MEASUREMENT OF PROMPT NEUTRON LIFETIME IN ZED-2

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Abstract

This paper presents results from a measurement of prompt neutron lifetime in ZED-2. An experimental method that mimics the 1/v method of calculating prompt neutron lifetime was used to determine it by combining critical height data obtained by poisoning the ZED-2 moderator using boric acid along with a measurement of the level coefficient of reactivity at critical for the unpoisoned reactor.

The experimentally determined value is compared to an MCNP calculation of prompt neutron lifetime using the alpha-static method. The agreement is very good, with the discrepancy between calculation and experiment being under 0.3 percent compared to an experimental uncertainty of 1.9 percent.

1. Introduction

Reactor transient analysis requires knowledge of a number of parameters. These include absolute yields of prompt neutrons from fission, absolute yields of delayed neutrons and the associated half-lives of the various precursors, as well as the prompt neutron lifetime of the system being studied.

The dynamic characteristics of reactors are strongly influenced by the presence of delayed neutrons. For transient analyses in heavy water systems, there is an additional requirement to know the absolute yields of photo-neutrons, both prompt and delayed, and the half-lives of the delayed gamma emitters. Photo-neutrons result from fission-product gamma rays energetic enough to dissociate the deuteron (threshold energy of 2.226 MeV). The delayed neutron fraction is enhanced due to the presence of delayed photo-neutrons. The relatively long prompt neutron lifetime results from the longer diffusion time of the thermal neutrons in the low neutron absorbing heavy water moderated lattice. These effects combine to result in the longer effective neutron lifetime for heavy-water moderated reactors relative to other reactor types (e.g., light-water reactors).

This paper describes a series of measurements in the ZED-2 reactor where the prompt neutron lifetime of the reactor is determined using an experimental approach that mimics the 1/v calculational method. Transient measurements are used to determine the Level Coefficient of Reactivity (LCR) for an unpoisoned lattice in ZED-2. The moderator level was varied and the resulting transients were analyzed to derive the reactivity state resulting from the change in moderator level.

A series of measurements were also performed where boric acid was added to the ZED-2 moderator and the moderator critical height was measured for a range of boron concentrations in the moderator to derive the Level Coefficient of Poison concentration (LCP). The slope of the poison concentration versus critical-height curve is determined at the point where the concentration is zero and this slope, the LCP, is used along with the LCR measurement for the unpoisoned lattice to derive the prompt neutron lifetime for the system.

The measured value of prompt neutron lifetime is compared to an MCNP calculation using the alpha-static method.

2. Calculation of Prompt Neutron Lifetime

Transient experiment analyses normally yield the prompt neutron decay constant, α, where

$$\alpha = \beta_{eff} \Lambda_p^{-1}. \quad (1)$$

β_{eff} is the delayed neutron fraction and Λ_p is the prompt neutron lifetime. The value of β_{eff} can then be inferred using a calculated value of Λ_p.

The 1/v insertion method [1] is a simple but accurate method to calculate the prompt neutron lifetime. If the entire reactor (including the reflector) is perturbed by a dilute and uniform distribution of a purely 1/v neutron absorber, the reactivity insertion, ρ, is given by

$$-\rho = N \sigma_{2200} v_o \Lambda'_p, \quad (2)$$

where N is the atomic density of the one-upon-v absorber (in units of atoms barn^{-1} cm^{-1}), σ_{2200} is the microscopic cross section of the absorber evaluated at 0.025 eV, v_o is the speed of a thermal neutron (i.e., a neutron velocity of 2200 meters per second) and Λ'_p is the prompt lifetime of the poisoned system. The prompt neutron lifetime of the unpoisoned system, Λ_p, is then derived from the value of Λ'_p in the limit that N goes to zero.

$$\Lambda_p = -(d\rho/dN)_{N=0}\, \sigma_{2200}^{-1} v_o^{-1}. \quad (3)$$

2.1 The Alpha Static Method using MCNP

There is an option supported by MCNP4C [2] that allows for the calculation of prompt neutron lifetime. The method is referred to as the alpha-static method and it allows MCNP to solve the following eigenvalue/eigenfunction equation,

$$k^{-1} F\, \Theta = (M + \alpha\, v_o^{-1})\, \Theta, \quad (4)$$

for k-effective as a function of α, where F and M are the production and loss operators, respectively, Θ is the neutron flux eigenfunction and α is held constant for each MCNP run (hence the name alpha-static). Negative values of α can result in a time creation (n, 2n) delta scattering reaction and positive α is treated as time absorption. Prompt neutron lifetime is then determined by calculating k-effective using both positive and negative values of α.

