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ATR PDQ AND MCWO FUEL BURNUP ANALYSIS CODES EVALUATION

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ABSTRACT

The Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) is being studied to determine the feasibility of converting it from the highly enriched Uranium (HEU) fuel that is currently used to low enriched Uranium (LEU) fuel. In order to achieve this goal, it would be best to qualify computational methods different than those that have been used at ATR for the past 40 years. This paper discusses two methods of calculating the burnup of ATR fuel elements. The existing method, that uses the PDQ code, is compared to a modern method that uses the Monte Carlo N-Particle (MCNP) transport code combined with the ORIGEN2 depletion code. This modern method, MCNP with ORIGEN2 (MCWO), has shown excellent agreement with the existing method (PDQ). Both MCWO and PDQ show very good agreement with ^{235}U burnup values generated using an analytical method.

1. Introduction

The Advanced Test Reactor (ATR) is a high power (250 MW) reactor, with 40 highly enriched fuel elements (FE) arranged in a unique serpentine shape. The ATR is located at the Idaho National Laboratory (INL) in the United States. Fueled with highly enriched uranium (HEU), 93 wt% ^{235}U, the ATR can produce a maximum unperturbed thermal neutron flux of 1.0×10^{15} n/cm^2–s. Research is currently being performed to explore the feasibility of converting ATR and other high power nuclear test reactors fueled with HEU, to low-enriched uranium (LEU). This research is being performed as part of the Reduced Enrichment for Research and Test Reactors (RERTR) program. This program has proposed the insertion of a modified test assembly (MTA) in an ATR driver fuel position. The MTA will be manufactured replacing 11 of the 19 HEU fuel plates in the current FE with LEU fuel plates. In order to assure the safe operation of ATR with this MTA in a driver fuel position, an extensive evaluation of the FE will be performed using the Monte-Carlo burnup analysis code to demonstrate compliance with the ATR safety requirements.

To demonstrate that the LEU FE performance can meet the Updated Final Safety Analysis Report (UFSAR) safety requirements, additional studies will be needed to evaluate and compare the MCWO burnup code to the existing fuel burnup methodology used for HEU FEs. These two burnup analysis methodologies are used to calculate the FE ^{235}U inventory values versus the ATR effective full power days (EFPD). Then, the calculated results will be compared to the analytical calculation in order to evaluate the effectiveness of the methodologies.

2. ATR Core and Fuel Element Description

The ATR has five lobes which are loosely coupled. These five lobes are identified as Northwest (NW), Northeast (NE), Center (C), Southwest (SW), and Southeast (SE) (Figure 1). Each lobe consists of 8 FE for a total of 40 FE in the core. During full power operation, operators can maintain desired lobe powers by rotating the Outer Shim Control Cylinders (OSCC) and withdrawing/inserting the neck shim control rods.

