Project No. 10-889

Study of the Open Loop and Closed Loop Oscillator Techniques

Fuel Cycle/Reactor Concepts
Mission Relevant Investigator Initiative Research

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NEUP Nuclear Energy University Programs
U.S. Department of Energy

Study of the Open Loop and Closed Loop Oscillator Techniques Final Report to Nuclear Energy University Programs

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April 11, 2015

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Abstract

This report presents the progress and completion of a five year study undertaken at Idaho State University of the measurement of very small worth reactivity samples comparing open and closed loop oscillator techniques. The study conclusively demonstrated the equivalency of the two techniques with regard to uncertainties in reactivity values, i.e., limited by reactor noise. As those results are thoroughly documented in recent publications, in this report we will concentrate on the support work that was necessary. For example, we describe in some detail the construction and calibration of a pilot rod for the closed loop system. We discuss the campaign to measure the required reactor parameters necessary for inverse-kinetics. Finally, we briefly discuss the transfer of the open loop technique to other reactor systems.

Statement of the Objectives

This project has several objectives:

1. Determine the theoretical uncertainty achievable in a reactivity measurement using both open- and closed-loop techniques.
2. Compare the actual uncertainties achievable in open- and closed-loop systems relative to each other.
3. Demonstrate the uncertainty in a reactivity measurement using both open- and closed-loop oscillator methods in an absolute sense.
4. Demonstrate the ability to measure reactivity worths of small samples of interest.
5. Assess the feasibility of reactivity measurement systems in both a NSUF reactor and MASURCA.

We fully satisfied these project objectives, and to our knowledge, this work represents the first time that the equivalency of the uncertainties using the two methods were demonstrated on the same reactor systems. In the following pages we will describe the work that led up to our ability to actually measure reactivities in the fractions of a cent range.

This project resulted in five M.S. Theses, one Ph.D. Dissertation, and four external publications. They are listed below (as well as being embedded in the bibliography of this report.

- Benjamin A. Baker, "Reactor Parameters for the ISU-AGN-201 Reactor", M.S. Thesis, Idaho State University, May, 2011.
- Tony R. Riley, "Calibration of Reactivity Oscillator for ISU-AGN-201 Reactor", M.S. Thesis, Idaho State University, May, 2013.
- Adam M. Langbehn, "Determination of the Prompt Neutron Generation Time for the ISU-AGN-201 Reactor Using Perturbation Theory", M.S. Thesis, Idaho State University, December 2013.
- Harishchandra Aryal, "Small Reactivity Measurement in Advanced Test Reactor Critical (ATR-C) and Neutron Radiography Reactor (NRAD) and an Oscillator Design", M.S. Thesis, Idaho State University, May 2014.
- M. Lamine Benzerga, "Demonstration that an Open Loop System Could be Implemented in a Fast Reactor", M.S. Thesis, Idaho State University, December 2014.
- Benjamin A. Baker, "Comparison of open loop and closed loop reactivity measurement techniques on the ISU AGN-201 reactor", Ph. D. Dissertation, Idaho State University, 2013.

- B. Baker, G. Imel. "Open Loop Oscillator Technique", Trans. American Nuclear Society Meeting, Hollywood, Florida, June 2011.
- B. Baker, G. Imel. "Propagation of Uncertainty in the Inverse-Kinetics Equation,", Trans. American Nuclear Society Meeting, Atlanta, Georgia, June 2013.
- B. Baker, G. Imel. "Minimization of Uncertainties in the Inverse-Kinetics Measurements Using the Oscillator Technique", Trans. on Nuclear Science (TNS) IEEE, ANIMMA Conf. Marseille, France, June 2013.
- B. Baker, G. Imel, "Equivalency of Open Loop and Closed Loop Reactivity Measurement Techniques", The Role of Reactor Physics toward a Sustainable Future, PHYSOR International Conf., Kyoto, Japan, October 2014.

All of these publications, including the theses and dissertation, have been submitted to the NEUP program office through the regular quarterly reports.

Introduction

In the years 2008-2014, we undertook a careful study of the theory and operation of absorbing samples of very low reactivity worth oscillated in our AGN-201 reactor. In this study both the open loop and closed loop techniques were directly compared, with the objective being to prove that the open loop technique (no feedback control) can achieve the same low degree of uncertainty as the technically more complicated closed loop system (requiring reactor control of power via a low worth control rod as well as a feedback control system). That is, the lower limit of uncertainty in either method is limited by reactor noise [1]. The progress of this project has been reported in a number of publications [2–5], and a very detailed description of the final results is found in Reference [6]. However, the entire project has not been documented with regard to the various supporting work that had to be done in order to realize our main objectives—the direct comparison of the open and closed loop techniques. In the following sections, we will describe the support phases of the project through the five years.