The expression for determining prompt neutron lifetime is:

$$\Lambda_p = -(d\rho/d\alpha)_{\alpha=0}. \quad (5)$$

3. Experimental Approach to Determine Prompt Neutron Lifetime

The Level Coefficient of Reactivity (LCR) is defined as follows:

$$LCR = (d\rho/dh)_{h=hc}, \tag{6}$$

where h is the moderator level and h_c is the critical moderator level of the unpoisoned system. Likewise, the Level Coefficient of Poison concentration (LCP) at zero poison concentration is defined as:

$$LCP = (dN/dh_c)_{N=0}. \tag{7}$$

Measurement of the LCR and LCP allows for the determination of prompt neutron lifetime using:

$$\Lambda_p = LCR\ LCP^{-1}\ \sigma_{2200}^{-1}\ v_o^{-1}. \tag{8}$$

4. The ZED-2 Reactor

The ZED-2 reactor is a heavy-water-moderated tank-type critical facility located at the Atomic Energy of Canada Limited's (AECL) Chalk River Laboratories (see Figure 1). The reactor vessel is a 3.36 m diameter by 3.36 m high cylinder sitting on a 0.9 m thick graphite base reflector and surrounded by a 0.6 m thick graphite radial reflector. Fuel assemblies consisting of five approximately 50 cm long bundles loaded into fuel channels are suspended within the reactor vessel from steel beams spanning its top opening. No "coolant" (such as light or heavy water) was included in the assemblies for these measurements.

ZED-2 is operated by introducing heavy-water moderator/reflector into the reactor vessel to achieve criticality. Reactivity is controlled by manually changing the moderator level, where nominal operating power is between 5 and 100W. The moderator level is measured by lowering a probe from a drum and cable drive system until it makes electrical contact with the moderator surface, and is accurate to ± 0.02 cm in relative height (± 0.2 cm absolute). Further details of the ZED-2 reactor and experimental lattice are listed in References [3] and [4], respectively. The 52 assembly lattice used for these experiments is depicted in Figure 2.