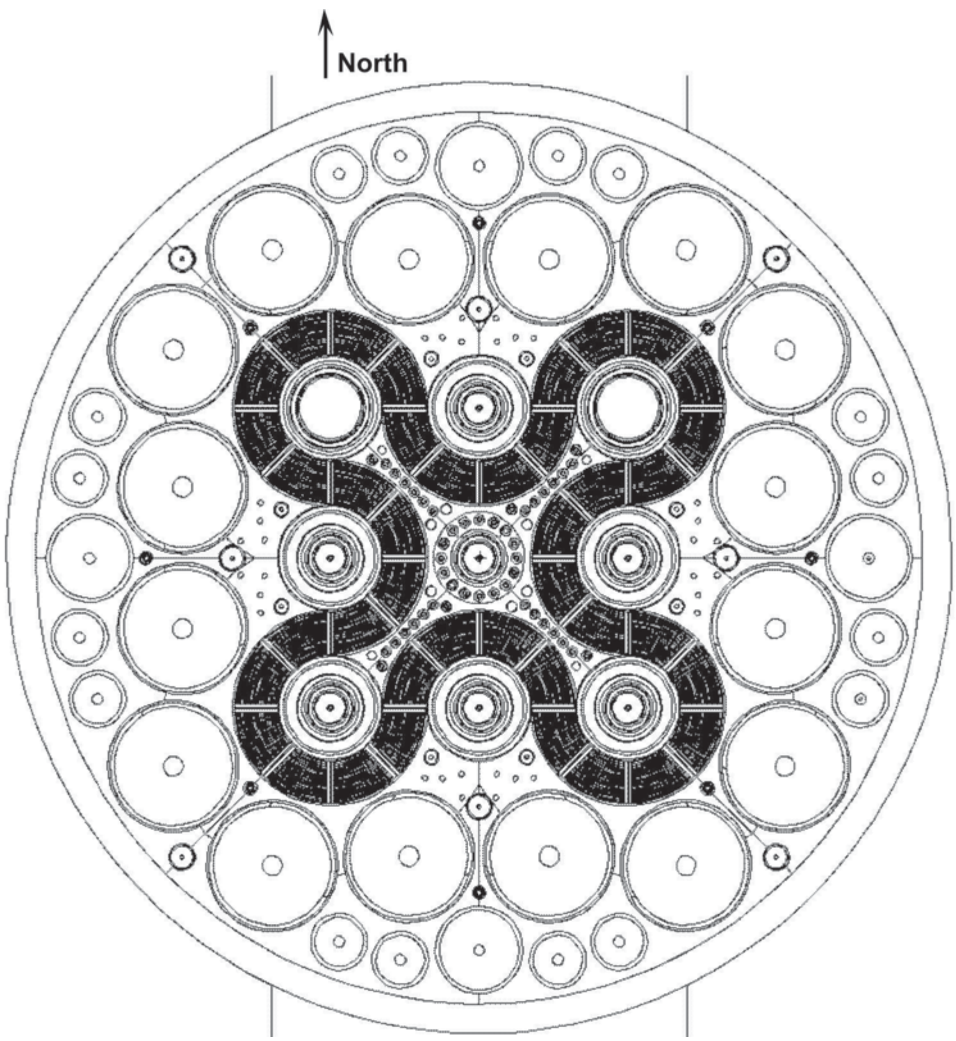

Figure 1. ATR core cross-sectional view.

3. Plate-by-Plate ATR 1/8th Core Model for Fuel Burnup Analysis

A detailed plate-by-plate MCNP [[1],[2]] ATR 1/8th core model (**Error! Reference source not found.**2) was derived from the validated [3] MCNP ATR full core model used for fuel cycle burnup analysis. There are five FE with a total of 95 fuel plates. During the fuel cycle burnup analysis, the fuel isotopes depletion and buildup are updated by the fuel burnup codes from cycle to cycles.

