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Validation of the Fast and Thermal Neutron Flux Profiles in the Advanced Test Reactor for the AGR-3/4 Experiment

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VALIDATION OF THE FAST AND THERMAL NEUTRON FLUX PROFILES IN THE ADVANCED TEST REACTOR FOR THE AGR-3/4 EXPERIMENT

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ABSTRACT

The AGR-3/4 experiment was designed to irradiate TRISO particle fuel in the Advanced Test Reactor (ATR) at the Idaho National Laboratory. Temperature control of the test capsules containing the TRISO particles was important since the goal was to measure diffusion rates of fission product elements through graphite as a function of temperature. During the experiment, differences were observed between temperatures measured by the thermocouples and temperatures calculated with the thermal analysis model. To rule out the possibility that the used ATR driver fuel elements were the root cause of these temperature differences, an experiment was devised to measure the axial fast and thermal neutron flux profiles in the northeast flux trap containing the AGR-3/4 experiment. An important input parameter to the thermal analysis model was the calculated compact heat rates from the MCNP physics model. To verify these calculated heat rates were consistent with the ATR driver fuel element loading and operating lobe power, axial flux wires were inserted into ATR northeast flux trap. The measured fast and thermal neutron axial flux profiles derived from the flux wire activation showed excellent agreement with the calculated flux profiles. This agreement dispelled any concerns that the used ATR fuel elements in the northeast lobe might have introduced unusual axial flux variation. In addition, the agreement provided a validation basis for the physics calculation, specifically, (1) MCNP physics model, (2) Monte Carlo depletion methodology, (3) method used to load the ATR driver fuel, and (4) ATR measured lobe power data used in the calculation.

Key Words: **TRISO, Neutron Flux, Validation, ATR, AGR, MCNP**

1. INTRODUCTION

The Advanced Test Reactor (ATR) has been used since 2006 to irradiate TRISO particle fuel as part of an ongoing Advanced Gas Reactor (AGR) research program sponsored by the U.S. Department of Energy. Three AGR experiments known as AGR-1, AGR-2, and AGR-3/4 have been irradiated to date with great success. A fourth and final TRISO particle fuel experiment (AGR-5/6/7) is planned and will be inserted into ATR for irradiation in the near future.

The temperature of the fuel compacts containing the TRISO particles is an important fuel performance parameter in all the AGR experiments. The compact temperature affects the stability and integrity of the TRISO particle coatings and the diffusion of radioactive fission products out of the particle and through surrounding graphite structures. Temperature therefore must be measured accurately and continuously during the irradiations. To measure the temperature, thermocouples (TC) are placed inside each test capsule containing fuel compacts. Compact temperatures are not measured directly with the TCs because of the excessively high 1000-1400°C compact temperatures during irradiation. Instead TCs are placed in the vicinity of the compacts typically in the much cooler graphite compact holders (500-600°C) where TC survivability increases substantially for the duration of the multi-cycle irradiation tests.

Detailed thermal analysis models are then used to predict the measured TC readings. The goal is to achieve good agreement between the model-predicted TC temperatures and the actual measured TC temperatures. The most significant input parameter to the thermal analysis models is the calculated compact heat rates; the primary heat source in each capsule. The compact heat rates are calculated values based on a full-core, three-dimensional MCNP model [1] of the ATR core with detailed geometry and material descriptions of the AGR test train, capsules, and TRISO-particle compacts.

When good agreement is achieved between the experimental and calculated result, the thermal model can be used with confidence to predict the radial, azimuthal, and axial temperature profiles in the compacts and all other component temperatures throughout the capsule. When good agreement is not achieved, the thermal model input parameters are questioned.

This paper focuses on the AGR-3/4 experiment in which the TC measurements and the thermal analysis model predictions were generally in good agreement, but did exhibit an unexplained axial bias. The calculated temperatures of the three capsules at the top of the 12-capsule stack were consistently predicted to be hotter than the TC measurements, and the capsules near the middle to bottom were consistently predicted to be colder than the TC measurements, leading to a possible axial asymmetry not accounted for in the physics model. This temperature difference or bias was not expected or readily explainable.

The AGR-3/4 test train was intentionally designed to be axially symmetric about the ATR core midplane. The six capsules above and below the midplane would then have corresponding locations of like burnups, heat rates, and neutron fluences. In addition, the fast and thermal neutron axial flux profiles in the ATR core are typically symmetric about the midplane. Plus, the AGR-3/4 MCNP physics model was predicting axially symmetric compact heat rates about the core midplane as well.

To explain the axial temperature bias, the question arose as to whether the ATR driver fuel in the northeast lobe of the ATR core, where the AGR-3/4 experiment was being irradiated, might be producing an asymmetric axial flux profile that is atypical of the usual cosine-shaped profile. This question led to the possibility that the actual compact heat rates in the ATR were also not symmetric about the core midplane, which was in direct conflict with the symmetric heat rates being predicted by the physics model, but which could possibly explain the temperature bias.

The AGR-3/4 experiment was irradiated in the northeast flux trap (NEFT) of the ATR core. To hold down power in the northeast lobe and prevent the TRISO-particle compacts from generating excessive fission heat, the eight ATR driver fuel elements in the northeast lobe were routinely loaded with used ATR fuel elements. Used fuel is defined as previously-burned or once-, twice-, and even three times-burned fuel elements and these used elements became the focus of the investigation.