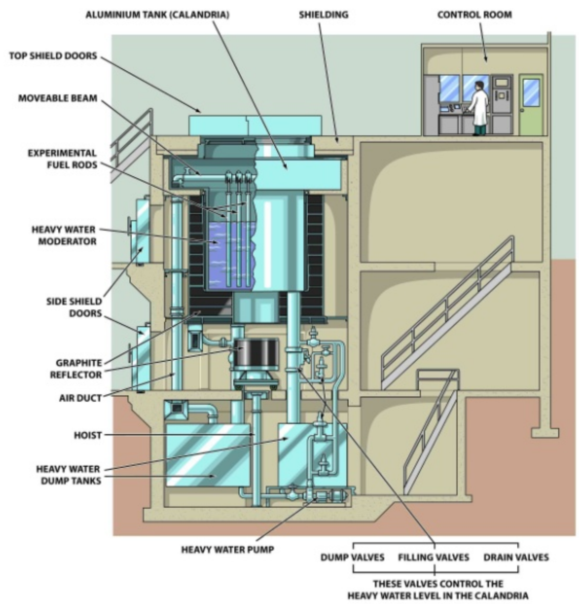

Figure 1 ZED-2 Reactor

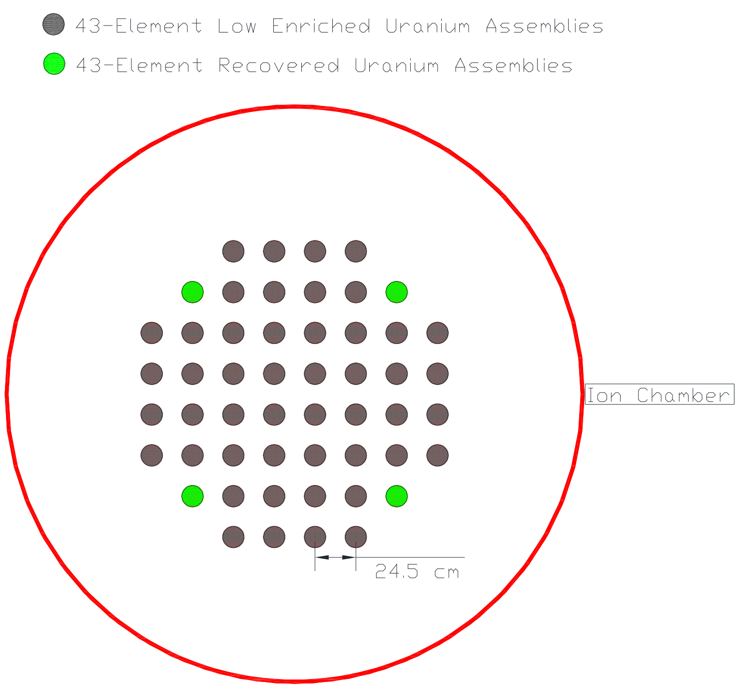

Figure 2 Plan View of the ZED-2 Lattice

5. Level Coefficient of Reactivity Measurement

Experiments were conducted to measure the reactor power transient resulting from draining about 5 cm of heavy water from the reactor vessel, after operating the reactor for about one hour. An inverse point kinetics analysis of the current from an ion chamber (see Figure 2) during the transient was used to determine the negative reactivity associated with the subcritical reactor state. Figure 3 illustrates the induced power transient as well and the reactivity worth of the drained water derived from an inverse point kinetics analysis of the transient.

These data were used to determine the relationship between reactivity (i.e., k-effective) and moderator level. The results are shown in Figure 4, where the measured critical level and supercritical level (associated with the approach to power) are also included. Note that the critical-level datum corresponds to k-effective equal to one (i.e., no transient) and the supercritical-level datum corresponds to a k-effective value derived from the positive transient e-folding time during the approach to power using the in-hour equation [5].