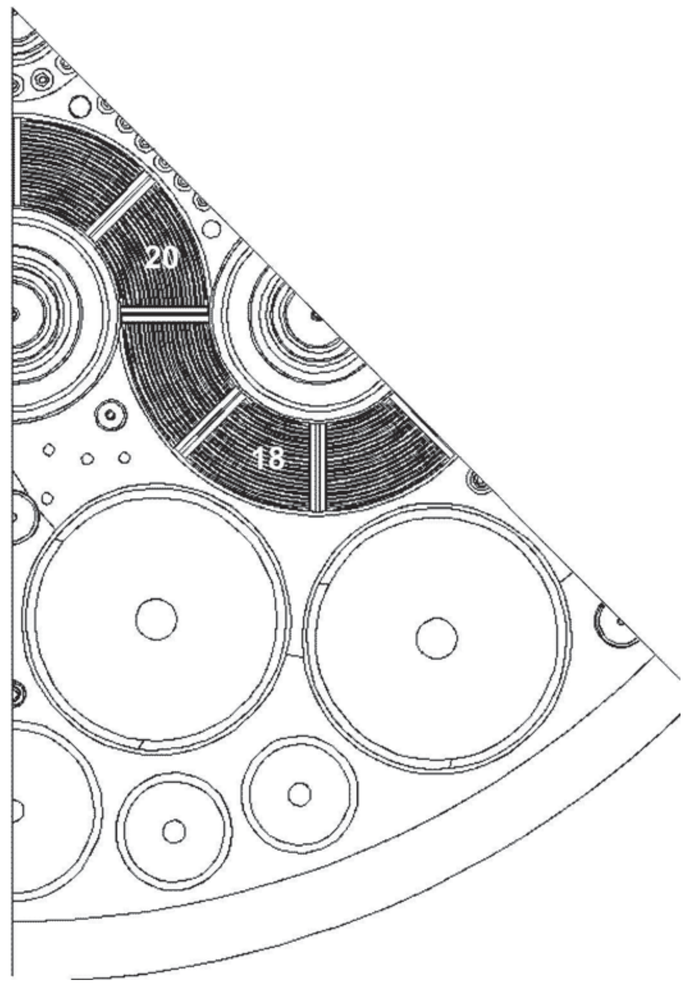

Figure 2. Detailed ATR SE-lobe 1/8th core MCNP model (FE-16 thru FE-20).

Model details for FE-18 are shown in **Error! Reference source not found.**3, which clearly shows the fuel meat, cladding, and water coolant configuration in the FE-18.

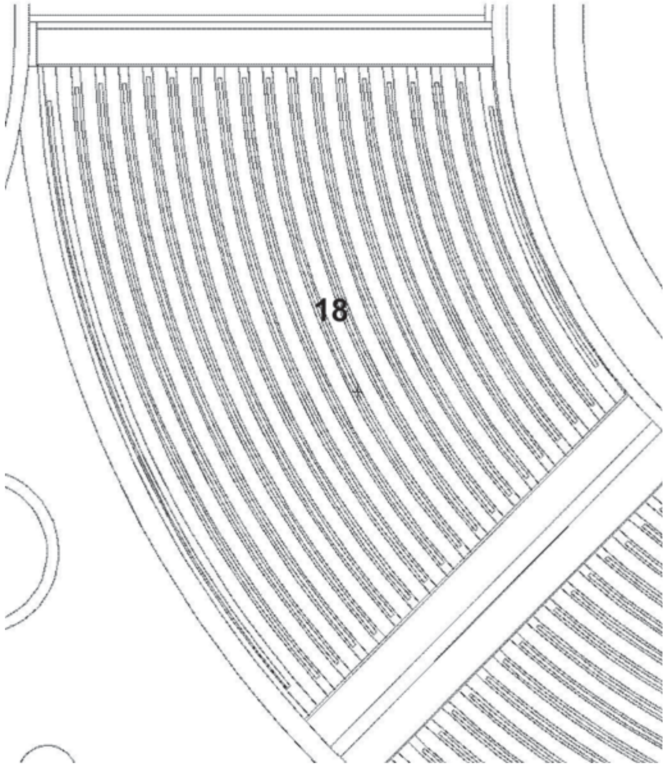

Figure 3. ATR MCNP model detail for FE-18.

4. ATR Fuel Burnup Codes

The ability of the fuel burnup analysis codes to accurately predict the fission power distribution within the 19 fuel plates is essential in the ATR FE ^{235}U inventory calculations. The existing methodology for calculating ATR fuel burnup and the MCWO methodology are presented in the following sub-sections.

4.1 PDQ ATR Core Model and Fuel Burnup Code

The PDQ [4] code solves neutron diffusion transport and depletion problems in 1-, 2-, and 3-dimensions. The detailed ATR PDQ 2-D (X-Y) calculations were performed using the PDQWS [5] computer code. The UFSAR PDQ core model uses a discrete X-Y mesh to divide the FE into cells. The detailed PDQ X-Y ATR full core model is shown in Figure 4. (Note: The North direction is in the upper right-hand corner of this figure.) All the recycle inventory values were calculated by the PDQ-GRAMS module.

