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Subcritical Reactivity Measurements in ZED-2

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ABSTRACT – The Zero Energy Deuterium (ZED-2) reactor was operated to provide validation data for subcritical reactor states. Moderator drain experiments were conducted to collect power transient data for analysis by inverse-point kinetics, determining the negative reactivity of the partially drained reactor core. Separate experiments employed a fission chamber to determine a count rate corresponding to these subcritical states. This chamber was calibrated to determine neutron flux at the chamber location. Analysis of these measurements is currently underway and preliminary results are presented here.

1. Introduction

Calculation of subcritical reactivity has suffered from a lack of experimental data with which to validate results. Consequently, the reactivity requirements for the Guaranteed Shutdown State (GSS) of a reactor are often exceedingly conservative. This can translate into an increase in costly down time for power reactors, and increased expenses due to maintaining the lower reactivity states. Additionally, the lower neutron signal results in greater sensitivity requirements of instruments monitoring the reactor core, and problems with tripping due to the lower signal-to-noise ratios from the instruments. Experiments were conducted in the Zero Energy Deuterium (ZED-2) reactor to provide validation data for subcritical reactor states. Specifically, these measurements were to investigate if core reactivity can be determined from measured neutron count rates.

2. 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 ~50 cm long bundles loaded into fuel channels are suspended within the reactor vessel from steel beams running East-West above its top opening. When not operating, the reactor safety instrumentation is kept on scale by a ^{239}Pu-Be startup source. ZED-2 is operated by filling the reactor vessel with heavy-water moderator/reflector to achieve criticality. Reactivity is controlled by manually changing the moderator level, where nominal operating power is ~5-100W. 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 fuel assemblies are listed in References [1] and [2]. The 52 assembly lattice used for these experiments is depicted in Figure 2.

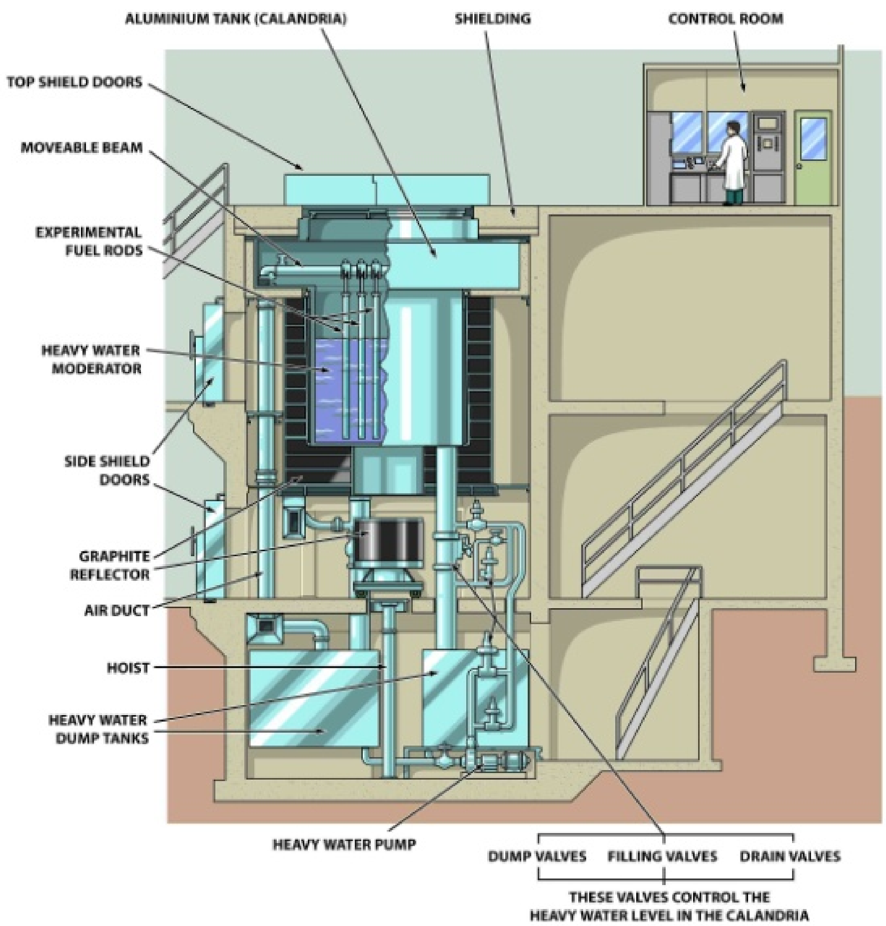

Figure 1 – Illustration of the ZED-2 Facility.

