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STARTUP REACTIVITY ACCOUNTABILITY ATTRIBUTED TO ISOTOPIC TRANSMUTATIONS IN THE IRRADIATED BERYLLIUM REFLECTOR OF THE HIGH FLUX ISOTOPE REACTOR

David Chandler and G. Ivan Maldonado
Nuclear Engineering Department
The University of Tennessee
Knoxville, Tennessee 37996-2300
dchandl6@utk.edu; imaldona@utk.edu

R. T. Primm, III
Oak Ridge National Laboratory
Research Reactors Division
P.O. Box 2008; Oak Ridge, Tennessee 37831-6399
primmrtii@ornl.gov

ABSTRACT

The objective of this study is to develop a methodology to predict the reactivity impact as a function of outage time between cycles of ^{3}He, ^{6}Li, and other poisons in the High Flux Isotope Reactor's (HFIR) beryllium reflector. The reactivity worth at startup of the HFIR has been incorrectly predicted in the past after the reactor has been shut-down for long periods of time. The incorrect prediction was postulated to be due to the erroneous calculation of ^{3}He buildup in the beryllium reflector. It is necessary to develop a better estimate of the start-of-cycle symmetric critical control element positions since if the estimated and actual symmetrical critical control element positions differ by more than $1.55 in reactivity (approximately one-half inch in control element startup position), HFIR is to be shutdown and a technical evaluation is performed to resolve the discrepancy prior to restart.

^{3}He is generated and depleted during operation, but during an outage, the depletion of ^{3}He ceases because it is a stable isotope. ^{3}He is born from the radioactive decay of tritium, and thus the concentration of ^{3}He increases during shutdown. The computer program SCALE, specifically the TRITON and CSAS5 control modules including the KENO V.A, COUPLE, and ORIGEN functional modules were utilized in this study. An equation relating the down time (t_d) to the change in symmetric control element position was generated and validated against measurements for approximately 40 HFIR operating cycles. The newly-derived correlation was shown to improve accuracy of predictions for long periods of down time.

Key Words: HFIR Be beryllium He-3 helium reactivity

1. INTRODUCTION

High Flux Isotope Reactor (HFIR) fuel cycle 407 ended on December 14, 2005 and cycle 408 began on May 13, 2007. The 484 day outage was due to the conversion of horizontal beam tube number four from a 30-m small angle neutron scattering facility to a high performance hydrogen cold source. The estimated symmetrical critical control element position (ESCCEP) for the startup of 408 was 18.656 inches [1]. During the startup of cycle 408 the difference between the estimated and actual symmetrical positions exceeded $1.55 requiring a pause in reactor startup. A reactivity difference of $1.55, which is

approximately equal to 0.5 inches in control element position at startup, is the maximum reactivity difference allowed at startup and thus if exceeded, a technical evaluation is performed to resolve the discrepancy prior to a restart. Following the pause in the approach to critical, the ESCCEP was reexamined and it was determined that the reactivity attributed to shutdown ^{3}He poison was too large using the current methodology.

The actual symmetrical critical control element position (ASCCEP) for the startup of cycle 408 was 18.090 inches, a difference of 0.566 inches from the original calculation. The current methodology, which was used to calculate the cycle 408 ESCCEP, predicted a $\Delta\rho$ (change in reactivity with respect to a reference cycle) attributed to shutdown ^{3}He of \$4.67 ($\Delta R \approx 1.53$ inches) whereas the revision, which utilized a more in depth calculation, predicted a $\Delta\rho$ of \$2.97 ($\Delta R \approx 0.97$ inches). The incorrect prediction of the ASCCEP for cycle 408 due to an incorrect prediction in the ^{3}He poisoning effect is the motivation behind developing a better ^{3}He poisoning correlation. The current methodology for calculating ΔR (change is symmetrical critical control element position with respect to a reference cycle) is explained in Ref. 2 along with the full documentation of this study.

1.1. Brief Description of the High Flux Isotope Reactor

HFIR, which is located at the Oak Ridge National Laboratory, is a versatile flux-trap type research reactor that was originally designed to produce gram quantities of transuranium elements such as californium-252. HFIR has the capability of thermal-neutron and cold-neutron scattering, materials irradiation, and neutron activation analysis. Currently, HFIR operates at a power level of 85 MW for 23 to 27 day periods and has a peak thermal neutron flux of approximately 2.6×10^{15} neutrons per square centimeter per second.

A bundle consisting of 37 target positions is located in the central region of HFIR and is referred to as the flux-trap. On the outside of the flux-trap are the fuel elements; two concentric rings referred to as the inner and outer fuel elements. The inner fuel element (IFE) and the outer fuel element (OFE) contain 171 and 369 fuel plates, respectively. The fuel plates, which are involute in shape, are made of highly enriched uranium (HEU) in a mixture of U_3O_8-Al (enriched to ~93 wt. % ^{235}U) sandwiched between two sheets of Al-6061. Each of the IFE and OFE fuel plates contain approximately 15.18 and 18.44 grams of ^{235}U, which sum to a total core loading of 9.4 kg ^{235}U. The flux-trap and involute fuel plate geometries were selected to enable the production of a high thermal flux to power ratio. The heat produced in this pressurized light water-cooled and –moderated reactor is removed by the down flow of cooling water and is dissipated through heat exchangers to a cooling tower.