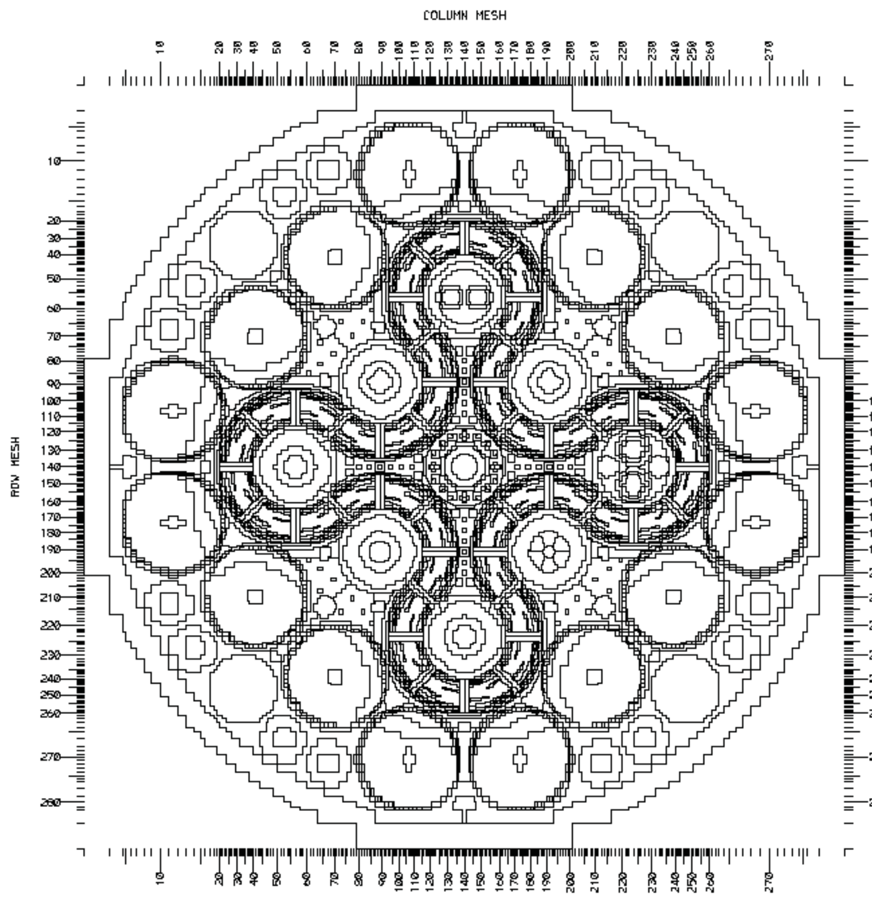

Figure 4. ATR PDQ X-Y cross-sectional view.

4.2 MCNP Coupled with ORIGEN2 Fuel Burnup Analysis Tool

The MCNP-based burnup methodology, Monte Carlo with ORIGEN2 (MCWO) couples the Monte Carlo transport code, MCNP [[1],[2]] with the radioactive decay and burnup code ORIGEN2. [6] MCWO [7,8] consists of a BASH script file that uses two FORTRAN data processing programs, m2o.f and o2m.f. [[7],[8]], to process the output from one code and create input for the other code. For each MCNP calculation step, MCNP updates the fission power distribution, neutron fluxes, and burnup-dependent cross sections (XS) for each fuel plate of the FE. Then the program, m2o.f provides the necessary XS 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. ORIGEN2 calculates the isotopic material compositions in the fuel region and the program o2m.f generates a new MCNP input file for the next time step.

5. RESULTS AND DISCUSSION

The energy derived from the complete fissioning of 1 gram of ^{235}U is 8.2 x 10^{10} joules = 0.949 MWd. There are 8 FE per lobe and if we assume that each FE depletes at the same rate, an FE will deplete 1/8 gram to generate 0.949 lobe-MWd. Note for ^{235}U, the XS for the (n,γ) reaction is

13.86 barns (ORIGEN2 one group XS) and the XS for the (n,f) reaction is 68.4 barns. As a result, the corrected analytical ratio of depleting 1 gram of ^{235}U in one FE to the lobe-MWd is 1/(8*0.949)*1.203 = 0.1585, where 1.203 is the ratio of ^{235}U total absorption to fission cross sections. For HEU fuel, the MCWO-calculated fuel burnup results as shown in Figure 5, this indicates that only about 0.41% of the total fission power comes from the conversion of ^{238}U to ^{239}Pu. So, it is reasonable to assume that all the fission energy is from ^{235}U without losing much accuracy in the analytical equation derivation. A standard new ATR fuel element, referred to as a 7F element, starts with 1075 g of ^{235}U. Therefore, assuming that GUR is the grams of ^{235}U remaining in an element, an analytical equation for GUR is:
GUR = 1075 - 0.1585 x lobe-MWd (1)