3. Fission Chamber Calibration

Counts were collected by a LND 30773 fission counter [3] suspended within an 11.4 cm outer diameter aluminum tube positioned in the D_2O reflector (see Figure 2). Saturation of the fission chamber occurs with the reactor still subcritical, and therefore the detector efficiency was determined from intercalibration against a Reuter-Stokes RS-C2-2511-137 ion chamber. This chamber is located in the radial graphite reflector where it has a dynamic range spanning several decades of useful count rates from the fission chamber, and all higher power operations (~100 W) conducted in ZED-2. The ion chamber is γ-shielded by the radial D_2O reflector during reactor operation, and past experience has shown that the response is linear with neutron flux over the normal range of ZED-2 reactor operation. The ion chamber is in turn calibrated to neutron flux at the location of the fission chamber by metal foil activation analysis.

The reactor was operated at approximately 100 W (nominal) for one hour with copper foils attached to the aluminum tube near the location of the fission counter, and copper wires attached to the fission chamber itself. Additional copper foils and wires were attached to a rotating reference wheel located in the heavy-water reflector (symmetricly positioned with respect to the fission chamber). A cobalt wire on the wheel was used to determine the absolute neutron flux at the reference wheel location, and related to the fission chamber location from the copper activation ratio between the two locations. The neutron flux spectrum at the reference wheel location was confirmed to be very well thermalized using a cadmium-ratio measurement employing gold-aluminum activation foils.

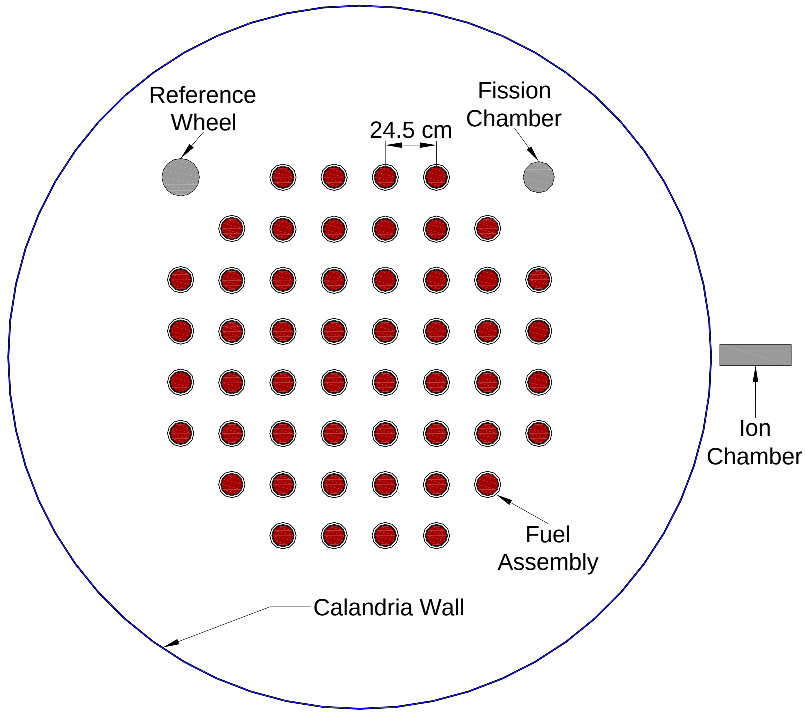

Figure 2 – Plan View of Core Lattice, Depicting location of Reference Wheel, Fission Chamber, and Ion Chamber.

4. Count Rate Measurements

The fission chamber count rates were measured for multiple subcritical moderator heights on several different days of operation. The results of these measurements were used to determine the correspondence between moderator height and absolute neutron flux. Note that the ZED-2 core temperature is measured but not controlled, and will vary somewhat between these experiments. However, the results of these experiments (shown in Figure 3) indicate a very low sensitivity to the variation of conditions between these reactor operations (including a minute decrease in moderator isotopic purity).