It was speculated that asymmetric burnup in used ATR fuel elements could potentially result from use in previous high-power flux trap experiments with axial variations in fuel loading or highly absorbing materials. In addition, the ATR has six hafnium safety rods parked 7.62 cm into the top of the axial core which contributes to a slight axial asymmetry in the core flux profiles. Despite these possibilities for asymmetric fuel element burnup, relatively strict operational limits are imposed on all ATR flux trap experiments that prevent any significant impact to the surrounding driver fuel plate fission rates and any deviation from the normal cosine-shape of the axial fission rate profile.

Used ATR elements under normal operating conditions, therefore, typically do not produce axially asymmetric neutron flux profiles even with substantial accumulated burnup. The fuel typically burns fastest around the core midplane. In the case of a highly burned element, the flux at midplane could exhibit a flux flattening or slight depression in the cosine profile at midplane. So even though typical ATR core burnup is not expected to produce substantial asymmetries in the driver fuel, the exact exposure history of every AGR-3/4 used fuel element in the northeast lobe led to the possibility that there might be some unknown asymmetries introduced by these used driver fuel elements.

Therefore, with the possibility in mind that used driver fuel elements were creating axial asymmetries in the compact heats, a method to measure the fast and thermal neutron axial flux profiles was developed and implemented to address this issue. The method chosen was to instrument the NEFT with long activation flux wires extending the full vertical height of the active core.

2. ADVANCED TEST REACTOR

The Advanced Test Reactor (ATR) is a 250 MW thermal test reactor. The active core comprises 40 plate fuel elements arranged in a serpentine configuration to create a 3x3 array of light water-cooled and light water-moderated flux traps. Each fuel element has 19 high-enriched aluminum clad fuel plates which are cooled by light water. Outside the serpentine core is a beryllium metal reflector with shim control cylinders to control core reactivity, lobe power, and flux gradients. One of the nine flux traps, namely the inboard northeast flux trap, was used to irradiate the AGR-3/4 experiment.

The ATR active core is 121.96 cm (48 in.) in axial height and the outer beryllium reflector radius is approximately 128.59 cm (50.6 in.) forming a right circular cylinder. The ATR currently runs at total core power level of between 100-110 MW during regular cycles. For a more detailed description of the ATR core see Reference [2].

3. AGR-3/4 EXPERIMENT

The AGR-3/4 experiment was a test train consisting of a long cylindrical steel pressure tube containing 12 individual test capsules [3]. The test train was centered in the northeast flux trap and surrounded by a cylindrical hafnium shroud acting as a neutron filter to absorb thermal neutrons and reduce the fission rate of the TRISO particle fuel under test. The test train and filter were cooled by ATR light water coolant in the flux trap.

The 12 test capsules were stacked vertically one on top of the other for a total length of approximately 122 cm or the length of the ATR active core. At the radial center of each capsule was a stack of cylindrical TRISO-particle fuel compacts. Four compacts per stack; each compact had a diameter of 1.231 cm and a length of 1.251 cm. The compact stack was centrally located in a matrix graphite annulus called the ring blank. Surrounding the ring blank were the inner and outer graphite sleeves; the outer sleeve had a top and bottom lid so as to create a gas tight container in which a blend of helium-neon gas could flow. The gas mixture together with the pre-determined gas gaps between the graphite annuli was used to control the temperature of the compacts and graphite over the course of the AGR-3/4 irradiation. Figure 1 shows a cross sectional view of an AGR-3/4 capsule.

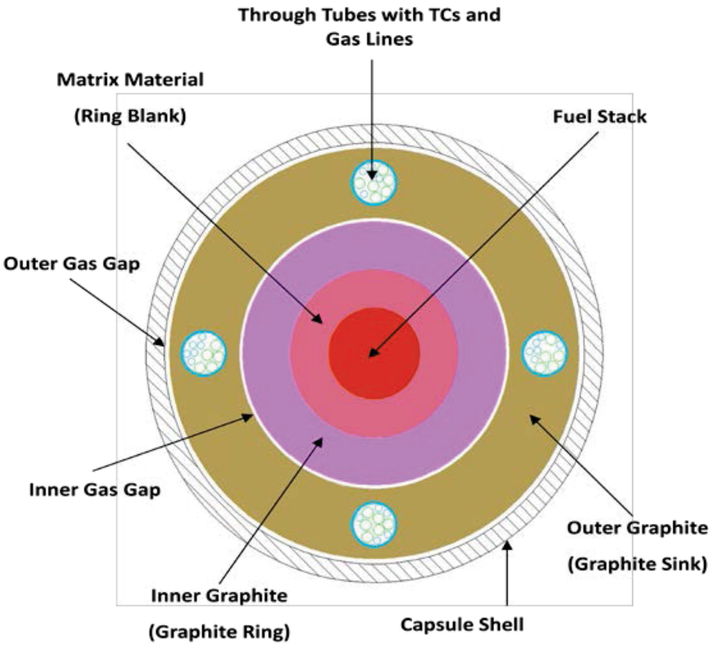

Figure 1. Cross sectional view of an AGR-3/4 capsule.