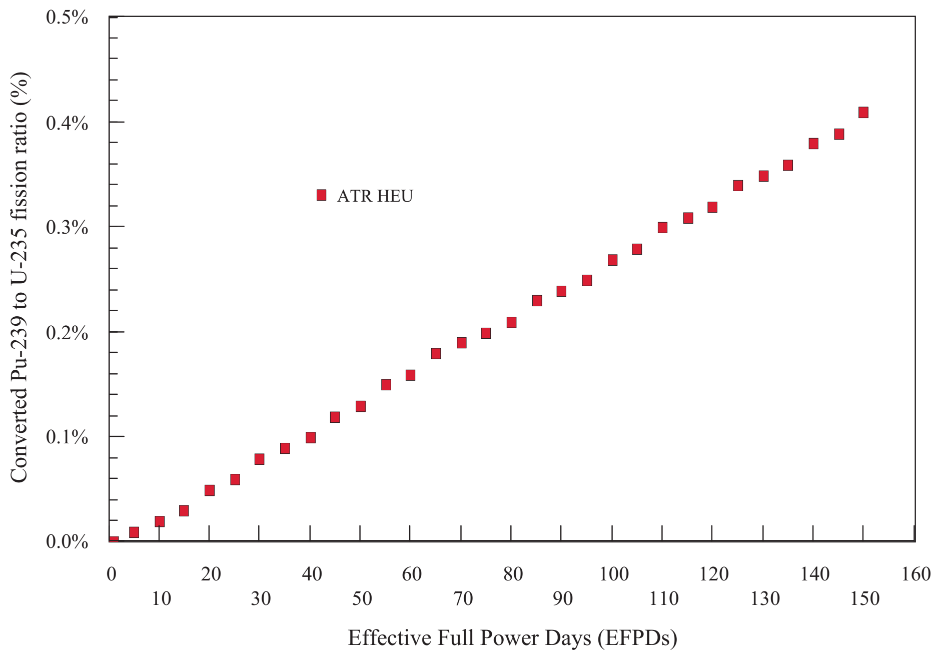

Figure 5. MCWO-calculated cumulative fissions ratio of the converted ^{239}Pu to ^{235}U versus EFPDs.

MCWO-calculated fuel burnup results and PDQ-calculated fuel inventory values for Cycles 124A to 142A will be compared. The burnup time interval for the MCWO model is 5 EFPDs with SE-lobe power of 23 MW. There are 30 intervals for a total of 150 EFPDs, which represents 3 typical full operation cycles.

The MCWO-calculated 19 fuel plates per FE fuel burnup values were converted to the remaining ^{235}U per FE versus lobe MWd for each 5 EFPD time step, which are plotted in the Figure 6. For comparison, the analytical equation (Eqn. 1) of the remaining ^{235}U versus the same 30 lobe-MWd time steps were also plotted in the Figure 6. Finally, the PDQ-calculated burnup for 453 standard 7F, FEs from ATR Cycles 124A to 142A fuel inventory reports with a linear least square fitted (LSF) curve are also plotted in Figure 6.

At the end of each cycle, the lobe power recorded by the data acquisition system is combined with cycle run-time to find the lobe-MWd for each lobe. This single lobe-MWd value is used for the exposure of each of the 8 elements in the lobe, ignoring the fact that the lobe power is not evenly divided amongst the 8 elements in the lobe. This causes the scatter in the PDQ-calculated values in Figure 6. Figure 6 also shows the LSF of the PDQ-calculated values. For elements with low burnup, the LSF points indicate that less fuel remains in the element than is indicated by the analytical result. However, once the FE has been placed in a second or third cycle, the effects of the scatter are reduced and, at high burnup, the LSF matches the analytical result. The MCWO-calculated FE burnup can be re-normalize to an even lobe fission power distribution among the FEs. As a result, MCWO-calculated FE burnup versus lobe MWd demonstrates excellent match with the analytical curve from low to high FE burnup.

