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ABSTRACT

In preparation for the proposed conversion of the National Institute of Standards and Technology (NIST) research reactor (NBSR) from high-enriched uranium (HEU) to low-enriched uranium (LEU) fuel, certain point kinetics parameters must be calculated. We report here values of the prompt neutron lifetime that have been calculated using three independent methods. All three sets of calculations demonstrate that the prompt neutron lifetime is shorter for the LEU fuel when compared to the HEU fuel and longer for the equilibrium end-of-cycle (EOC) condition when compared to the equilibrium startup (SU) condition for both the HEU and LEU fuels.

THE 1/v ABSORBER INSERTION METHOD

A traditional means to calculate the prompt neutron lifetime is the 1/v insertion method [1] where a small amount (~1E-8 atoms/b-cm) of 1/v absorber is uniformly distributed throughout a reactor system. This absorber results in a negative reactivity insertion, ρ. The negative reactivity insertion is determined by calculating the value of k_{eff} after the 1/v absorber is introduced and is:

$$\rho = \Delta k/k = 1/k_{eff,u} - 1/k_{eff,p}$$

where the subscripts *u* and *p* represent the unperturbed (no 1/v absorber) and the perturbed (with the 1/v absorber) values of k_{eff}.

Because models of operating nuclear reactors are not perfect, it is not unusual for the calculated value of $k_{eff,u}$ to exhibit a bias [2]; that is, a consistent deviation from the expected critical value (1.0). The calculations performed for this work used MCNP5 [3] with the ENDFB-VII libraries [4]. The model used for the NBSR has been developed over several years and explicitly includes most of the major structures in the reactor [5]. The differences between the HEU model and the LEU model are: (1) the material in the fuel; (2) the density of each fuel; (3) the thickness of each fuel: (4) 0.00254 cm (0.001 in.) of zirconium surrounding the LEU fuel.

For the NBSR the bias is determined by knowing the constituents of the fresh, unirradiated HEU fuel elements, and calculating equilibrium inventories for the NBSR at the end-of-cycle. The EOC occurs after 38.5 days of full 20 MW operation and at that point in time there is not enough excess reactivity to maintain operation and the reactor shuts itself down. The bias is then determined by calculating the value of k_{eff} at the EOC of the equilibrium core, noting that the true value should be unity. Therefore any calculation for the reactivity is then compared to the value of $k_{eff,u}$ with the built-in bias, and it is assumed that all the bias is a constant for all calculations.

For the prompt neutron lifetime calculation, the value of $k_{eff,p}$ is calculated for varying amounts of 1/v absorber added to the system. According to Bretscher [1], the reactivity insertion from the addition of the 1/v absorber is:

$$-\Delta k/k = N\sigma_o v_o l'_p$$

where:

N = the atomic density of the 1/v absorber (in atoms/b-cm)

σ_o = the thermal neutron absorption cross section of the absorber (3837b for ^{10}B used here)

v_o = the speed of a thermal neutron = 2.2E5 cm/s

l'_p = neutron lifetime (s) when N atoms/b-cm of 1/v absorber is added to the system

The prompt neutron lifetime, l_p, for the unperturbed core is calculated as the amount of 1/v absorber approaches zero:

$$l_p\,(s) = \lim_{N\to 0} l'_p = \lim_{N\to 0} \left[-\Delta k/k / (N\sigma_o v_o)\right]$$

For this work, the 1/v absorber method was performed by including ^{10}B uniformly throughout all materials of the NBSR at concentrations between 4E-9 and 15E-9 a/b-cm. The calculations were performed at 1E-9 a/b-cm increments for a total of 12 calculations for the HEU and LEU fuels at startup (SU) and end-of-cycle (EOC). The value of k_{eff} was calculated for each value of ^{10}B loading and the reactivity change associated with the ^{10}B addition was calculated. Concentrations of ^{10}B below 4E-9 a/b-cm did not provide enough change in the reactivity to result in reliable values of ρ for inclusion in the neutron lifetime calculation. In these cases, even though the statistical error for each calculation of k_{eff} is small, the calculation of $\Delta k/k$ is the difference between two numbers that have similar values and the error in $\Delta k/k$ becomes too large to be useful.