Each TRISO-particle compact contained approximately 1,892 TRISO particles. Each TRISO particle consisted of a central spherical uranium oxy-carbide (UCO) kernel surrounded by a low-density graphite buffer, an inner pyrolytic carbon coating, a silicon carbide pressure vessel coating, and an outer pyrolytic carbon coating. The kernel had a nominal 350 μm diameter and an enrichment of 19.717 wt% U-235. The total particle diameter was approximately 0.8 mm.

The primary goal of the AGR-3/4 experiment was to produce measureable fission product concentration gradients in the graphite annuli in order to determine fission product diffusion rates out of the kernels and through the compacts and graphite annuli as a function of time and temperature. In addition to the standard TRISO particles, special “designed-to-fail” particles were also incorporated into the compacts to ensure a specified number of early particle failures and guarantee fission product release over the course of the irradiation.

4. MCNP PHYSICS MODEL

Standard full-core MCNP models of the ATR were used to perform the physics depletion analysis for the AGR-3/4 experiment. The MCNP models were also used to estimate compact and capsule component heat rates as well as the fast and thermal neutron fluence at each 24-hr depletion timestep and at the end of each of the 7 ATR irradiation cycles that comprised the AGR-3/4 irradiation. A detailed description of the MCNP model with the AGR-3/4 experiment, Monte Carlo depletion methodology, beginning-of-cycle ATR fuel element loading strategy, and calculated core physics parameters and compact burnup results from the AGR-3/4 physics depletion calculation can be found in Reference [4].

Figure 2 is a plot of the MCNP ATR full-core model showing a cross section view of the ATR northeast flux trap containing the AGR-3/4 experiment. This figure is just a small portion of the full-core MCNP model of the ATR core. Several of the major NEFT features are labeled including the central TRISO-particle compact fuel stack in the center of each AGR-3/4 capsule surrounded by the three graphite annuli and the capsule wall. Outside the capsule wall is ATR light water coolant (blue), the shroud (neutron filter), and more ATR coolant with the four flux wire holders situated at the North, East, South, and West positions. The gray annulus is the aluminum flux trap baffle and beyond the baffle, the fuel elements forming the northeast lobe. Although not shown in the figure, each TRISO particle is explicitly modeled in the compact region.

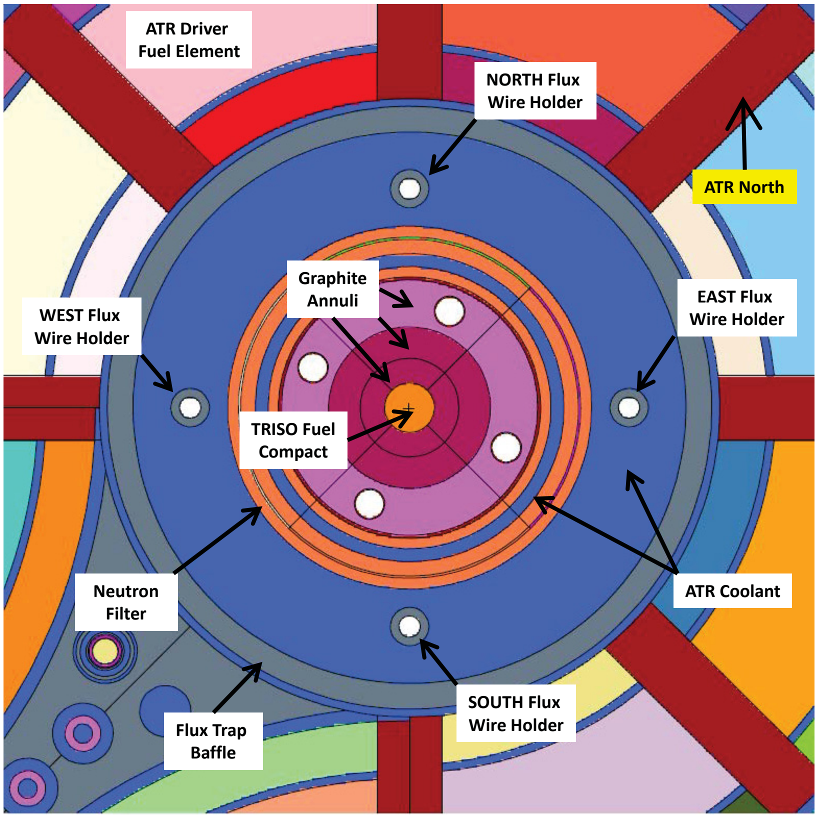

Figure 2. MCNP plot of the ATR northeast flux trap with the AGR-3/4 experiment.

5. FLUX WIRE MEASUREMENT

With the possibility in mind that the used fuel elements were creating axial asymmetries in the compact heat rates, a method to measure such asymmetries was developed and implemented to address this issue. The method chosen was to instrument the northeast flux trap with 142.88 cm (56.25 in.) long flux wires extending from above the top of the active core to below the bottom of the active core. Four aluminum flux wire holders contained the flux wires and were positioned vertically in the light water coolant between the AGR-3/4 neutron filter and the ATR flux trap aluminum baffle. The cylindrical holders were equally spaced on a fixed radius from the center of the flux trap in the North, East, South, and West azimuthal directional positions as shown in Figure 2.