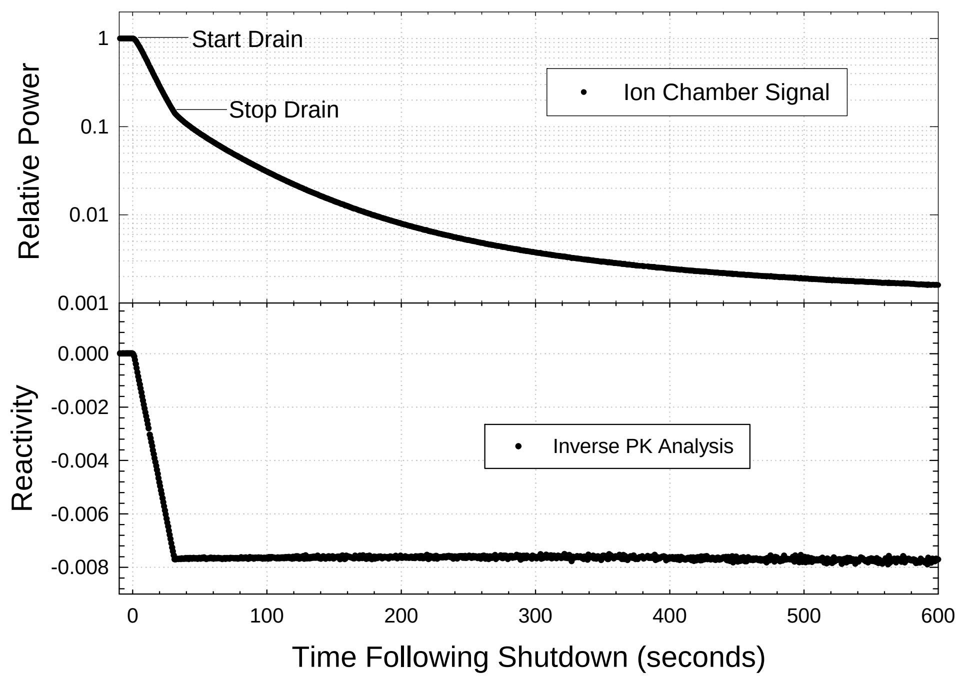

Figure 3 Inverse Point Kinetics Analysis

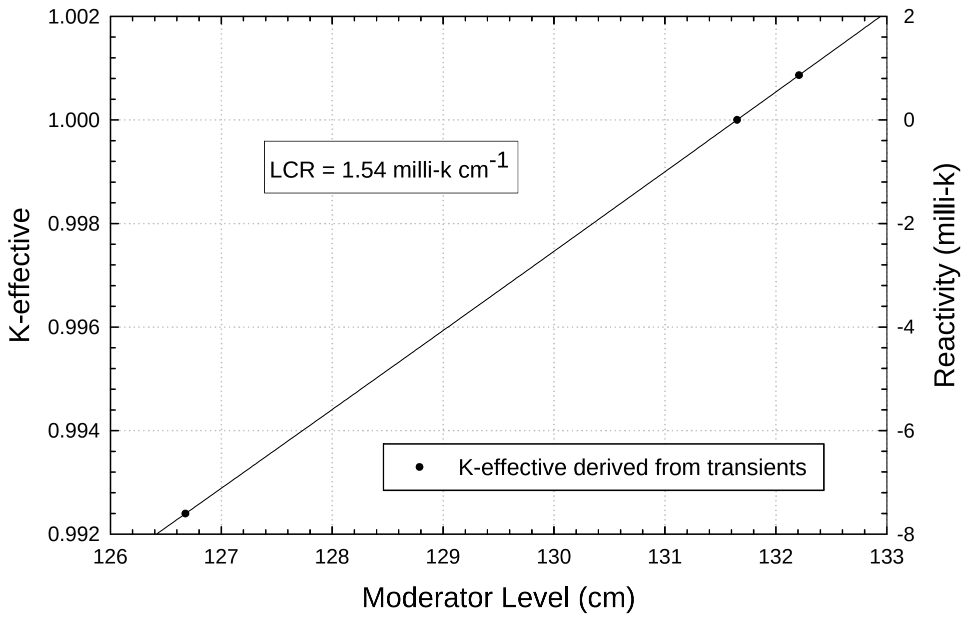

Figure 4 Level Coefficient of Reactivity

6. Moderator Poison Measurements

A reference critical-height measurement was performed without poison in the moderator. Boric acid ($B(OH)_3$) was chosen to poison the moderator because B-10 is known to be a very good 1/v absorber. A master-mix solution of heavy-water and boric acid was prepared for addition to the ZED-2 moderator. A sample of the master-mix solution was analyzed by mass spectroscopy at CRL to determine the boron isotopics.

The boron concentration in the moderator was raised from 0.0 ppm to 6.05 ppm in three equal intervals. Each addition of boron solution was mixed uniformly in the moderator by "pump and dump".

Moderator critical height and core conditions were recorded. A sample of the poisoned moderator was also analyzed by mass spectroscopy to confirm the boron concentration in the moderator. Boron-10 concentration versus moderator critical height is plotted in Figure 5. This curve is labeled as "Concentration in Heavy Water" in the figure.

The 1/v absorber method of determining prompt neutron lifetime assumes that the poison is distributed uniformly in the reactor. However, for these measurements it was only possible to add poison to the heavy-water moderator and heavy-water reflector. A simple correction was applied to the data to correct the boron concentration in the moderator by determining the ratio of the lattice cell volume to the volume of moderator in the lattice cell. This curve is also plotted in Figure 5 and is labeled as "Cell Average Concentration" in the figure.

