effectiveness of these two proposed options to flatten the FPD profile versus EFPDs were investigated and the results are compared in this study.

I. INTRODUCTION

The advanced Very High Temperature gas-cooled Reactor (VHTR), which is currently being developed, achieves simplification of safety through reliance on ceramic-coated fuel particles to contain the fission products under extreme accident conditions. Each TRISO-coated fuel particle has its own containment which serves as the principal barrier against radionuclide release under normal operating and accident conditions. These fuel particles in the form of graphite fuel compacts are currently undergoing a series of irradiation tests in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) to support the Advanced Gas-Cooled Reactor (AGR) fuel qualification program.

Typical TRISO-coated fuel particles are covered by four layers, which are (1) a low-density porous buffer layer; (2)

an inner high-density isotropic pyrolytic carbon (PyC) layer; (3) a silicon carbide (SiC) layer; and (4) an outer high-density isotropic PyC layer. These TRISO-coated fuel particles are then dispersed within graphite compacts. Irradiation testing of these graphite fuel compacts is currently being performed in the large-B positions of the ATR in support of the AGR fuel qualification program. For these AGR fuel compacts, the fission power density (FPD) due to neutron fission is an important design parameter which is used to demonstrate compliance with ATR operation safety requirements.

One of the AGR fuel testing requirements is to maintain the fuel compact temperature close to 1250°C during the proposed irradiation campaign of 750 EFPDs needed to achieve a burnup of 20% FIMA (fissions per initial heavy metal atoms). Based on the Monte-Carlo With ORIGEN-2 (MCWO) calculated FPD, the fixed gas gap for the helium

and neon gas mixture was chosen to regulate the fuel compact temperature through the entire fuel irradiation campaign. The chosen fixed gas gap can only regulate the fuel compact temperature in the desired range during the fuel irradiation if the ratio of the peak power density to the time-dependent low power density (P/T) is less than 2.5 up to 550 EFPDs of irradiation. However, under the near constant neutron flux of the ATR driver core and the depletion of ^{235}U versus irradiation time, the P/T ratio was determined to be greater than 5, which is unacceptable for the fuel compact temperature control requirement. To flatten the FPD profile versus irradiation time, two proposed options were investigated and compared in this work which are – (a) add fertile (^{232}Th) particles to the fuel compact and (b) add burnable absorber (B_4C) to the graphite holder.

II. AGR FUEL ASSEMBLY MODEL AT B-10 POSITION

The ATR full core was modeled (Fig. 1.) to represent the power splits and operating conditions projected for a typical ATR operating cycle with an East lobe source power of 22.5 MW. The simplified AGR test assembly model consisted of 6 capsules. The simplified model did not include thermal couples and instrumentation through the guide tubes. Each capsule has 3 fuel compact stacks. The MCNP model of a fuel compact stack was subdivided into 8 axial nodes. Fuel nodes for each stack were numbered sequentially from test assembly top to bottom, i.e., stack-1 is comprised of nodes 1-48 (8 nodes per capsule times 6 capsules), stack-3 is comprised of nodes 49-96, and stack 2 is comprised of nodes 97-144. The radial cross-section of the capsule assembly and the axial cross-section of fuel compact stack-1 are shown in Fig. 2. The detailed axial view is shown in Fig. 3.

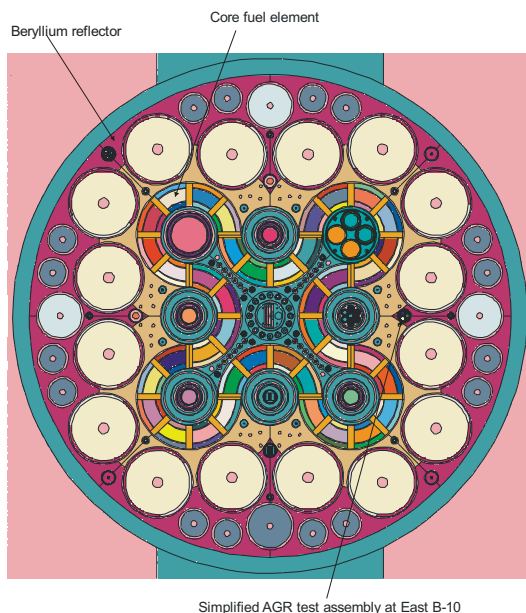


Fig. 1. MCNP full core radial cross-section view and the simplified AGR test assembly at the ATR B-10 position.