In the design phase, during the years 2008 and 2009, undergraduates at Idaho State University (ISU) completed two senior design projects: the first to design and build a simple open loop oscillator, and the second to design and build a simple closed loop oscillator (capable of maintaining reactor power constant through a small worth "pilot" rod using feedback control [7], [8].

During the pilot rod calibration phase, through the years 2010 to 2013, our team refined the two oscillators regarding actuator control and data acquisition, and designed, fabricated, and calibrated a low-worth pilot control rod. Additionally through this period, the important reactor delayed neutron parameters(λ_i, β_i) as well as generation time (Λ) were quantified and uncertainties carefully studied. This phase was crucial to the success of the open loop system which relies on inverse kinetics to unfold the reactivity of a small worth

sample. The results of the reactor parameter measurement phase have been extensively described in References [2], [3], and [4].

The low-worth oscillator experiments themselves were performed in the next phase and the prime objective was met: a clear demonstration of the equivalency of the open and closed loop techniques as well as showing that both were only limited by reactor noise regarding achievable uncertainties. The results were most recently published in Reference [5].

Finally, two simple designs were produced to implement the open loop system in a thermal reactor (a TRIGA) and a generic fast reactor. We will present some of the highlights of this study in this paper as they have not been previously presented except in theses.

Background

Future fast reactor designs are in need of confirming the correctness of the differential physics data by comparing it with integral physics data for minor actinides (transmutation studies) and fission products (burn-up credit). In France, the MINERVE [9] facility has been used for low-worth reactivity measurements in different spectra using a closed-loop oscillator technique. In the 1980's, the MINERVE chimney was loaded with fast reactor fuel from the MASURCA [10] reactor, and oscillation experiments were performed (but not on minor actinides of current interest). In our project, we sought to demonstrate that low worth reactivities could be measured in a much simpler (mechanically) open loop system, possibly even in an actual fast reactor such as MASURCA.

This was the first time, as far as we know, that the open and closed loop techniques have been compared on the same reactor system, making the results directly comparable. To show that the open and closed loop techniques are equivalent in their ability to measure small worth samples, an initial set of measurements was taken to show that the results of the measured reactivities were limited only by reactor noise and were independent of reactor power and frequency. Further experiments were performed to show that the open loop techniques could be performed at higher frequencies than the closed loop technique. Lastly, several measurement sets were taken for a very small worth sample for comparison of results between methods.

Schematics of the open and closed loop systems are shown in Figure 1. As is seen, in the open loop the reactivity is perturbed and the reactor power is allowed to follow the perturbation. An analysis of the resulting time dependent power allows the reactivity to be inferred via inverse kinetics.

In this case, the reactor power is controlled by a feedback loop operating a pilot rod; if the pilot rod is properly calibrated, one can immediately obtain the perturbing reactivity from the required control reactivity.

ISU's AGN-201 nuclear reactor located at the Nuclear Engineering Laboratory in Lillibridge Engineering Building was used for all experiments. The AGN-201 is a low power research reactor. The reactor is licensed to operate up to 6 watts, but for most experiments lower power levels were chosen so neu-

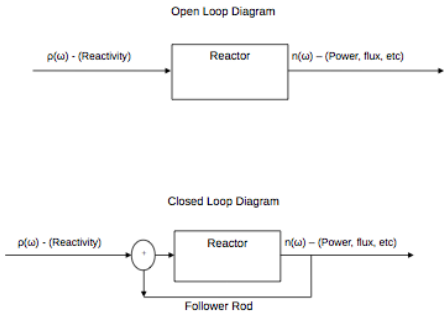

Figure 1: Open Loop and Closed Loop Schematic

tron detectors would be operating in ideal ranges. The AGN-201 consists of a polyethylene core with uranium dioxide (UO2) grains homogeneously mixed throughout the polyethylene. The core is then surrounded by a graphite reflector, a lead shield, a water shield and the outer steel tank. The reactor has five experimental ports to allow for insertion of materials near the core: four experimental beam ports running north to south through the graphite reflector just outside the core region and one port running east to west through the center of the core (known as the glory hole).

Oscillator Design

The original oscillator system that was designed as a senior design project was intended to be a tool to be used in our laboratory to determine the worth of unknown samples. An oscillator system provides a simple way to acquire smaller uncertainties, smaller sample worths, and shorter experimental times compared to individual asymptotic period measurements. The following were studied: program development of the inverse kinetics equation, mounting system, push bar, oscillator, data acquisition systems, and cost. Decisions were made for each component of the control system. The key design parameters of the oscillator are briefly discussed below.

The frequency capability of the oscillator is an important parameter, and we would like to be able to operate in the plateau of the transfer function where the gain is nearly constant. It should be noted, however, that operation on the plateau is not necessary for accurate measurements. In many circumstances it may be more feasible to operate at frequencies just before the plateau. It is also important to know the range in which the samples have an effect on the reactor (effectively the span of the active core). These two parameters set the required velocity and distance ranges for the oscillator.