The value of l'_p [$= -\Delta k/k / (N\sigma_o v_o)$] is plotted as a function of N in Figure 1 for the HEU fuel at EOC with the value of N ranging from 4E-9 to 15E-9 ^{10}B a/b-cm. For the HEU fuel at EOC, the intercept, as is shown in Figure 1, is 801 µs. The error bars shown on this plot are from the statistical uncertainty in the calculation of ρ using the two calculated parameters, $k_{eff,u}$ and $k_{eff,p}$ The results of the analyses are shown in Tables 1 and 2 (along with other results which will be discussed below) for the HEU and LEU fuels, respectively, at SU and EOC. These values are denoted as "1/v Insertion". The values of the standard deviation, σ, in these tables are calculated from variations of the values of l'_p from the curve fit (y=-1221.1x + 800.91). The uncertainty in the calculated lifetime for the HEU fuel at SU was larger than other conditions because there was a larger fluctuation from the trend line for that case than there was for the other cases.

THE NEUTRON PULSE METHOD

The second method determines the prompt neutron lifetime by using MCNP to calculate the decay of a pulse of neutrons in a subcritical nuclear reactor [6] at some point in the reactor. After the higher harmonics have died away, the fundamental mode exhibits an exponential decay:

$$N = N_o e^{\alpha t}$$

where

N_o = the initial neutron population of the fundamental mode at time zero

t = the decay time

$\alpha = (\rho - \beta) / l_p$

ρ = reactivity of the subcritical assembly ($1 - 1/k_{eff}$) relative to unity

β = delayed neutron fraction

l_p = prompt neutron lifetime (desired quantity)

In this situation, α is always negative and if the reactor was not subcritical, the pulse would not decay. The value of ρ is changed by positioning the shim arms and the decay of the pulse is related to the value of k_{eff} different from unity.

Plots of several decay curves as calculated by MCNP for the LEU fuel at EOC for several shim arm positions are shown in Figure 2. It is the slope of each curve in Figure 2 that provides the values of α (for each value of ρ) in the equation above. In order to determine a representative value of α for each curve, ten subsets of calculated data points were chosen from each curve (usually including 50-90 points) and the value of α was determined for each subset of data. The value of α that is representative of the overall curve was then the average of the 10 different values of α. Each shim arm angle represents a negative insertion of reactivity, which is taken from the shim arm worth curve [5] and the value of β was calculated by MCNP5-1.60 [3] using the ENDFB-VII [4] evaluations.

A value of the prompt neutron lifetime can be calculated for each shim arm position. Since the MCNP calculation does not include any delayed neutrons from the (γ, n) reactions on deuterium, they were not included in the value of β used for this calculation.

The calculations from the decay of pulsed neutrons were performed for a total of 10 different shim arm positions, and hence 10 different value of ρ. From those calculations, 10 neutron lifetime values were determined and averaged to determine the prompt neutron lifetime for the NBSR with LEU fuel at SU and EOC. Those calculated values of prompt neutron lifetime are shown in Figure 3 as a function of reactivity insertion. The average values are included in Tables 1 and 2 under the "Pulse" heading.

The uncertainties presented in these tables were calculated from the combination of (1) the spread in the 10 values of α for each decay curve, (2) the deviation between the calculated values of the shim arm worth curve and the fit of those values (a negligible contribution), and (3) the uncertainty in β, which was assumed to be 5%.

THE ADJOINT FLUX WEIGHTING METHOD

The third method of calculating the prompt neutron lifetime utilizes the definition of l_p obtained by deriving the point kinetics equations from the more detailed transport equation. It employs tallies (integrals over space, angle and energy) weighted by the flux and the adjoint flux. This capability has been incorporated into MCNP5-1.60 [3]. The adjoint flux is calculated several (usually 10) cycles after the calculation of the flux [7,8]. This calculation is invoked with the *kopts* card (new to MCNP5-1.60).