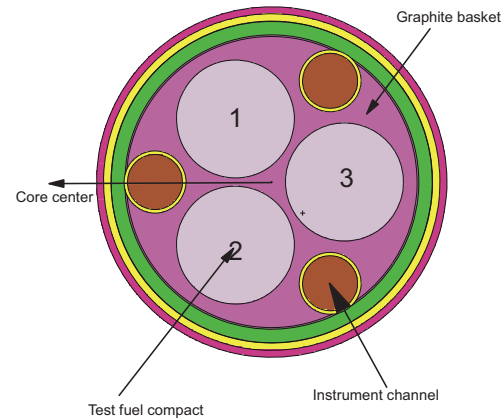


Fig. 2. Radial cross section view of the simplified fuel test assembly.

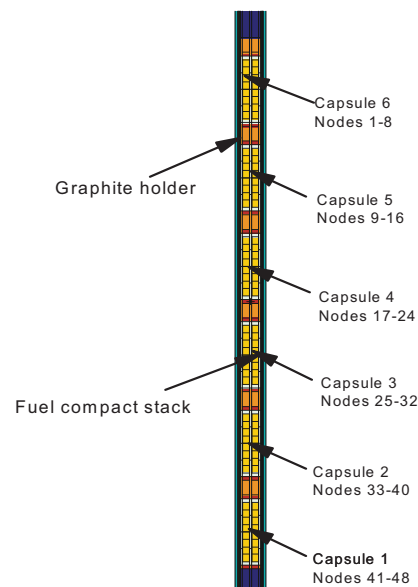


Fig. 3. Detailed axial cross-section of fuel compact stack-1.

III. REPRESENTATIVE FISSILE AND FERTILE FUEL COMPACT AND STUDY CASES

The AGR fuel experiment, when inserted in the ATR East B-10 position, experiences a nearly constant thermal neutron flux from the driver core. Given that the ^{235}U within the fuel compact depletes over the course of the irradiation campaign, the peak FPD occurs at the beginning of irradiation (BOI). As a result, the FPD decreases monotonically toward the end of irradiation (EOI), such that the P/T ratio is much larger than the project requirement of 2.5. The main objective of this study is to flatten the FPD profile versus irradiation time by using either of two proposed options: (a) adding fertile (^{232}Th) particles in the fuel compact to raise the FPD at EOI by transmuting ^{232}Th to ^{233}U , or (b) add burnable absorber (B_4C) to the graphite fuel compact holders to reduce the FPD at BOI, such that the P/T ratio can satisfy the project fuel compact temperature requirement.

This study used a hypothetical representative TRISO-coated fuel particle (non-specific to any particular fuel design) and comprised of a central UO_2 kernel (350 μm outer diameter), covered by four layers. The four layers are (1) a low-density porous buffer layer in 100 μm thickness; (2) an inner high-density isotropic pyrolytic carbon (PyC) layer in 40 μm thickness; (3) a silicon carbide (SiC) layer in 35 μm thickness; and (4) an outer high-density isotropic PyC layer in 40 μm thickness. These TRISO-coated fuel particles are then dispersed within graphite fuel compacts.

Table I lists the three cases used in this study and provides a brief description for each. The reference case, Case-1, has UCO only fuel (Table II). Case-2, has the proposed fissile UCO and fertile ThO_2 fuel (Table III). Case-3 also has UCO only fuel (Table II), as well as using graphite fuel compact holders containing a natural burnable absorber with 5.5 wt% B_4C for all graphite compact holders.

Table I
UCO, UCO- ThO_2 , and UCO- B_4C Cases

Case	Description
1	Reference Case UCO only fuel compact
2	Fissile UCO and Fertile ThO_2 fuel compact
3	UCO only fuel compact Graphite holders with 5.5 wt% B_4C

Table II
Fissile Particle and Fuel Compact Specifications
for Case-1 and Case-3

Fissile Particle	Case-1, Case-3 UCO only
^{235}U enrichment (wt %)	19.8
C/U atomic ratio	0.4
O/U atomic ratio	1.5
Kernel diameter (μm)	350
Kernel density (Mg/m^3)	10.9
Buffer thickness (μm)	100
IPyC thickness (μm)	40
SiC thickness (μm)	35
OPyC thickness (μm)	40
Buffer density	1.05
IPyC density	1.9
SiC density (Mg/m^3)	3.19
OPyC density	1.9
Particle diameter (μm)	780
Compact	
Compact length (mm)	25.21
Compact diameter (mm)	12.34
Matrix density (Mg/m^3)	1.5
Number fissile particles/compact	4360
Fissile particle packing fraction (%)	35.93
U loading (g U/compact)	0.95
Mass compact matrix (g)	2.9
Compact mass (g)	6.15
Effective compact density (Mg/m^3)	2.04

Table III
Fissile Particle, Fertile Particle, and Fuel Compact
Specifications for Case-2