The control elements, which are located in the annulus just outside of fuel elements, are thin metallic cylinders that contain europium, tantalum, and aluminum sections. A large cylinder approximately 30.5 centimeters thick of beryllium metal surrounds the fuel and control elements and is used as a neutron reflector. The reflector is subdivided into three regions: a removable beryllium reflector (RB), a semi-permanent reflector (SPB), and a permanent reflector (PB). A view of the 1970 configuration of HFIR at the horizontal midplane is depicted in Fig. 1.

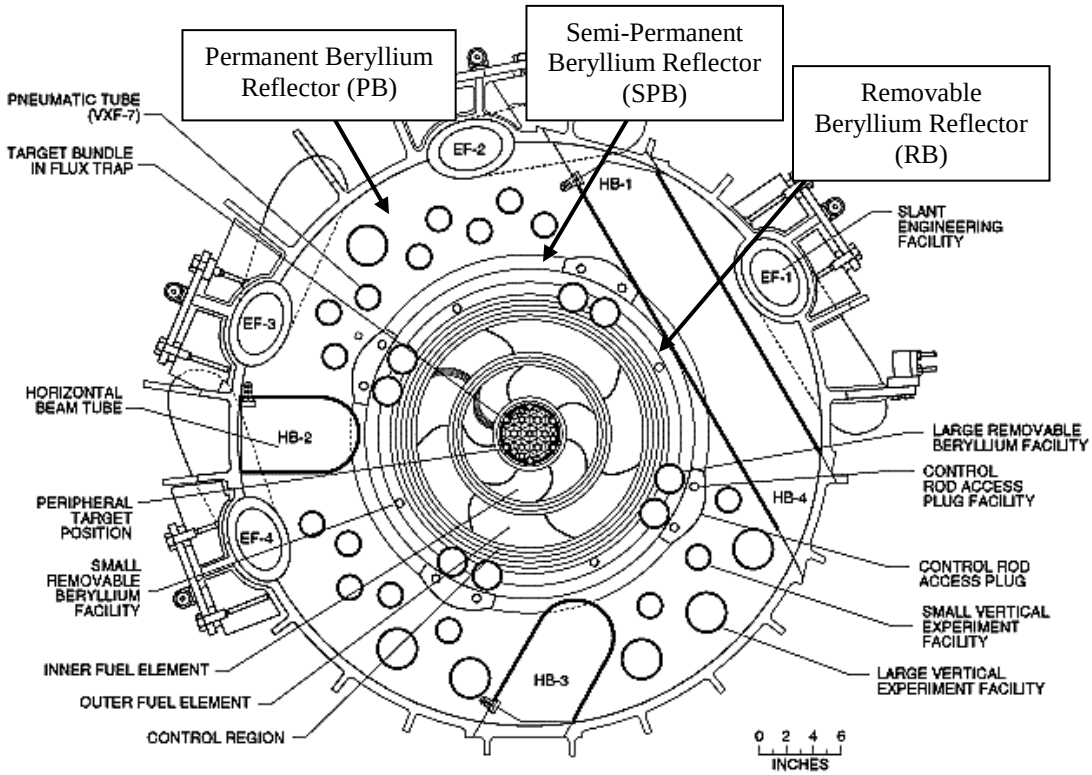

Figure 1. Cross section of HFIR at the horizontal midplane.

1.2. Isotopic Transmutations Due to Irradiation on Beryllium

Beryllium is a light metal (ρ = 1.85 g/cm^3) with an atomic number of 4 and an atomic mass of 9.012182 amu. The most common isotope of beryllium is the stable ^{9}Be. Be is used in nuclear applications because of its relatively low neutron absorption cross section and its relatively high neutron scattering cross section. Thus, it works well as a neutron moderator or reflector. The main disadvantage of using Be is the buildup of ^{3}He, a neutron poison that can lead to swelling and mechanical property changes. Be reflectors must be changed out periodically due to the internal stresses that are caused by swelling.

When ^{9}Be is irradiated by neutrons above ~1 MeV, it undergoes (n,α) and (n,2n) reactions [3]. ^{9}Be can also undergo (n,γ) reactions when irradiated by thermal neutrons. The main type of reaction that causes poisoning is the (n,α) reaction that leads to the buildup of ^{6}Li and ^{3}He, two isotopes with large thermal absorption cross sections. Thus, a negative reactivity is introduced in the Be reflector, which has to be accounted for in order to accurately predict the startup position of control elements. The main Be nuclear reactions that govern the transmutations and lead to poisoning are defined in equations 1 through 7.

$$^9\text{Be} + \text{n}(1-2\ \text{MeV}) \xrightarrow{20\ mb} {}^6\text{He} + {}^4\text{He} \tag{1}$$

$$^9\text{Be} + \text{n}(2-4\ \text{MeV}) \xrightarrow{85\ mb} {}^6\text{He} + {}^4\text{He} \tag{2}$$

$$^9\text{Be} + \text{n}(4-10\ \text{MeV}) \xrightarrow{10\ mb} {}^6\text{He} + {}^4\text{He} \tag{3}$$

$$^6\text{He} \xrightarrow{0.8\ s} {}^6\text{Li} + \beta^- \tag{4}$$

$$^{6}\text{Li} + \text{n(thermal)} \xrightarrow{950\ b} {}^{4}\text{He} + {}^{3}\text{H} \quad (5)$$

$$^{3}\text{H} \xrightarrow{12.33\ yr} {}^{3}\text{He} + \beta^{-} \quad (6)$$

$$^{3}\text{He} + \text{n(thermal)} \xrightarrow{5327\ b} {}^{3}\text{H} + p \quad (7)$$

^{6}He is the result of the ^{9}Be(n,α) reaction and decays quickly into ^{6}Li. The relatively large cross section of ^{6}Li, along with the abundance of thermal neutrons in the Be reflector lead to a ^{6}Li(n,α) reaction. The ^{6}Li(n,α) reaction produces tritium (^{3}H), a radioactive isotope of hydrogen that has a half life of 12.33 years. The daughter product of ^{3}H is ^{3}He, which is produced and depleted during reactor operation. During irradiation, ^{3}He is produced by the decay of ^{3}H and is depleted according to the ^{3}He(n,p) nuclear reaction. However, in a no flux environment (i.e. an outage) the ^{3}He concentration significantly increases since there is no destruction mechanism. This phenomenon must be considered, especially during long outage periods, to account for its reactivity effects on the startup of HFIR.