Two flux wires were placed in each holder, one nickel and one 0.1% cobalt-aluminum wire. The nickel wire (0.0508 cm dia.) measured the fast fluence rate from the Ni-58(n,p)Co-58 reaction rate. The cobalt-aluminum wire (0.1016 cm dia.) was used to determine the thermal fluence rate from the Co-59(n,γ)Co-60 reaction rate. The mounted full-length flux wires were irradiated, activated, removed, chopped, and activities measured. The post-irradiation analysis provided cycle-average thermal and fast fluence rates or fluxes. The measured thermal fluence rate was reported as a 2200-m/s flux which had to be derived assuming a theoretical Maxwellian thermal neutron distribution. The measured fast fluence rate was reported for >1 MeV neutrons.

Although the aluminum flux wire holders with exact dimensions were modeled in the MCNP model, the actual nickel and cobalt flux wires were not modeled. The calculated neutron spectra and absolute flux in the flux wire holders then represent unperturbed energy fluxes without the flux wire self-shielding, although the flux wire self-shielding is expected to be small, based on flux wire mass and wire radius.

6. THERMAL FLUX RESULTS

The ATR flux wire measurements did not include enough spectral information to unfold a complete thermal neutron energy spectrum in the NEFT. In order to convert the measured activation counts to a 2200-m/s flux, a thermal neutron energy distribution had to be assumed and integrated over a thermal neutron energy range to obtain the 2200-m/s fluxes. In the measurement report [5], a Maxwellian distribution with a temperature of 20.45°C was assumed based on previous ATR experience. For light water reactors, a Maxwellian distribution is typically valid over a thermal neutron energy range up to approximately $E=5kT\approx0.1$ eV.

To verify the measurement usage of a Maxwellian distribution and to also verify the energy range over which it is valid, a 296-group neutron energy spectrum was calculated with MCNP in each of the four aluminum holders and compared to a theoretical Maxwellian distribution. Figure 3 shows one example of a comparison between a theoretical Maxwellian distribution and a MCNP calculated thermal neutron spectrum in the North flux wire holder at core midplane. The theoretical Maxwellian distributions agreed extremely well with the MCNP-calculated spectra over the 0.001 to 0.1 eV neutron energy range. It was therefore concluded that use of the theoretical Maxwellian distribution to derive the measured 2200-m/s pseudo flux was a good assumption.

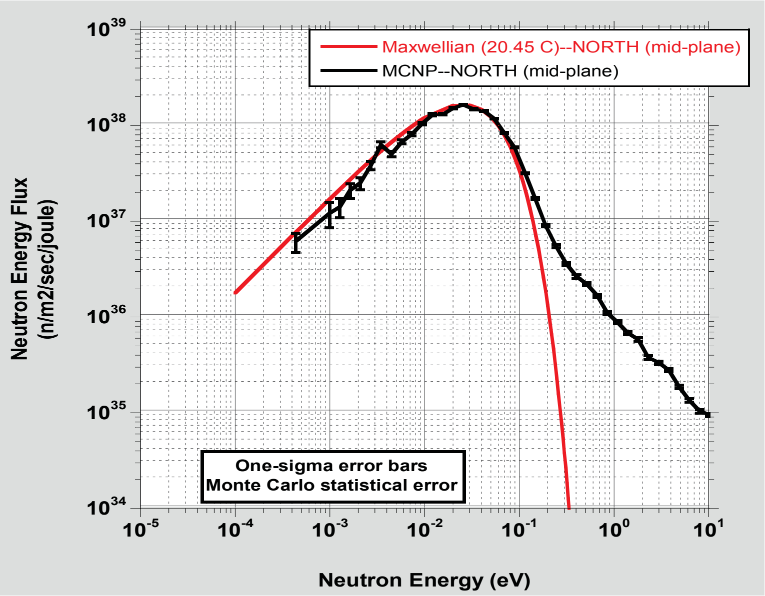

Figure 3. Comparison of a theoretical Maxwellian distribution and a MCNP calculated thermal neutron spectrum in the North flux wire holder at core midplane.

Similar agreement was obtained for the Maxwellian distribution and MCNP-calculated thermal spectra at the other three flux wire locations and at core midplane as well as at the top of the active core. The Maxwellian distribution appears to be valid throughout the NEFT test volume.

Figure 4 is a comparison of the measured and calculated 2200-m/s thermal neutron fluxes (cycle average) as a function of axial distance from core midplane. The zero point is at the center or midplane of the active core. The top of the core is at +60.96 cm and the bottom of the active core at -60.96 cm. This particular comparison is for the South flux wire holder. Each axial measured flux value (red) is based on an assumed Maxwellian thermal neutron energy spectrum (T=20.45 °C) integrated over the 0 to 0.1 eV neutron energy range, normalized to the measured wire segment activities, and divided by the cycle length to obtain the cycle-average flux.

The calculated flux values (black) in Figure 4 are the result of integrating the calculated thermal neutron spectrum from 0 to 0.1 eV and normalizing to the measured northeast lobe power. The calculated flux values are also cycle-average fluxes. All results presented are for a single ATR cycle, Cycle 154B, although two other AGR-3/4 irradiation cycles were also instrumented with flux and measured. Results from these other two cycles were very similar to the Cycle 154B results presented here.