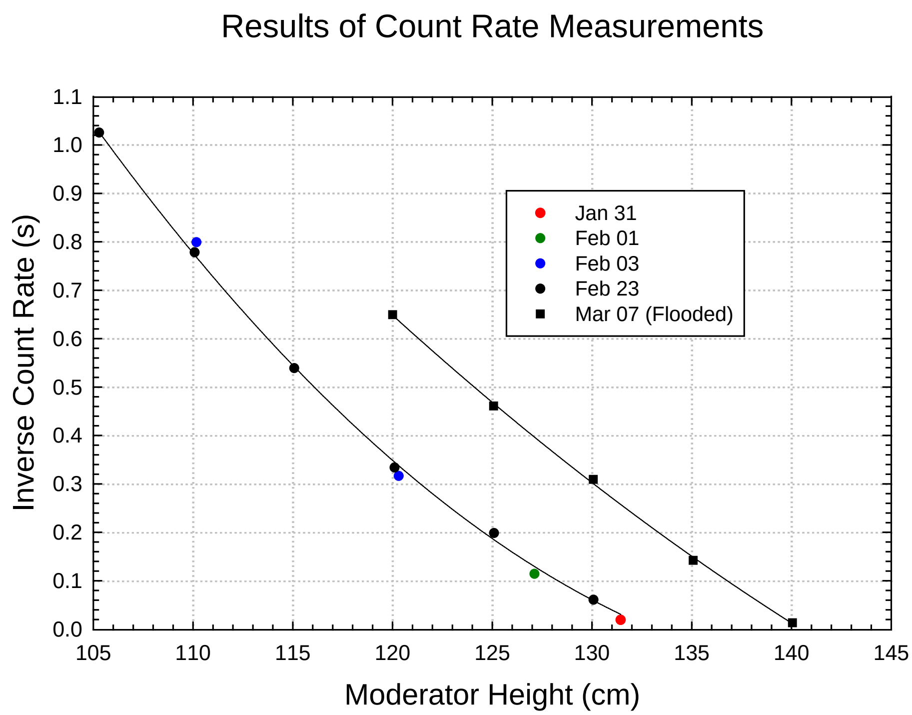

Figure 3 – Subcritical Count Rates Detected as a Function of Moderator Height.

5. Reactivity Measurements

Several experiments were conducted to measure the reactor power transient after draining between 5 and 25 cm of heavy-water from the reactor vessel, after operating the reactor for ~one hour. An inverse point kinetics analysis of the current from the Reuter-Stokes ion chamber during these transients was used to determine the negative reactivity associated with the subcritical reactor state. These measurements were used to determine the relationship between reactivity (i.e. k-effective) and moderator height. The results are shown in Figure 4, where measured critical heights and supercritical heights (associated with the approach to power) are also included. Note that the critical height data correspond to k-effective equal to one (i.e. no transient) and the supercritical height data correspond to k-effective values derived from the positive transient e-folding times during the approach to power using the in-hour equation [5].

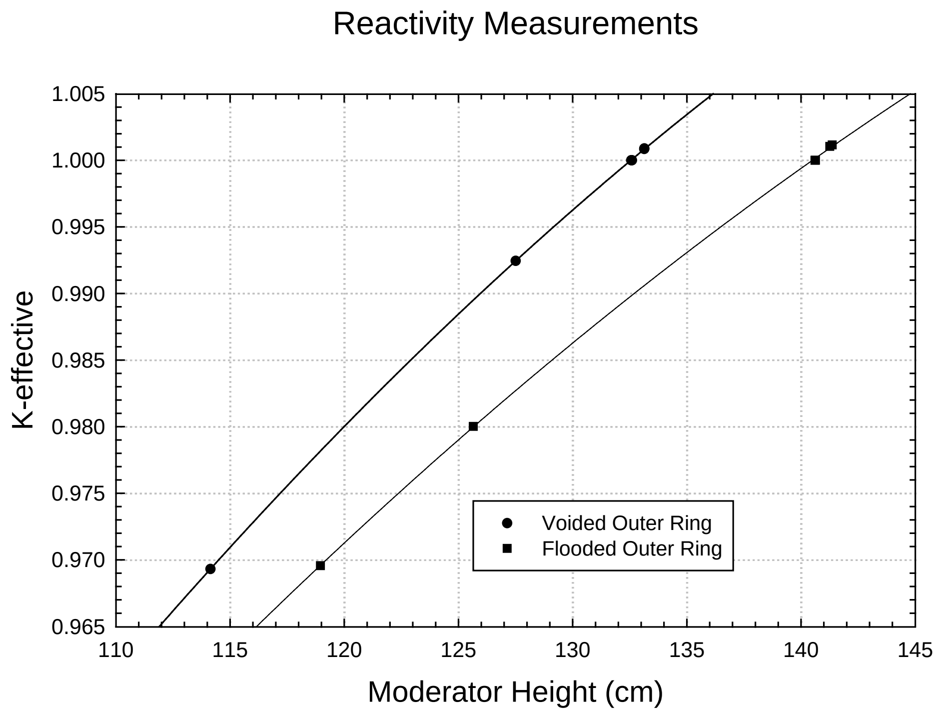

Figure 4 – K-effective Values Derived as a Function of Moderator Height.

