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PROGRESS ON REACTOR KINETICS MEASUREMENTS IN ZED-2

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ABSTRACT – The zero-power, D_2O-moderated reactor ZED-2 is currently being used to perform reactor kinetics experiments on mixed oxide (MOX) fuels. These experiments can be used to provide data on the kinetics parameters of cores containing nuclides such as ^{235}U, ^{233}U, and ^{239}Pu. This extended abstract will present the ongoing transient measurements in ZED-2 being used to calculate the "in-core" delayed neutron parameters: the effective delayed neutron fractions $\beta_{eff,i}$ by precursor group. This is strongly tied to validation of computationally-determined delayed neutron parameters.

Introduction

The timescales and yield of delayed neutrons are essential to predict the kinetic behaviour of a given fuel and reactor core configuration. Consequently, they are required for transient analyses to establish a safety case for a particular system. Delayed neutron parameters are reasonably well understood for conventional homogenous cores such as the natural uranium fueled pressurized heavy water reactor (PHWR), which is essentially a U-Pu reactor at equilibrium. However, there is a lack of data for advanced mixed-oxide (MOX) fuel containing nuclides such as ^{239}Pu and ^{232}Th or ^{233}U and ^{232}Th.

Two distinct types of delayed neutrons are of particular interest when discussing a D_2O-moderated PHWR reactor: direct delayed neutrons and delayed photoneutrons. The former directly result from the decay of fission products, comprising ~0.7% of ^{235}U neutron yield per fission and ~0.2% of ^{239}Pu neutron yield per fission, for example. The latter result from the $^{2}H(\gamma,n)^{1}H$ interaction of high energy (>2.25 MeV) delayed gamma-rays (from the decay of fission products) with the heavy water coolant and moderator. Historically, the direct delayed neutron parameters have been largely obtained by "in-core" irradiation followed by "out-of-core" measurements, where a quantity of the nuclide considered is irradiated inside a reactor core and rapidly removed from the core in order to measure the neutron activity decay of the sample. The measured delayed neutron yields are reported group-wise by measured precursor half-lives, typically in 6- or 8-groups [1]. The delayed photoneutrons are reported in the same way in either 9- or 11-group form [2].

Out-of-core measurements do not capture the relative importance of a delayed neutron due to two significant shortcomings. First, the energy spectrum of a delayed neutron is softer than that of a prompt neutron, and it requires fewer moderator interactions to thermalize and generate additional fission neutrons. Second, the importance of a neutron at a particular point within a reactor to further fissions is not accounted for in any out-of-core data. This could be accounted for in calculation by weighting the flux distribution with the adjoint flux φ^*, often called the importance function. Alternately, a transient measurement can determine the experimental delayed neutron parameters.

Zero Energy Deuterium 2 (ZED-2), a pool-type heavy water reactor, provides a room temperature, zero power environment which we can leverage to provide in-core measurements of both direct delayed neutrons and delayed photoneutrons for cores comprised of various fuels. In this paper, we discuss progress on experimental and computational methods used in tandem to calculate these delayed neutron parameters for MOX cores.

1. Methods

Due to the limited number of test fuel bundles available, a critical homogenous core of test fuel cannot be assembled in ZED-2 for these experiments. Rather, the test fuel in question is substituted into a reference lattice. In order to achieve criticality, the remaining fuel assemblies of the reference lattice act as driver fuel assemblies at the periphery of the test fuel. The substitution method is routinely used in ZED-2 experiments and documented in numerous past studies (e.g. [3]). The measurements discussed here used a MOX test fuel containing fissile U and Pu. After operating the reactor at critical for various periods to saturate direct delayed neutron precursors (though not all photoneutrons are saturated; this would require >1000 hours at power), various types of negative reactivity insertions were used to create a reactor transient. These include traditional methods such as absorber rod drops and moderator drains [4], as well as a novel method of on-power channel flooding. Throughout the reactor operation, the neutron flux is monitored by 6 ion chambers at various locations in the core.

Primarily, these flux measurements can be used as input, along with calculated delayed neutron parameters, to the point kinetics equations. Using a known reactivity insertion (either calculated in MCNP6.1 or known from previous measurements), we can verify that the point kinetics analysis yields the same change in reactivity. Alternately, with known delayed neutron parameters and a measured reactor period, the reactivity worth of an unknown insertion can be determined. However, the ability to obtain the delayed neutron parameters for a given core from a transient experiment would be extremely useful. A method for this type of measurement was demonstrated by Spriggs using a light-water uranium-fuelled reactor [5]. The method involved measuring multiple small step reactivity insertion transients and completing a least squares minimization fit of multiple decay curves to the same set of delayed neutron parameters. Nominally, a method such as this could be applied to determine delayed neutron parameters.

Monte Carlo reactor physics codes also play an important role in this work. Both MCNP6.1 [6] and SERPENT 2 [7] have added adjoint-weighted calculations of kinetics parameters, including delayed neutron parameters, based on the iterated fission probability method. The current deficiency in these codes is that delayed gammas are not accounted for in criticality calculations, and thus the effective delayed photoneutron contribution cannot be directly output. We have used alternate methods to combine the results of multiple criticality (eigenvalue) calculations in order to determine the total effective delayed neutron fraction. In this case, we use a variation of the method put forward by Bretscher [8], the “prompt” method.