Figure 4 shows excellent agreement between the calculated and measured axial profiles for the South flux wire holder. This is also true for the other three flux wire holder positions as well (Figures 5, 6, and 7). For clarity, the experimental errors associated with the 2200-m/s flux values (estimated to be 6.6%) and the calculated errors (approximately 3-6%) are not plotted on these figures due to the large number of points (86 experimental and 106 calculated).

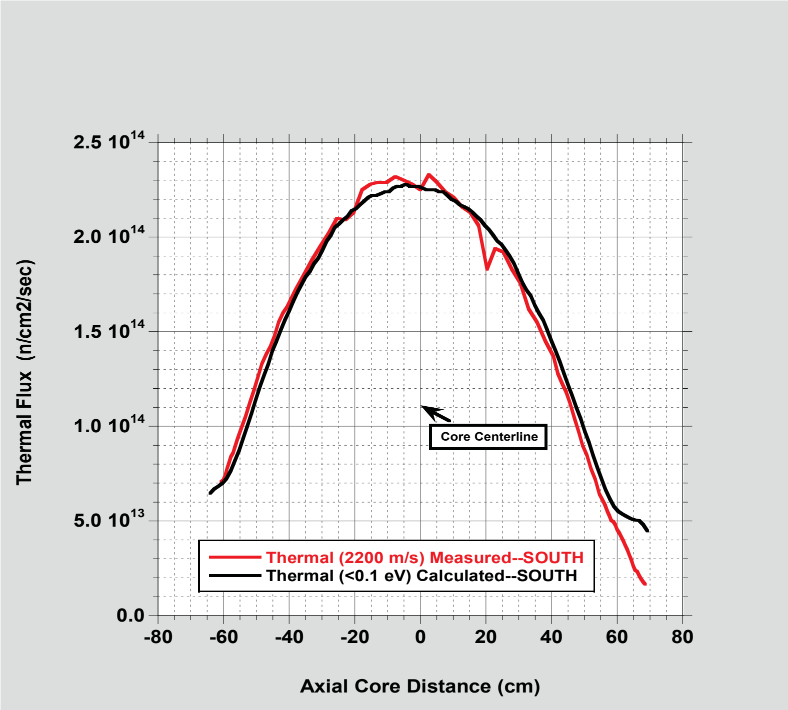

Figure 4. Average thermal fluence rate (thermal flux) for the **South** flux wire holder.

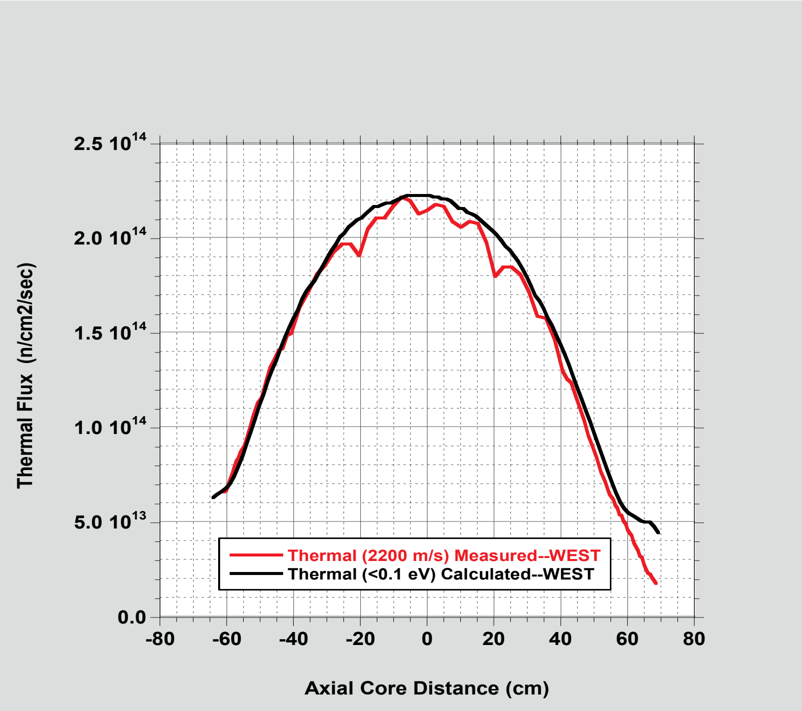

Figure 5. Average thermal fluence rate (thermal flux) for the **West** flux wire holder.