2. COMPUTATIONAL MODEL DEVELOPMENT

Version 6 of the Standardized Computer Analysis for Licensing Evaluation (SCALE) [4] code was utilized for this study. SCALE was developed and is maintained by Oak Ridge National Laboratory (ORNL) under contract with the Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC). The 238 group ENDF/B-VII release 0 library was utilized in the analyses reported here.

Depletion calculations were performed using the TRITON control module. The t5-depl sequence was used for three-dimensional (3-D) depletion calculations using burn-up dependent cross section preparation 3-D Monte Carlo transport calculations - KENO V.a. COUPLE was utilized to couple the problem dependent cross section constants and flux weighting factors into libraries used by ORIGEN and ORIGEN was utilized to calculate transmutations. A current 3-D MCNP model of HFIR [5] was converted into a simplified 3-D SCALE/KENO V.a model.

HFIR currently operates at a power of 85 MW for an average of about 25 days per fuel cycle. With a capacity factor of approximately 50 %, the average down time between cycles (t_d) is approximately 25 days. Twenty typical HFIR cycles were simulated and the 11 radial Be reflector regions (3 RB, 1 SPB, and 3 PB) were depleted by flux while the materials of all the other regions remained constant. The selection of 20 cycles was arbitrary, but was sufficient to allow ^{6}Li to reach equilibrium and the ^{3}He inventory to reasonably approach equilibrium (^{3}He doesn't reach equilibrium in the HFIR fuel cycle).

In order to calculate the poisoning effect of ^{3}He as a function of t_d, TRITON cases were executed with multiple decay times following the 20 cycle irradiation sequence. Atomic densities within the reflector at each decay step were then passed to "standalone" k_{eff} calculations. These calculations were performed with the same KENO-V.a model as used in the TRITON sequence but with the CSAS5 module. Although one more step in TRITON could have been simulated to calculate the necessary data (k_{eff}), standalone k_{eff} calculations were performed in CSAS5 so more histories could be simulated.

2.1. Conversion of MCNP HFIR Model to a KENO V.a Model

The HFIR cycle 400 model is a 3-D MCNP model, named HFV4.0 [5] that accurately represents the HFIR as loaded in cycle 400. HFV4.0 is based on an older model previously developed at ORNL. The MCNP (and KENO V.a) model is broken up into six major regions (parts) as listed in Table I.

Table I. Radial dimensions of major HFIR model regions.

Region	Inner Radius (cm)	Outer Radius (cm)
[1] Flux Trap Target Region (FTT)	0.00	6.43
[2] Active Inner Fuel Element (IFE)	7.14	12.60
[3] Active Outer Fuel Element (OFE)	15.13	20.98
[4] Control Elements (CE)	21.75	23.97
[5] Removable Reflector (RB)	23.97	30.17
[6] Permanent Reflector (PB)	30.17	54.61

The KENO V.a model was created by extracting the material compositions (atomic densities) and dimensions from HFV4.0 and inserting them into KENO V.a. The KENO V.a model developed for this study is a simplified 3-D model of HFIR in comparison to the MCNP model because physics parameters for the core region are not needed. For this study, only an accurate representation of the flux magnitude and spectra leaking from the core to the reflector is needed. The creation of the KENO V.a model is briefly described in Sections 2.1.1 to 2.1.4. Refer to Ref. 2 for a more detailed description.

2.1.1. Flux Trap Target Region (FTT)

The 37 target rods modeled in the FTT of HFV4.0 contained target, clad, shroud, and coolant regions. These regions were homogenized in the KENO V.a model such that one region was defined for each of the rods. The outer radius of the interior target rods (31, in center of the FTT) and peripheral target positions (6 PTPs, at outer edge of the basket) are 0.835 and 1.00076 cm, respectively. HFV4.0 models an Al ring that surrounds the targets, but the KENO V.a model was simplified by homogenizing the water and the Al ring. An x-y cross section of the flux trap as modeled in KENO V.a is depicted in Fig. 2.

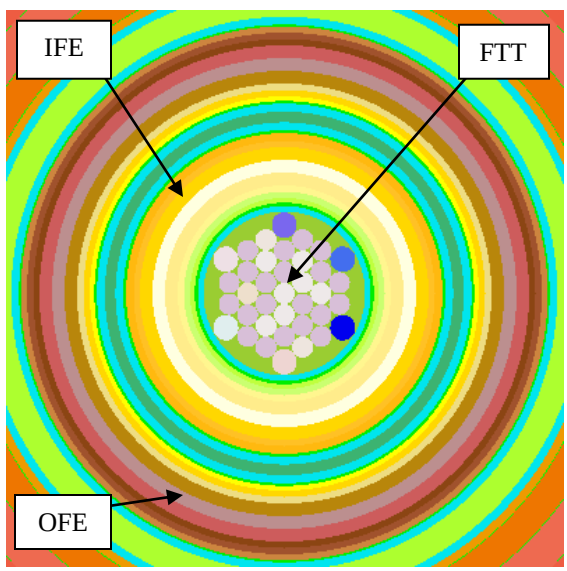

Figure 2. Cross section of KENO V.a model across the flux trap and fuel elements.