6. Conclusions

For this study, the detailed plate-by-plate MCNP ATR 1/8th core model was used for the FE neutronics burnup analysis. This method can handle complex spectral transitions at the boundaries between the plates in a straight forward manner. The MCWO-calculated ^{235}U depletion versus lobe MWd results indicates excellent agreement when compared with the analytical solution curve. PDQ-calculated FE burnup also shows good agreement with respect to the analytical burnup curve, with the exception of the first low burnup fuel cycle.
Therefore, we can conclude that the MCWO fuel burnup analysis code can be used to analyze fuel burnup in the LEU core conversion for the ATR. We have demonstrated that the LEU FE experiment core fuel cycle performance can be analyzed by the validated MCWO fuel burnup analysis code.

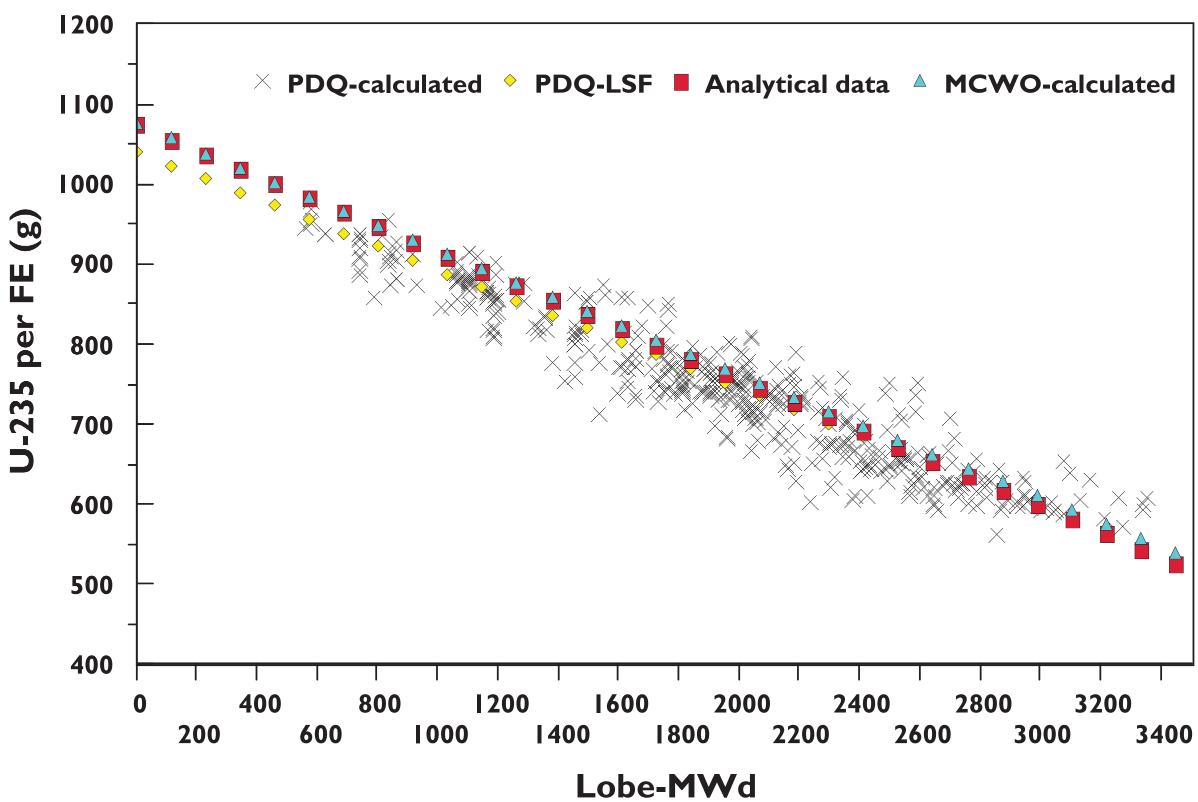

Figure 6. Comparison of analytically calculated, MCWO-calculated, and PDQ-calculated remaining grams of ^{235}U per FE versus lobe-MWd.

7. References

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