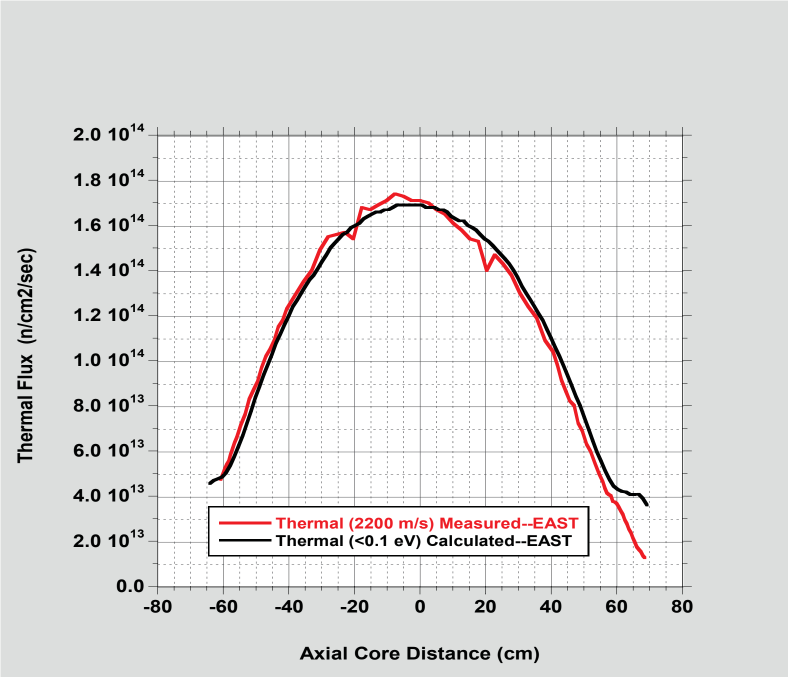

Figure 6. Average thermal fluence rate (thermal flux) for the **East** flux wire holder.

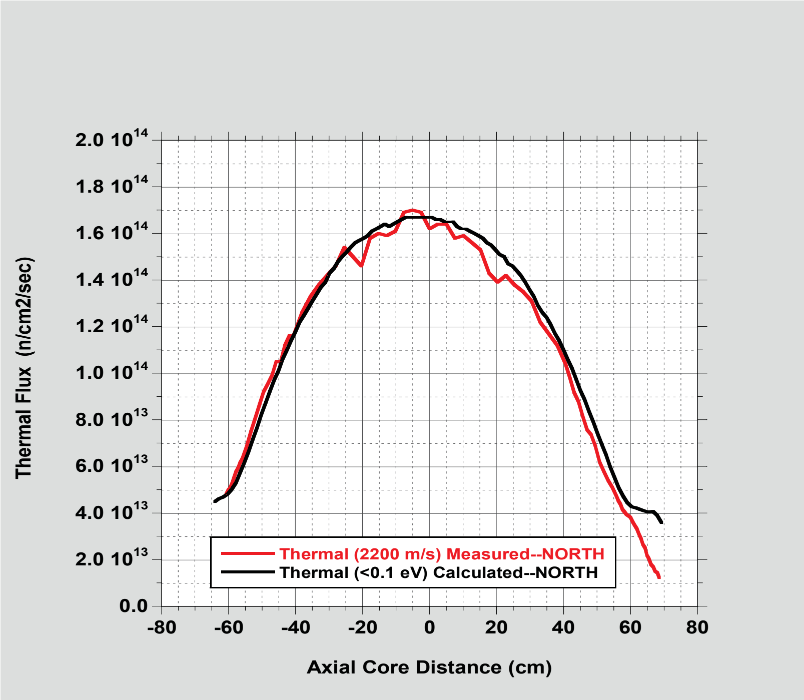

Figure 7. Average thermal fluence rate (thermal flux) for the **North** flux wire holder.

It is interesting to note similar magnitudes of the peak thermal fluxes for the South and West positions at approximately 2.2E+14 n/cm^2/s and similarly for the North and East positions at approximately 1.7E+14 n/cm^2/s. This clearly shows a thermal neutron flux gradient across the NEFT with the gradient vector pointing from the center of the NEFT to the center of the ATR core.

7. FAST FLUX RESULTS

The measured fast flux fluence rates were reported for neutron energies greater than 0.1 MeV [5]. Figure 8 compares the measured and calculated cycle-average fast neutron fluxes as a function of axial distance from the core midplane for the South flux wire holder and Cycle 154B. The measured and calculated curves overlay one another demonstrating excellent agreement. This is also true for the other three flux wire holder positions (Figures 9, 10, and 11). For clarity, the experimental errors associated with the fast flux values (estimated to be 4.7%) and the calculated errors (approximately 3-6%) are again not plotted on these figures due to the large number of points.