2.1.2. Fuel Elements (FEs)

The fuel meat and burnable poison in the form of boron (only in the IFE) are non-uniformly distributed along the arc of the involute fuel plates to reduce power peaking. The fuel plates are 0.127 cm thick and are separated by 0.127 cm water gaps. The HFIR FEs are modeled by dividing them into radial regions of varying, spatially-averaged ^{235}U concentrations. These regions are created by homogenizing the fuel, Al filler, burnable poison (boron in IFE), Al side walls, and the water in the channels. The IFE and OFE are modeled as 8 and 9 concentric radial zones, respectively. The HFV4.0 model divides the FEs into multiple axial layers, but the KENO V.a model only uses one axial layer because fuel burn-up is not analyzed in this study. The fuel elements as modeled in KENO V.a are illustrated in Fig. 2.

2.1.3. Control Elements (CEs)

Two poison-bearing concentric CEs are located between the FEs and the beryllium reflector. The inner CE is a single cylindrical plate and is used to regulate power and the outer CE is composed of four separate quadrants thereby forming four safety plates. Both are composed of three axial regions of different poison content: a white (Al), grey (Ta-Al), and black (Eu_2O_3-Al) region. The MCNP input explicitly models the CEs and uses transformation cards so the user can easily adjust their positions.

Due to the complexity introduced in modeling the CEs and the fact that numerous cycles are to be modeled in this analysis and only one axial fuel and reflector region is defined for each radial region, the CEs are not explicitly modeled in the KENO V.a input. For this analysis, the core leakage spectra and energy-dependent flux magnitudes are the needed physics parameters. To control reactivity (i.e. keep k_{eff} ~1.00), ^{10}B was mixed with the water that already exists in the CE channel (area where reactivity is controlled). ^{10}B was chosen rather than homogenizing the Eu, Ta, and Al sections because both Eu and Ta are resonance absorbers, and therefore would yield perturbations in the neutron leakage spectra greater than that caused by the assumption of ^{10}B. A comparison of the average cycle flux spectra from MCNP and that used in KENO V.a is provided in Ref. 2 and shows excellent agreement between the two.

2.1.4. Beryllium Reflector

The reflector is approximately 30.5 cm thick and is subdivided into three regions: the removable reflector (RB), the semi-permanent reflector (SPB), and the permanent reflector (PB). The RB has an inner and outer radius of 24.4475 cm and 30.25267 cm, respectively, and is replaced after approximately 40 full power cycles. The SPB has an inner and outer radius of 30.32125 cm and 33.02 cm, respectively, and is replaced after approximately 80 cycles. The PB has an inner and outer radius of 33.3375 cm and 54.61 cm, respectively, and is replaced after approximately 135 cycles.

The reflector is used to reflect neutrons that leak out of the fuel region back into the fuel region and to house numerous experimental facilities. Four small and 8 large removable beryllium facilities are located in the RB. Four control rod access plug facilities are located in the SPB. Sixteen small and 6 large vertical experiment facilities penetrate the PB. HFIR is equipped with 4 horizontal beam tubes that penetrate the PB at the horizontal midplane and 2 slant engineering facilities located at the outer periphery of the PB. Refer to Fig. 1 for the location of these experimental facilities.

The MCNP model contains all of the experimental facilities, but the reflectors in the KENO V.a input are modeled as solid concentric cylinders of ^{9}Be. Since the volume fraction of the experimental sites in the reflectors is relatively small, especially in the RB and SPB where the neutron flux is the largest (in the reflector) and thus the ^{3}He and ^{6}Li buildup is the greatest, the effects of neglecting the experimental

facilities for this study are negligible. In both models, the reflector regions are modeled as 1 axial region and the RB, SPB, and PB are divided into 3, 1, and 7 radial regions, respectively.

Beyond the reflector is about 50 cm of water and the steel pressure vessel. The outermost region modeled in KENO V.a is the water reflector since the neutrons arriving at the pressure vessel are very unlikely to return to the reflector or the FEs. The beryllium reflector regions, along with the rest of the HFIR core as modeled in KENO V.a are depicted in Fig. 3.