Fissile Particle	Case 2 UCO ThO_2
^{235}U enrichment (wt %)	19.8
C/U atomic ratio	0.4
O/U atomic ratio	1.5
Kernel diameter (μm)	350
Kernel density (Mg/m^3)	10.9
Buffer thickness (μm)	100
IPyC thickness (μm)	40
SiC thickness (μm)	35
OPyC thickness (μm)	40
Buffer density	1.05
IPyC density	1.9
SiC density (Mg/m^3)	3.19
OPyC density	1.9
Particle diameter (μm)	780
Fertile Particle	
U^{238} or Th^{232} enrichment (wt %)	100
C/U atomic ratio	0
O/(U or Th) atomic ratio	2
Kernel diameter (μm)	452
Kernel density (Mg/m^3)	9.88
Buffer thickness (μm)	53
IPyC thickness (μm)	33
SiC thickness (μm)	38
OPyC thickness (μm)	44
Buffer density	1.11
IPyC density	1.85
SiC density (Mg/m^3)	3.22
OPyC density	1.85
Particle diameter (μm)	788
Compact	
Compact length (mm)	25.21
Compact diameter (mm)	12.34
Matrix density (Mg/m^3)	1.5
Number fissile particles/compact	2910
Number fertile particles/compact	1410
Fissile particle packing fraction (%)	23.98
Fertile particle packing fraction (%)	11.98
U loading (g U/compact)	0.64
Th loading (g Th/compact)	0.59
Mass compact matrix (g)	2.9
Compact mass (g)	5.87
Effective compact density (Mg/m^3)	1.95

IV. FUEL BURNUP ANALYSIS CODE – MCWO

The fuel burnup analysis code used in this neutronics study couples the Monte-Carlo transport code MCNP^{1,2} with the radioactive decay and burnup code ORIGEN^{2,3,4}. The burnup methodology Monte-Carlo with ORIGEN2 (MCWO) has been previously validated for irradiation testing in ATR^{5,6}. The MCWO methodology uses MCNP-calculated one-group microscopic cross sections and fluxes

as input to a series of ORIGEN2 burnup calculations. ORIGEN2 depletes/activates materials and generates isotopic compositions for subsequent MCNP calculations. MCWO performs one MCNP and one or more ORIGEN2 calculations for each user-specified time step. For each MCNP calculation step, MCNP updates the fission power distribution and burnup-dependent cross sections for each fuel target then transfers data to ORIGEN2 for cell-wise depletion calculations. The MCNP-generated reaction rates are integrated over the continuous-energy nuclear data and space within the region.

V. RESULTS AND DISCUSSION

MCWO-calculated results for all three case studies will be compared and discussed herein. The burnup time interval is 50 EFPDs with an East lobe of 22.5 MW. There are 15 time intervals for a total of 750 EFPDs. For each time step, an MCNP fixed-source calculation with 3.5×10^8 source neutrons for each time step is run, requiring ~ 35 minutes of CPU time on a workstation with two dual-core 2.86 GHz XEON processors. The fission tally calculation for each fuel node can achieve a 1σ standard deviation of 1.5% or less.

The typical ATR axial power profile is a chopped cosine shape with a core center peak-to-average ratio of 1.414. From Fig. 3, it is seen that node-24, nearest the core center plane, will have the highest FPD. So, only node-24's burnup, FPD, and P/T ratio profiles versus EFPDs will be compared and discussed.

V.A. Fission Power Density Profile versus EFPDs

MCWO-calculated FPD profiles versus EFPDs with 15 time steps are shown in Fig. 4. The AGR fuel ^{235}U was depleted in the ATR under a nearly constant thermal neutron flux at East B-10 position. For Case-1 with UCO only, clearly a peak fission power density of 215 W/cm^3 occurred at BOI, and exponentially decreased to 31.2 W/cm^3 at 750 EFPDs. By adding fertile ThO_2 particles and less fissile UCO particles in Case-2, the peak FPD is 148.3 W/cm^3 at BOI. Because the fertile particle ^{232}Th transmuted to ^{233}U , which contributes some fission power and elevates the FPD to 39.9 W/cm^3 at 750 EFPDs. Because of the added B_4C in Case-3, the FPD is 90.9 W/cm^3 at BOI. Then, due to the ^{10}B depletion, the FPD increases to the peak 123.2 W/cm^3 at 175 EFPDs. Finally, the FPD of Case-3 decreased to 37.4 W/cm^3 at 750 EFPDs.