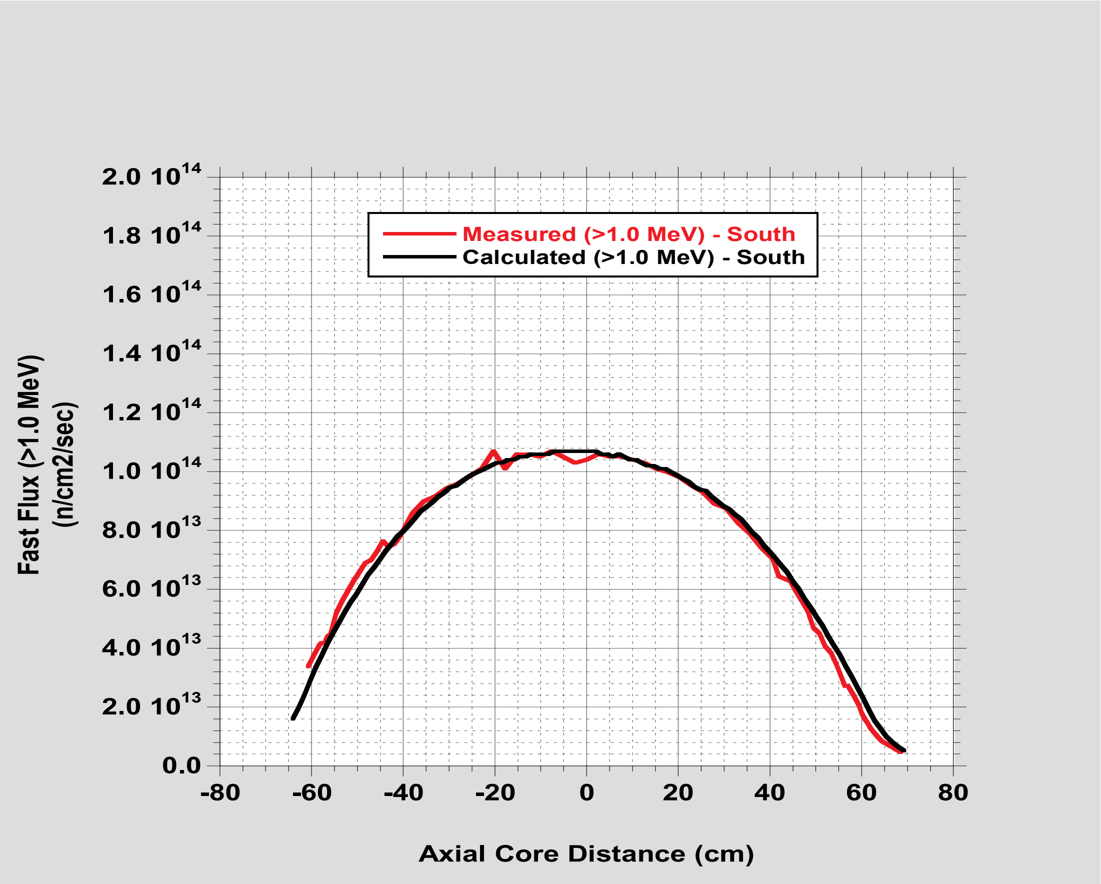

Figure 8. Average fast fluence rate (fast flux) for the **South** flux wire holder.

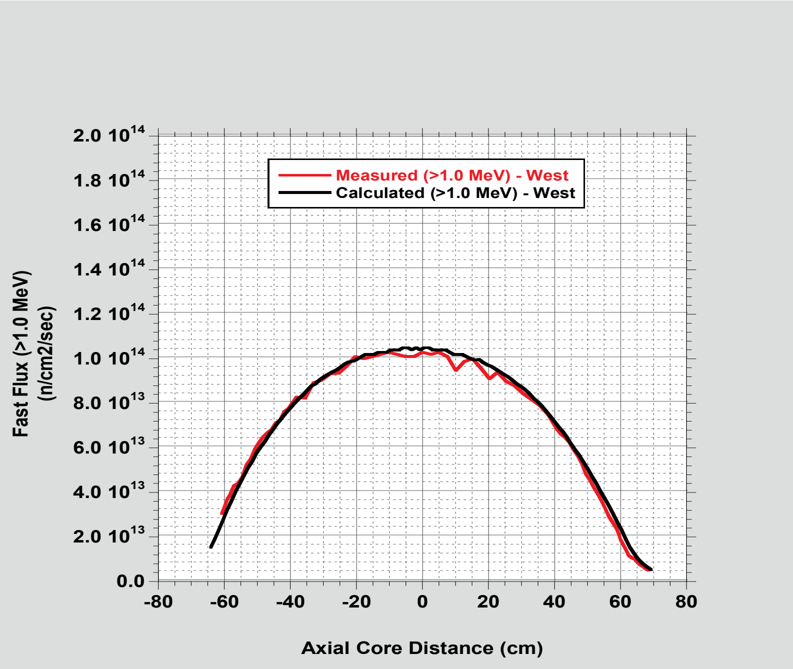

Figure 9. Average fast fluence rate (fast flux) for the **West** flux wire holder.

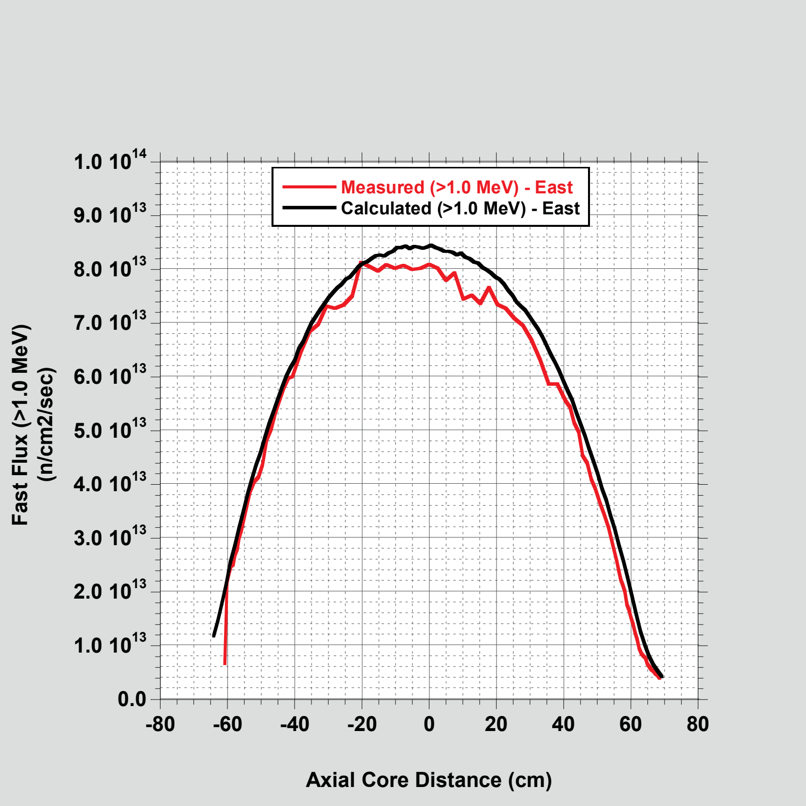

Figure 10. Average fast fluence rate (fast flux) for the **East** flux wire holder.