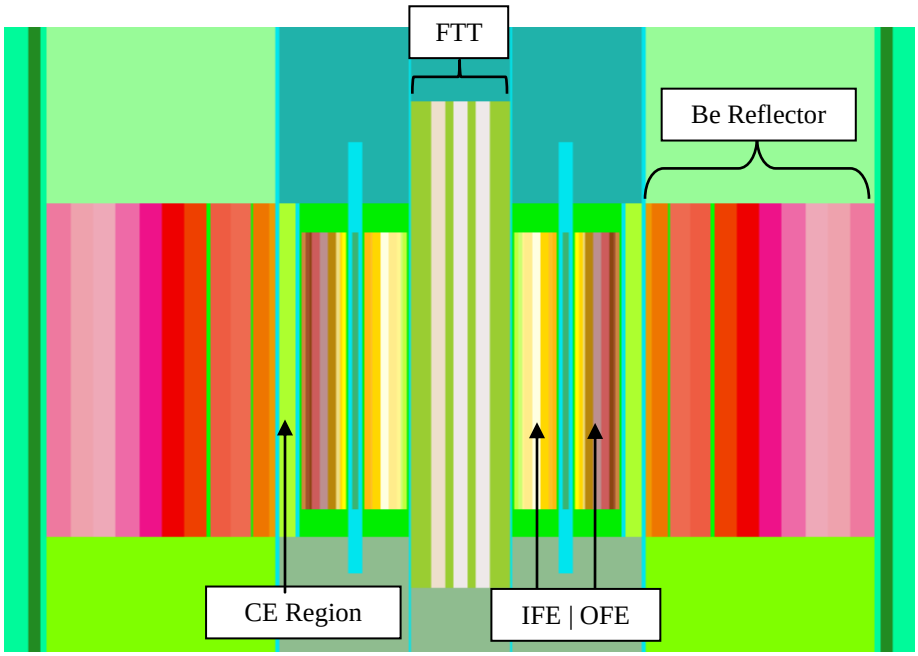

Figure 3. x-z cross section of HFIR as modeled in SCALE.

2.2. TRITON Input for Depletion and Decay Calculations

The t5-depl sequence was utilized, which invokes the CRAWDAD, BONAMI, WORKER, CENTRM, PMC, KENO V.a, KMART, COUPLE, ORIGEN, and OPUS modules. The reflector materials were depleted by the radially varying flux while the material compositions of all other regions remained constant. Thus, in the READ DEPLETION block, flux depletion was specified along with the material numbers corresponding to the 11 reflector regions. Twenty-one, 25 day irradiation periods at a constant power of 85 MW (~8423 MW/MTIHM) were modeled with 25 days of down time (t_d) between each cycle. The 21 burn-up steps were specified in the READ BURNDATA block. Following the end of the 21st cycle, multiple decay steps (3, 6, 12, 24, 48, 96, 192, 384, 492, 611, and 730 days) were defined (in separate runs). The first 20 cycles were modeled to allow for poison buildup. The beginning-of-cycle (BOC) 21 k_{eff} was calculated for the "reference" case and the BOC 22 k_{eff} values (based on the composition following the decay steps) were calculated in order to determine a correlation attributed to shutdown poisons as a function of t_d.

The OPUS functional module was utilized to output the reflector compositions in atoms/barn-cm for the reflector regions as generated by the ORIGEN code, while the READ PARAMETER block was used to specify the number of histories to run in the transport calculations. A total of 11.5 million histories were

simulated at each step (10,000 histories per generation, 1,150 generations, first 150 generations skipped). Test cases utilizing up to 50 million histories per step were run and almost no compositional differences in the reflector regions were observed.

2.3. CSAS5 Input for Multiplication Factor Calculations

The TRITON input was converted into a CSAS5 input by deleting the TRITON specific inputs and inserting the CSAS5 specific inputs and by inserting the beryllium reflector's compositions, which were output by OPUS. Thus, the geometry and material compositions, except for the reflector's, were the same for both the CSAS5 and TRITON inputs. Since ENDF data are not available for ^{10}Be and ^{12}C, these isotopes were emitted from the k_{eff} calculations. However, only trace quantities of ^{12}C were calculated, the change in concentrations of these isotopes from one cycle to the next is very small, and they are stable, so their effect on reactivity with respect to the reference case is negligible. PARM=CENTRM was specified, which invokes the execution path BONAMI, CENTRM/PMC, and KENO V.a. The PARAMETER card was defined to simulate 51.5 histories: 10,000 histories per generation, 5,150 generations, and 150 skipped generations.

3. BERYLLIUM IRRADIATION POISONING AND REACTIVITY CALCULATIONS

The beginning composition of the reflector regions was 100 % ^{9}Be and equilibrium ^{6}Li was achieved after approximately 5 cycles (Fig. 4). The number of cycles was arbitrarily selected, but the results shown in Fig. 4 reveal that the ^{3}He inventory reasonably approaches equilibrium. The goal of these studies is to revise a procedure for *estimating* the reactivity impact of ^{3}He and the most accurate determination of ^{3}He reactivity worth would be obtained by modeling the equilibrium conditions.