In this method ψ is the neutron flux, $\psi^\dagger$ is the adjoint flux, *F* is the total fission operator and the operator in the numerator is 1/v. The prompt neutron lifetime is calculated with the integrals:

$$l_p = \frac{\langle \psi^\dagger, 1/v\, \psi \rangle}{\langle \psi^\dagger, F\, \psi \rangle}$$

MCNP calculates the initial flux, ψ in one cycle of calculations. It processes several cycles before it determines the adjoint flux, $\psi^{\dagger}$, with the default being 10 cycles. For these analyses the MCNP code was run for 3000 kcode cycles with 125,000 particles per cycle. The results of the analyses for the HEU and LEU fuels at SU and EOC are presented in Tables 1 and 2 under the heading "MCNP". The uncertainties quoted in these tables are the statistical uncertainties as reported by MCNP. Changing the number of neutron generations for the adjoint flux to 15 resulted in no significant change in the value of the neutron lifetime.

DISCUSSION

The values of the prompt neutron lifetime calculations are in reasonable agreement for the three methods. The three methods show that the prompt neutron lifetime for the SU condition is less than the prompt neutron lifetime for the EOC condition. The calculations also show that the prompt neutron lifetime for the LEU fuel is expected to be shorter than the prompt neutron lifetime for the HEU fuel.

The value of the prompt neutron lifetime used for the safety analysis in the current Safety Analysis Report for the HEU fuel is 650 µs; a value considered to be conservative because it was chosen to be smaller than the smallest calculated value. Based on the values in Table 2, 650 µs would still be a conservative number for the LEU fuel at EOC, but one would probably need to use a shorter value, such as 600 µs, at SU in order to guarantee a conservative calculation.

Table 1. Calculations of the Prompt Neutron Lifetime (in µs) for the HEU fuel.

Method	l_p SU	σ±	l_p EOC	σ±
1/v Insertion	712	35	801	14
Pulse	732	34	774	48
MCNP	698	1	802	1

Table 2. Calculations of the Prompt Neutron Lifetime (in µs) for the LEU fuel.

Method	l_p SU	σ±	l_p EOC	σ±
1/v Insertion	610	16	766	12
Pulse	675	35	734	38
MCNP	651	1	730	1

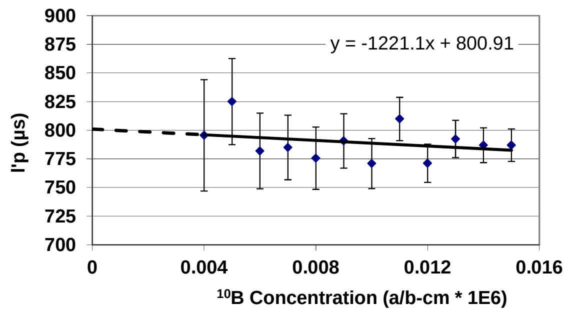

Figure 1. Plot of l'_p as a function of ^{10}B concentration. The solid line and the equation are the results of a linear fit of the data points.

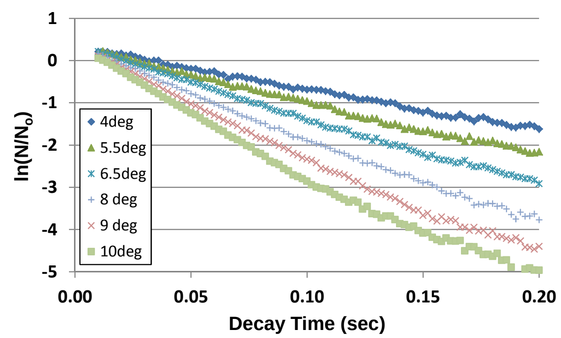

Figure 2. Decay curves for pulses of neutrons into an LEU core at EOC with the shim arms at several positions.

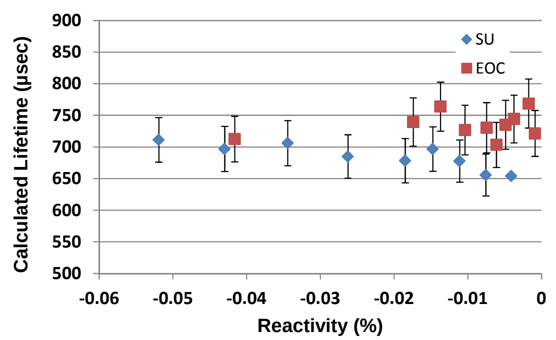

Figure 3. Calculation of neutron lifetime as a function of reactivity insertion by the pulse method

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