6. Core Alteration and Repeat Measurements

The measurements were repeated with the outer ring of fuel assemblies in the core lattice flooded (i.e. "cooled" with light-water). These results are also shown in Figure 3 and Figure 4. The assemblies were flooded one at a time in three stages, with level coefficient of reactivity measurements conducted at each stage. Flooding these assemblies caused the critical moderator height of the core to increase from H_c (voided) = ~132.6 cm to H_c (flooded) = ~140.6 cm. The change in critical height was used with the reactivity vs. moderator height curves to determine the negative reactivity of the core with the moderator height set to H_c (voided), i.e. the initial critical height, but with the outer ring of assemblies flooded. The neutron flux versus height curve was then interpolated to determine the associated neutron flux at the detector location, thereby providing a second determination of subcriticality for this reactor state (compared to the moderator drain transient analysis).

6. Code Calculation Methodology

The results of the experiments will be compared to MCNP predictions for neutron flux and k-effective values. A fixed source calculation of the reactor will be conducted using the Monte-Carlo N-Particle Code (MCNP) [5] and the predicted count rates compared to the measured subcritical flux measurements. This calculation does not produce a k-effective value in the output, and therefore the reactivity associated with the calculated count rate will be calculated from an MCNP criticality (KCODE) calculation using the following method.

The KCODE calculation tracks neutrons through a series of fission cycles, where the source for each cycle is determined by the fission sites produced by neutrons of the previous cycle. k-effective values are stored for each individual cycle of the criticality calculation (k_1 for cycle 1,

k_2 for cycle 2, etc.). For each S neutrons generated by the startup source, multiplication of this source produces $S \cdot k_1$ neutrons in the first generation, $S \cdot k_1 \cdot k_2$ neutrons in the second generation, which in turn directly induce $S \cdot k_1 \cdot k_2 \cdot k_3$ additional neutrons, and so on. For subcritical states, this series converges and the multiplication factor is then calculated as

$$M = 1 + k_1 + k_1 k_2 + k_1 k_2 k_3 + k_1 k_2 k_3 k_4 + \cdots = 1 + \sum_{i=1}^{\infty} \prod_{j=1}^{i} k_j \qquad (1)$$

Where k-effective = $1 - 1/M$. After a sufficient number of cycles are calculated, the fission distribution will have converged and $k_i = k_{i+1} = k_N$. Eq. 1 can then be rewritten as

$$M = 1 + \sum_{i=1}^{N-2} \prod_{j=1}^{i} k_j + \prod_{j=1}^{N-1} k_j \cdot \left(\frac{1}{1-k_N}\right) \qquad (2)$$

Additional MCNP calculations using the ZED-2 model, employing an initial calculated flux distribution, will also be performed to derive k-effective values for the various critical, subcritical and supercritical core configurations that have been studied. These calculated k-effective values will be compared directly to the experimental results, and to the k-effective values derived using the fixed-source method.

7. Known Issues

It's noted that the methods for determining reactivity from the power transients and critical moderator height change yield the reactivity associated with the converged eigenmode fission distribution, as opposed to the source driven fission distribution present during the count rate measurements. The magnitude of the bias produced in the reactivity measurements can be determined by comparing the results of Eq. 2 to the k-effective value outputted directly from an MCNP KCODE simulation. Alternatively, provided the power transient from a moderator drain can be followed to sufficiently low powers, any deflection of the reactivity calculated from the inverse-kinetics analysis to a new value (associated with the source driven state) might be used to determine the magnitude of the bias.

8. Conclusions

Experiments have been conducted in the ZED-2 reactor to validate predictions of subcritical reactivity based on count rate measurements in the core. A full analysis of these experiments is ongoing, but preliminary results suggest that there is good reproducibility for the count rate measurements made while the reactor is subcritical.

9. References

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