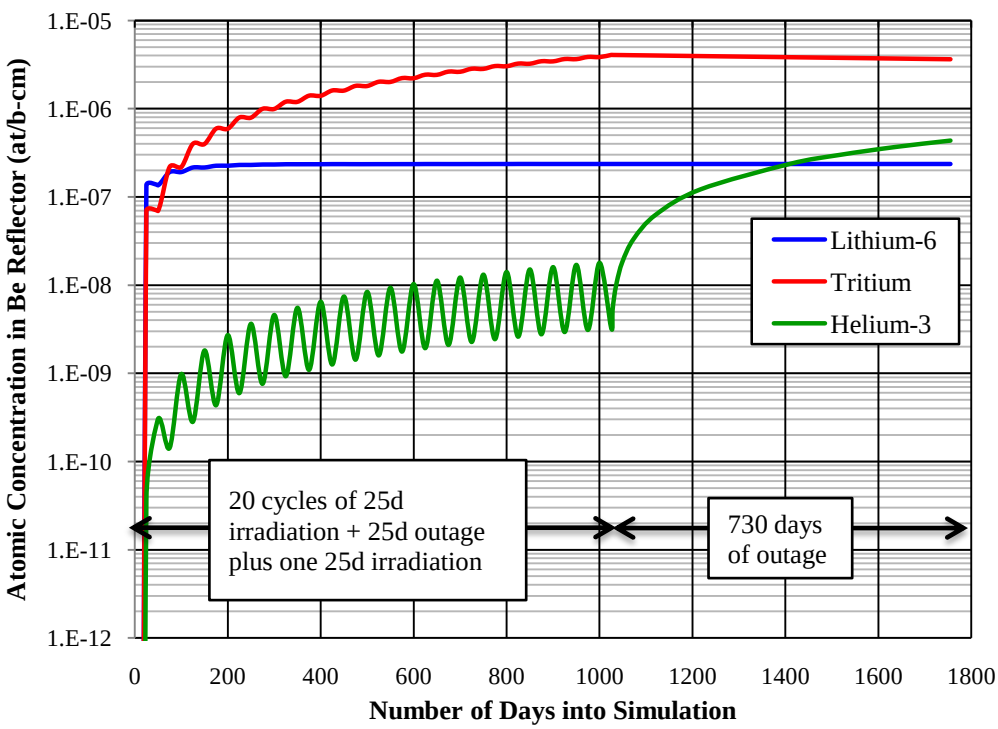

Figure 4. Poison buildup in beryllium reflector as a function of simulation time.

3.1. Reactivity Calculations

For the CSAS5 calculations, the ^{10}B, which was being used to control reactivity, was removed from the CE channel so there were no poisons that would affect reactivity that is not normally present during operation. A 25 day irradiation period (cycle 21) was inserted into the original 20 cycle input case. In order to calculate the reactivity effect of ^{3}He as a function of t_d, multiple decay steps (3, 6, 12, 24, 48, 96, 192, 384, 492, 611, and 730 days) were analyzed following cycle 21. Multiplication factors were calculated for the reference case (BOC 21 k_{eff}) and the cases corresponding to the multiple decay steps (BOC 22 k_{eff}'s). Since the ^{3}He concentration increases as a function of t_d, the k_{eff} values decrease as a function of t_d. All of the k_{eff} values were inserted into a spreadsheet and the $\Delta k_{eff}/k_{eff}$ (%) values (reactivity effect of ^{3}He as a function of t_d) were calculated using equation 8.

$$reactivity\ (\%) = \frac{\Delta k_{eff}}{k_{eff}} = \frac{k_{eff}^{current} - k_{eff}^{reference}}{k_{eff}^{current} \times k_{eff}^{reference}} \tag{8}$$

The $\Delta k_{eff}/k_{eff}$ values were converted into $\Delta\rho$ ($) (change in reactivity) by dividing by 0.0076, the delayed neutron fraction (β_{eff}) associated with HFIR. The $\Delta\rho$'s were then converted into ΔR's, which are used to show the change in symmetrical critical control element position associated with ^{3}He worth with respect to the reference case using the conversion factor $3.10/in. The actual differential rod worth (DRW) is dependent upon the control element position, but a value of $3.10/inch corresponds to "typical" startup positions (between 17.5 and 18 inches withdrawn). The calculated reactivity values are listed in Table II.

Table II. $\Delta\rho$ and ΔR results.

Case	k_{eff}	σ_{keff}	$\Delta k_{eff}/k_{eff}$ (%)	$\sigma_{\Delta keff/keff}$ (%)	$\Delta\rho$ ($)	σ_{ρ} (¢)	ΔR (in)	$\sigma_{\Delta R}$ (in)
reference	1.11415	0.00012	-	-	-	-	-	-
3	1.11578	0.00012	0.00131	0.00016	0.17252	2.12744	0.05565	0.00686
6	1.11547	0.00012	0.00106	0.00016	0.13975	2.12757	0.04508	0.00686
12	1.11499	0.00012	0.00068	0.00016	0.08897	2.12778	0.02870	0.00686
24	1.11415	0.00012	0.00000	0.00016	0.00000	2.12815	0.00000	0.00686
48	1.11226	0.00013	-0.00153	0.00017	-0.20068	2.21921	-0.06473	0.00716
96	1.10890	0.00012	-0.00425	0.00016	-0.55913	2.13048	-0.18036	0.00687
192	1.10286	0.00013	-0.00919	0.00017	-1.20897	2.22245	-0.38999	0.00717
384	1.09357	0.00012	-0.01689	0.00016	-2.22250	2.13782	-0.71694	0.00690
492	1.08948	0.00013	-0.02032	0.00017	-2.67419	2.22760	-0.86264	0.00719
611	1.08548	0.00012	-0.02371	0.00016	-3.11924	2.14203	-1.00621	0.00691
730	1.08169	0.00012	-0.02693	0.00016	-3.54396	2.14408	-1.14321	0.00692

3.2. Proposed Shutdown Poison Accountability Procedure

The reactivity effect for decay times up to 24 days in Table II are positive since cycles of equal irradiation and down times are simulated and ^{3}He is burned during irradiation and produced during decay (Fig. 4). However, the purpose of this study is to determine the "added" reactivity poisoning effect of ^{3}He that

builds in following shutdown. Therefore, the Δρ curve produced from Table II was shifted such that the Δρ value at $t_d = 0$ is zero. The curve based on a zero Δρ value at zero shutdown time is compared to the curve used in the current ESCCEP calculation in Fig. 5.