V.B. UCO Burnup Profile versus Irradiation EFPDs

MCWO-calculated burnup profiles versus EFPDs with 15 time steps are shown in Fig. 5. The project requires that the fuel compact exceed a burnup of 20% FIMA at the end of irradiation. As expected, Case-1 reached the highest burnup of 24% FIMA at 750 EFPDs. However, for Case-2, the ^{233}U transmuted from ^{232}Th undesirably competes with ^{235}U to absorb thermal neutrons. As a result, it causes the

burnup to reach only 18.6% FIMA at 750 EFPDs. Finally, Case-3 with UCO and B_4C 5.5 wt% in the graphite compact, achieved a burnup of 22.8% FIMA at 750 EFPDs.

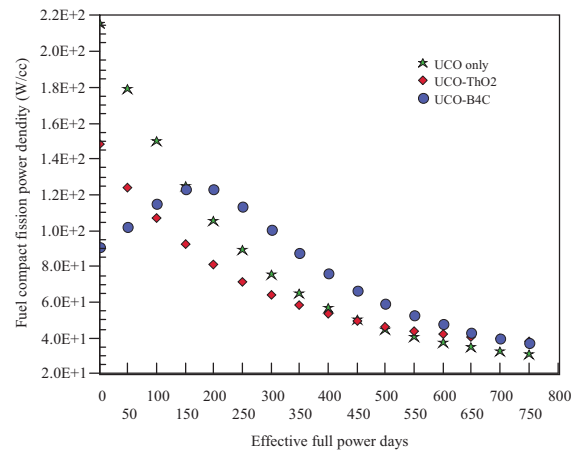


Fig. 4. Fission Power Density Profile versus Irradiation EFPDs.

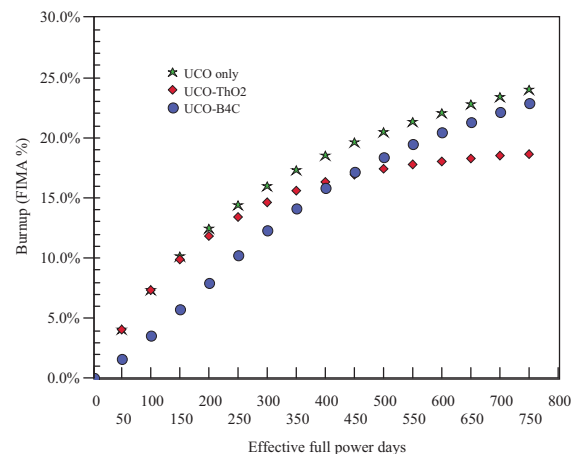


Fig. 5. UCO Burnup Profile versus Irradiation EFPDs.

V.C. P/T Ratio Profiles Comparison and Discussion

MCWO-calculated P/T ratio profiles versus EFPDs with 11 time steps are shown in Fig. 6. As expected, Case-1 has the highest P/T ratio of 5.3, which does not meet the project fuel compact temperature control requirement. For Case-2, the ^{233}U transmuted from ^{232}Th lowers the P/T ratio to 3.28, which still does not meet the project requirement of P/T ratio less than 2.5. Finally, Case-3 with UCO only fuel and B_4C 5.5 wt% in the graphite fuel compact holder, effectively reduced the P/T ratio to 2.33, which satisfies the project fuel compact temperature control requirement.

VI. CONCLUSIONS

MCWO has been demonstrated in analyzing the burnup, FPD, and P/T ratio profiles versus irradiation EFPDs. The MCWO-calculated FPD and burnup profile results indicate that Case-3, UCO and graphite holder with natural B₄C 5.5 wt%, does meet the project temperature control requirement with a P/T ratio of 2.33 at 550 EFPDs. Moreover, the Case-3 option, with B₄C in the graphite holder, has been successfully applied in the current AGR-1 fuel testing in ATR, which will complete fuel irradiation by the end of fiscal year 2009.

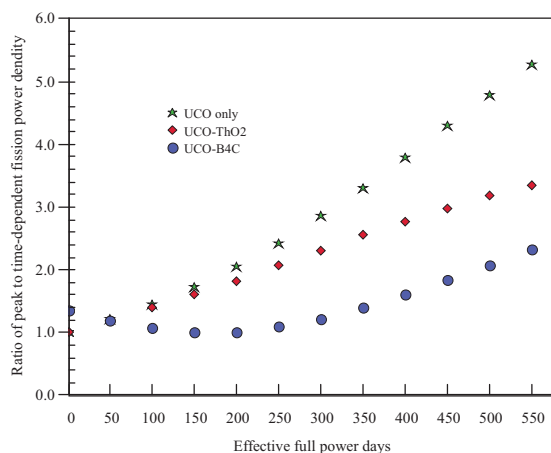


Fig. 6. UCO P/T ratio Profile versus Irradiation EFPDs.

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