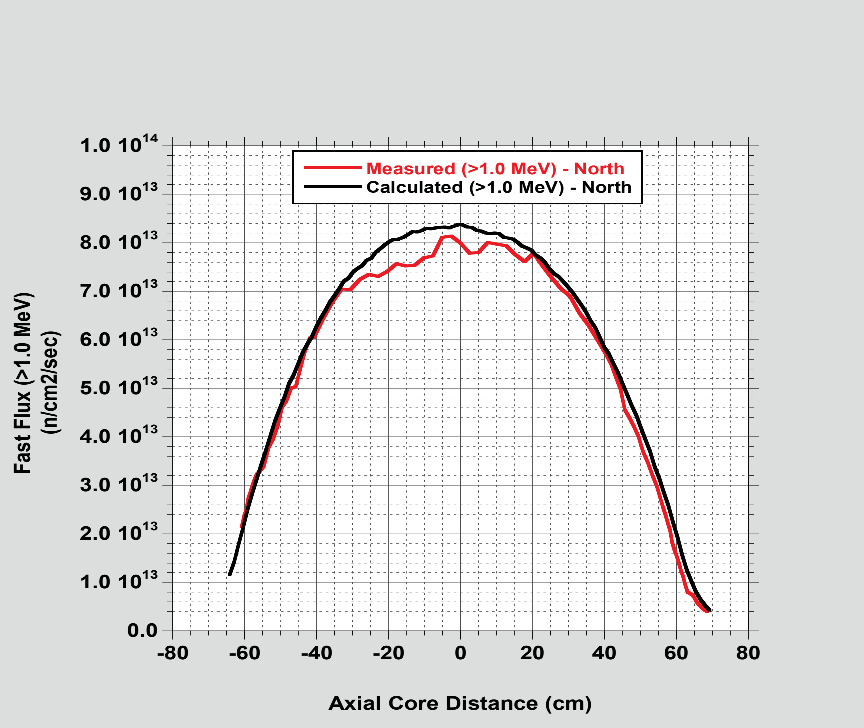

Figure 11. Average fast fluence rate (fast flux) for the **North** flux wire holder.

A fast flux gradient is also observed across the NEFT. The South and West positions have peak fast fluxes of approximately 1.05E+14 n/cm^2/s and the East and North positions at approximately 8.4E+13 n/cm^2/s. The fast flux gradient vector points in the same direction as the thermal flux gradient vector.

8. CONCLUSION

Cycle-average fast and thermal axial neutron flux profiles from flux wire measurements in the ATR northeast flux trap containing the AGR-3/4 experiment show excellent agreement with calculated profiles using an MCNP full-core model of the ATR core. The results indicate no unusual asymmetrical axial flux profile behavior in ATR. The axial flux profiles exhibit the usual well-behaved cosine-shaped curves expected in the ATR core. Therefore, the temperature bias observed between the thermocouple measurements during the AGR-3/4 irradiation and those calculated using the AGR-3/4 thermal analysis models does not appear to originate with the used ATR driver fuel elements nor with the MCNP-calculated compact heat rates which go into the thermal analysis model.

The excellent agreement between the measured and calculated values also provides a solid validation basis for the MCNP-calculated fast and thermal flux profiles, along with the underlying physics depletion methodology, the MCNP full-core physics model, the beginning-of-cycle used and fresh ATR fuel element loading methodology, and the ATR lobe power measurements used in the calculations to normalize and derive the calculated absolute fast and thermal neutron fluxes.

REFERENCES

[1] X-5 Monte Carlo Team, MCNP—A General Monte Carlo N Particle Transport Code, Version 5, Volume I (LA UR 03 1987) and Volume II (LA CP 03 0245), Los Alamos National Laboratory, Los Alamos, New Mexico, April 23, 2003.

[2] "Advanced Test Reactor National Scientific user Facility User's Guide (FY2008)," INL/EXT-07-13577, Idaho National Laboratory, Idaho Falls, ID, December 2007.

[3] PLN-3867, "AGR 3/4 Irradiation Experiment Test Plan," Revision 1, INL/MIS-11-22351, Idaho National Laboratory Advanced Reactor Technology Program, Project No. 23841, Idaho National Laboratory, May 20, 2015.

[4] J.W. Sterbentz, "JMOCUP As-Run Daily Physics Depletion Calculation for the AGR-3/4 TRISO Particle Experiment in the ATR Northeast Flux Trap," Engineering Calculation and Analysis Report 2753 (ECAR-2753), Rev. 1, Idaho National Laboratory, Idaho Falls, ID, July 2014.

[5] R.K. Murray, and C.C. Jensen, "Measured Thermal and Fast Neutron Fluence Rates ATR CYCLE 154B 07/14/13 thru 10/16/13," INL/INT 13 30822, December 2013.