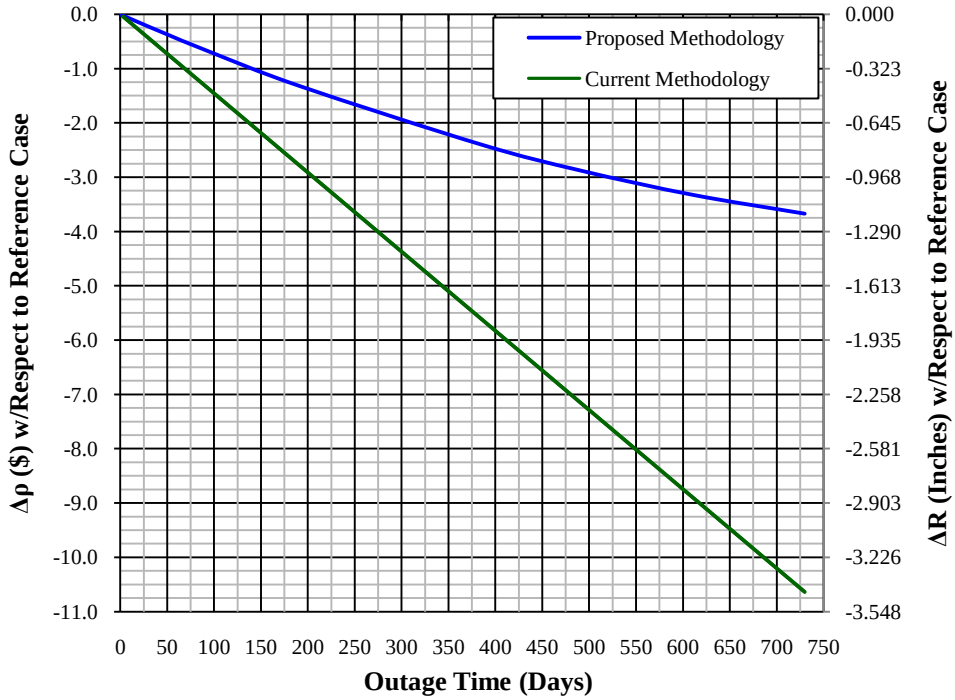

Figure 5. Comparison of current procedure and newly derived ^{3}He poison effect estimates.

The proposed methodology for the ESCCEP calculation to calculate the ΔR associated with shutdown ^{3}He poisoning of the reflector is shown below. A 2nd order correlation was chosen for implementation. Refer to Ref. 2 for a comparison of using the linear, 2nd order, and 3rd order correlations. The current cycle is the cycle in which the ESCCEP is being calculated and the reference cycle is a typical, comparable cycle (usually the previous cycle).

a. Current Cycle
   - ☐ The reflector is new at start of cycle Δρ = 0.0
   - ☐ The reflector has one or more cycles of irradiation.

     $Td_c = \underline{t_c}$ days (the decay time on the reflector)

     $\Delta\rho_c = -(3.47692\text{x}10^{-6})\, t_c^2 + (7.56879\text{x}10^{-3})\, t_c$ (6.8a)

b. Reference Cycle
   - ☐ The reflector is new at start of cycle Δρ = 0.0
   - ☐ The reflector has one or more cycles of irradiation.

     $Td_r = \underline{t_r}$ days (the decay time on the reflector)

     $\Delta\rho_r = -(3.47692\text{x}10^{-6})\, t_r^2 + (7.56879\text{x}10^{-3})\, t_r$ (6.8b)

c. Δρ Current Cycle $\underline{\Delta\rho_c}$ dollars (6.8a)

   Δρ Reference Cycle $\underline{\Delta\rho_r}$ dollars (6.8b)

   Δρ8 = (6.8a) - (6.8b) = $\underline{\Delta\rho 8}$ dollars (6.8c)

d. DRW = Differential Rod Worth at ESCCEP dollars/inch
$\Delta R8 = \Delta\rho 8 / (DRW) =$ ΔR inches (6.8d)

In the above procedure Td_c and Td_r denote the current and reference t_d (days), respectively, while $\Delta\rho_c$ and $\Delta\rho_r$ denote the current and reference change in reactivity ($), respectively. The symbols $\Delta\rho 8$ and $\Delta R8$ represent the change in reactivity and the change in symmetrical critical control element positions between the current and reference cycles, respectively. The 8 signifies that the reactivity effects were derived from step 6.8 of the ESCCEP calculation. The reactivity difference ($) must first be calculated and then the user must input the DRW at startup ($/inch) before calculating $\Delta R8$.

3.3. Validation of Proposed Methodology against Measured Data

ESCCEP calculations for HFIR cycles 383 – 421 were utilized to compare the current and proposed methodologies. For this study, it was assumed that uncertainty only exists in the ^{3}He poison effect (i.e. reactivity effects associated with fuel worth, cylinder/plate burn-up, cylinder/plate ^{182}Ta worths, and etc remained unchanged from the original calculations). The ESCCEP calculated with both the current and proposed methodologies were compared to the ASCCEPs and the differences are shown in Fig. 6.

On average, the proposed methodology better estimates the symmetrical critical control element positions. The average absolute difference between actual and estimated positions for the current and proposed methodologies for the 39 cycles is 0.174 and 0.154 inches, respectively. The proposed methodology better predicts the ^{3}He effect for longer outages, but little difference is observed for shorter outages. The lines in Fig. 6 that extend at a delta of 0.5 inches were included because a difference of ~0.5 inches will cause the reactor to be shutdown and a technical evaluation to be performed to resolve the discrepancy prior to startup. The difference of -0.56 inches calculated for cycle 408 using the current methodology was the motivation of this study. A more involved calculation was used for cycle 383 (t_d = 430 days), which produced an ASCCEP – ESCCEP value of -0.180 inch. However, if the current methodology would have been utilized instead, a difference of -0.858 inches would have been obtained (denoted with a star on Fig. 6). Thus, the current methodology over predicts the effects attributed to shutdown ^{3}He. The proposed methodology mitigates the overprediction.