Additional corrections were determined to account for the graphite reflector not being poisoned and for the heavy-water reflector poison concentration no longer corresponding to the cell-average-concentration curve. MCNP calculations were used to derive the reactivity effect of adding poison to the graphite and to account for the concentration in the D_2O reflector not being consistent with the cell-average concentration in the moderator. The reactivity values, along with measured LCR values were used to correct the measured moderator levels to account for the lack of poison in the graphite and reduced concentration in the D_2O reflector. Figure 5 includes a plot labeled as "Graphite and D_2O Reflector Correction". This corrected curve was used to derive the LCP for determining Λ_p.

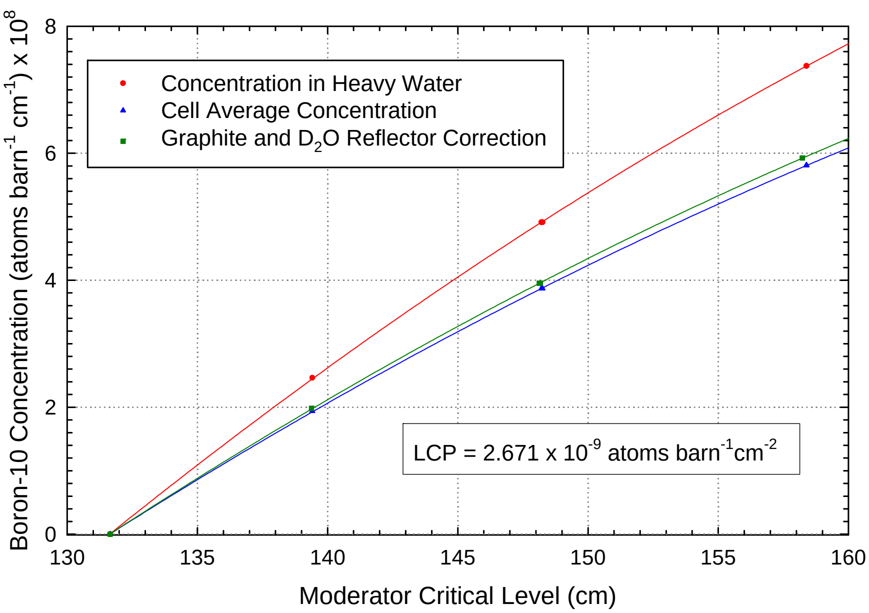

Figure 5 Level Coefficient of Poison Concentration

7. Derived Prompt Neutron Lifetime and Comparison to Calculation

As stated in Section 3 the measurement of the LCR and LCP allows for the determination of prompt neutron lifetime using equation (8):

$$\Lambda_p = \text{LCR LCP}^{-1}\, \sigma_{2200}^{-1}\, v_o^{-1}. \tag{8}$$

The values of LCR and LCP are taken from Figure 4 and Figure 5, respectively. Using the above equation the value of prompt neutron lifetime for the lattice derived from this study is 0.684 ± 0.013 milliseconds. This value can be compared to the MCNP calculated value of 0.682 milliseconds. The analysis is summarized in Table 1.

Analysis Parameters	Value	Uncertainty	Percentage Error
Boron content (ppm)	6.05	0.07	1.16%
B-10 abundance (percent)	19.82	0.08	0.40%
B-10 cross section (barns)	3837	9	0.23%
LCR (cm^{-1})	1.54×10^{-3}	2.0×10^{-5}	1.30%
LCP (atoms $barn^{-1}$ cm^{-2})	2.671×10^{-9}	1.2×10^{-11}	0.45%
Neutron Velocity (cm $second^{-1}$)	2.20×10^{5}		
Total			1.86%
Λ_p measured (milliseconds)	0.684	0.013	
Λ_p MCNP (milliseconds)	0.682		

Table 1 Analysis Summary

8. Conclusion

This paper has shown that using appropriately corrected measurements it is possible to determine the prompt neutron lifetime experimentally. This was done for the ZED-2 critical facility. The value obtained matched the result from MCNP to within uncertainty.

We believe that this is first time this technique has been used to measure Λ_p in a heavy-water reactor. ZED-2 is a very flexible facility and has been used in the past to provide data to support the IST physics toolset for CANDU [6]. An interesting follow-up study would be to repeat the prompt neutron lifetime measurement in a lattice designed to be more representative of CANDU.

9. References

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