2. Results

Two preliminary results are presented: using the “prompt” method delayed neutron parameters in point kinetics calculations of the measured transients, and attempting to utilize the Spriggs method to determine those parameters from the measured transients. First, it is found that the “prompt” method

utilizing multiple eigenvalue and transport calculations does not produce delayed neutron parameters which completely describe the measured flux. Figure 1 demonstrates three different transients: a rod drop, a moderator drain, and an on-power flooding transient. The flux at two detectors, normalized to 1 at power, begins to differentiate as the power levels drop, with the radial ion chamber reading consistently lower in all three measurements. This differentiation is apparent in the calculated reactivity for each detector, using the same delayed neutron parameters, though least significant in the on-power channel flooding experiment. Some of this mismatch may be due to 3-D effects; the reactivity according to the flux measured by various detectors in the core was not equal in magnitude throughout the core, suggesting both the global flux shape and magnitude evolved in time.

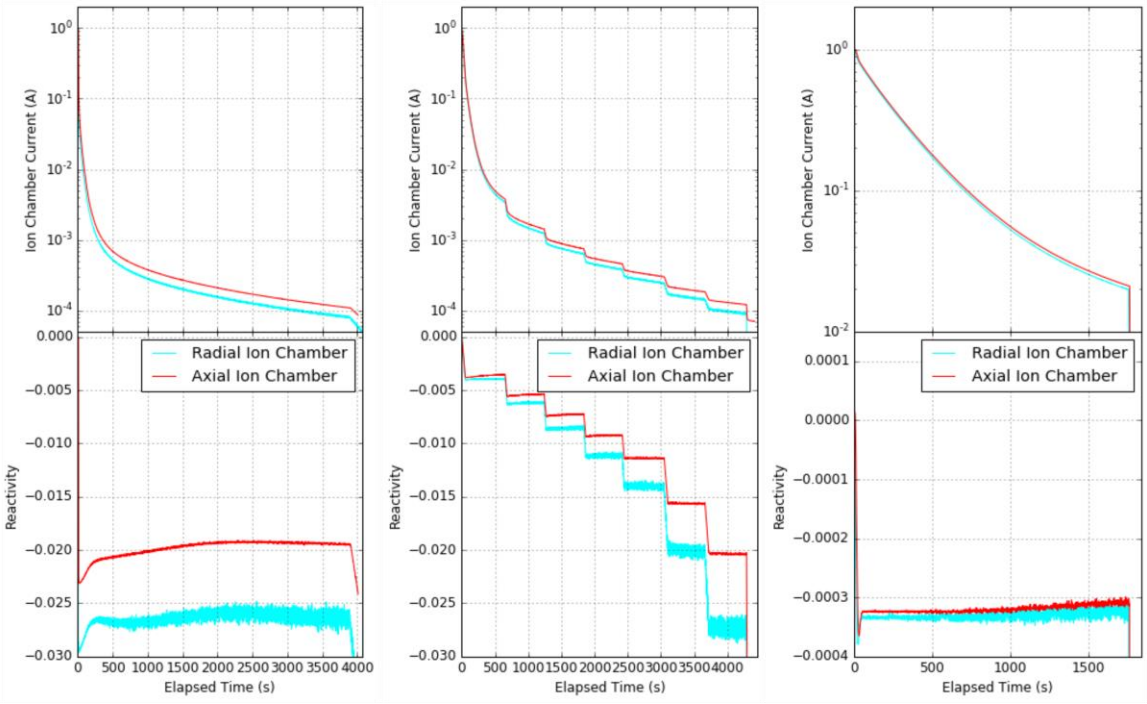


Figure 1 The measured neutron flux and calculated reactivity for rod drop (left), moderator drain (centre), and on-power channel flooding (right) transients.

Second, the results of using the Spriggs method to extract delayed neutron parameters are discussed. The method has not yielded suitable results with the transients presented here. The implementation is complicated by the difficulty of introducing a true step change on the time scale of the delayed neutron precursors in ZED-2. Nominally, any ramp in reactivity (which is the reality of any reactivity change) must occur on a timescale less than the half-life of the shortest-lived precursor (20 ms). One additional challenge is the number of free parameters introduced by the Spriggs method; in a heavy water reactor, 19 free parameters are required, in comparison to the 3 to 7 parameters used by Spriggs. Future measurements need to use shorter ramp times and smaller reactivity changes, such as in the on-power flooding experiment.

3. Conclusions

Methods of generating sub-critical transients in ZED-2 are presented, which support measurements of the kinetics parameters of heterogeneous cores in D_2O-moderated reactors. The limits of the point kinetics model are being explored with heterogeneous cores and intentionally biased transients in two extremes: implementing more subtle transients to determine the delayed neutron parameters using point kinetics, and implementing more disruptive transients to use ZED-2 as a test space for 3-D kinetics. Future measurements will be refined in order to extract delayed neutron parameters for a given core using fitting routines such as in [5]. Refinement of these methods will provide further knowledge of the delayed neutron parameters of various fissionable nuclides, including those present in thoria-based fuel cycles. Additional value is also provided by potential benchmarking opportunities for Monte Carlo codes reporting kinetics parameters for heavy water moderated reactors.

4. References

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