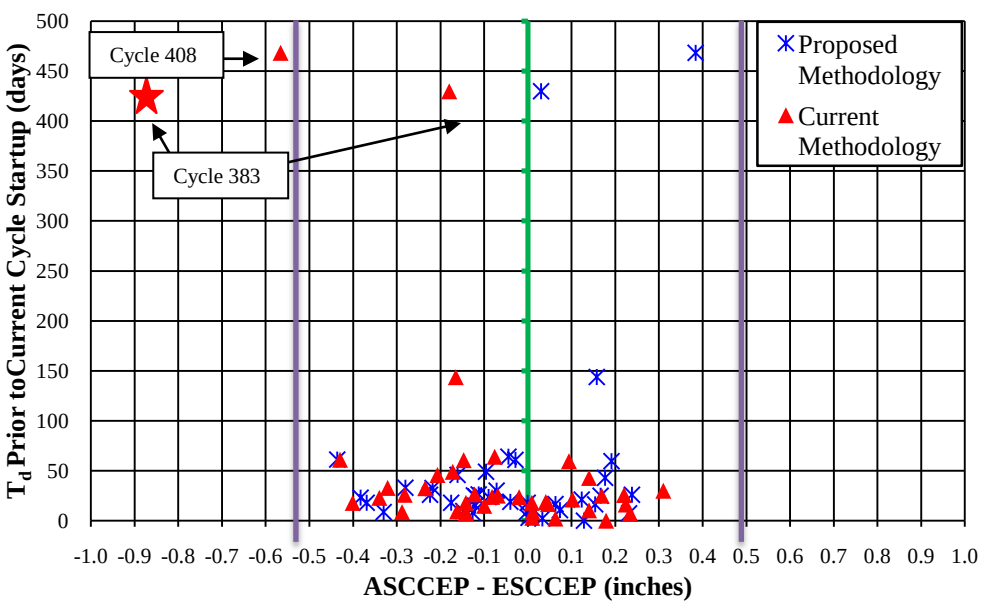

Figure 6. Comparison of current and proposed ESCCEP methodologies against ASCCEP data.

3. CONCLUSION

A new methodology for predicting the reactivity impact of ^{3}He, ^{6}Li, and other poisons in the beryllium reflector of the High Flux Isotope Reactor (HFIR) was developed to amend the ORNL Research Reactor Division's Estimated Symmetrical Critical Control Element Position (ESCCEP) calculation procedure. A new procedure is needed to better estimate the critical control element position following a long outage because the current procedure has proven to be inaccurate following long outages.

When ^{9}Be is irradiated by fast neutrons (energies above ~1 MeV), it undergoes (n,α) reactions that lead to a buildup of the ^{3}He and ^{6}Li isotopes. Both of these isotopes have large neutron absorption cross sections in the thermal energy range and thus the negative reactivity impact due to these poisons must be correctly accounted for at reactor startup when predicting the symmetrical critical control element position.

Through calculations, it was shown that ^{6}Li reached an equilibrium concentration after approximately 5 cycles, which when averaged over the entire volume of the reflector amounts to about $2.36\text{x}10^{-07}$ atoms/barn-cm. Unlike ^{6}Li, ^{3}He didn't reach an equilibrium concentration. The amount of ^{3}He in the reflector decreased during irradiation primarily due to the ^{3}He(n,p) reaction, which produces tritium. During outages the amount of ^{3}He significantly increased due to the decay of tritium, which is produced by the ^{6}Li(n,α) and ^{3}He(n,p) reactions.

The methodology developed in this study was compared to the methodology that is currently employed, and on average the proposed methodology better estimates the symmetrical critical control element positions, especially for long outages which allow for large amounts of ^{3}He to buildup in the reflector. Utilizing the correlation between the beryllium poison and change in symmetrical control element position developed in this report, an average absolute difference between actual and estimated positions of 0.154 inches (assuming all other reactivity effects were correctly calculated) was observed after reevaluating the ESCCEP calculations for 39 startups between HFIR cycles 383-421.

The explanation for the observed inadequacy of the current procedure for predicting the poisoning effect following long (several months) shutdowns was due to less than linear buildup of ^{3}He in the reflector as a function of shutdown time. The current procedure for estimating poisoning effect had assumed a linear relationship and an operating power of 100 MW. While not the focus of this study, the results derived serve to validate the SCALE system and associated cross section libraries for predicting the in-growth of nuclides during irradiation of beryllium.

NOMENCLATURE

ASCCEP – actual symmetrical critical control element position (inches)
β_{eff} – delayed neutron fraction
BOC – beginning-of-cycle
CE – control element
DRW – differential rod worth
EOC – end-of-cycle
ESCCEP – estimated symmetrical critical control element position (inches)
FTT – flux trap target
HEU – highly enriched uranium
HFIR – High Flux Isotope Reactor
IFE – inner fuel element

k_{eff} – effective multiplication factor
$\Delta k_{eff}/k_{eff}$ – reactivity (%)
OFE – outer fuel element
ORNL – Oak Ridge National Laboratory
$\Delta\rho$ – change in reactivity ($)
PB – permanent beryllium reflector
PTP – peripheral target positions
ΔR – change in symmetrical critical control element position
RB – removable beryllium reflector
SPB – semi-permanent beryllium reflector
t_d – down time in between cycles (days)
wt. % - enrichment in weight percent (%)

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