Using nominal AGN-201 reactor parameters, we find the frequency of interest

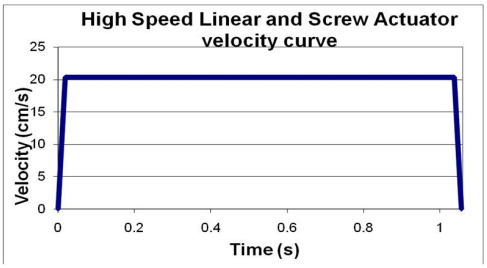

Figure 2: Velocity Profile

in which the gain is nearly constant should be around 0.5-2 Hz. The distance over which the sample must travel was experimentally determined by slowly inserting a cadmium sample through the reactor. It was found that the effective span of travel required was about 10 cm from the center of the core. Five different oscillator devices were considered for this project: slider and crank, cam drive, chain drive, high speed linear actuator, and screw actuator.

After consideration of cost, simplicity, reproducibility, and frequency capability, both the high speed linear and screw actuator systems were found to be the superior of the five. Both are very similar in design.

The high speed linear actuator has guide rails and is driven by a motor that is mounted on the carriage that runs on the track. The motor turns a gear that then runs on a rack to drive the carriage. The screw actuator has a motor that is permanently mounted to the base of the frame, which turns a threaded rod that moves the acme threaded nut, driving the push rod in and out. Both systems have encoders that read the position, velocity, and acceleration of the motor. The high speed linear and screw actuators can both meet the velocity requirements. An added benefit of these options is that the motion can be changed easily, and both are able to perform a wide range of motions, depending on the capability of the motor controller. The actuators can achieve a linear velocity of 60 cm/s over a range of 20 cm. The frequency of oscillation can reach 3 Hz. Figure 2 shows the velocity profile for both actuators. Both of these actuators are capable of oscillating to the center of the core or all the way across the core. They are also relatively small compared to the other options, requiring only a 50 cm X 10 cm area and could mount in the front or rear of the reactor. The safety concerns with these devices are also small because they have few exposed moving parts.

The power of the reactor needs to be measured and recorded along with the position of the actuator for use in the inverse kinetics code. The neutron detector is located towards the edge of the reactor, thus providing a global view of the reactor. The current from a neutron detector is very small (on the order of nanoamps) so a pico-ammeter is required to measure it. The pico-ammeter measures the current produced by the neutron detector and then turns the value into a digital number which will be sent to the computer data acquisition program.

LabView[1] was chosen for our data acquisition. In addition, a data acquisition board that connects the wires from the motor encoder to the computer is required. There is also a need for a board for the pico-ammeter to connect to the computer. Next, the motor on the linear actuator needs to be controlled. The controller must be able to set the position, velocity and acceleration of the linear actuator, which is done by sending power to the motor and the encoder located on the motor which then sends feedback to the controller. The controller needs to be able to keep each oscillation the same, given the distance and frequency of oscillation. To keep the oscillations the same, the controller will increase or decrease the current sent to the motor. The motion of the actuator is controlled through software which is programmed into the controller. The data from the encoder needs to be transferred into the computer data acquisition program, where the position of the actuator is determined in real time. This will then be plotted with the power of the reactor to determine the lag of the reactor power. While positioning information is not used in the analysis by inverse kinetics, it is useful in determining precise direction change time of the oscillator. This can be difficult to determine strictly from the power history.

To measure the current from the neutron detector, a Keithley^{TM} pico-ammeter model 6485 was used. For controlling the motor on the linear actuator, the ION500 from Performance Motion Devices[2] was selected. This was chosen because it is delivered with software that gives full control of the motor, including position, velocity, acceleration, and jerk. It was also chosen because it is the only device that can handle the power pulled by the motor. However, to control the motor, the ION500 needs a power supply of its own. For this a 24VDC, 13A power supply from Allied Electronics^{TM} was chosen.

For analyzing the data coming into the computer, LabView was used. A data acquisition box from National Instruments was chosen which has the option of 12 digital inputs/outputs. For our project we used one analog input for the detector, and two RS-232 connectors converted to USB to send information to the motor controllers and receive the position information.

The total cost of equipment for the construction of the oscillator was about $3000.

Pilot Calibration

A closed loop technique is a measurement that uses two oscillators, a sample oscillator and a calibrated pilot rod. The sample oscillator moves a small sample through the core region. As the sample moves to a location, the neutron population will increase or decrease based on the type of sample used. The pilot rod consists of a finely calibrated absorber used to keep the reactor exactly critical while the sample is moved through the reactor core. As the population changes, the power will follow the same trend. The pilot rod is then used to offset this power change. During the process, the pilot rod's position and that

[1]National Instruments Corporation, LabVIEW, Version 10.0, Austin,TX (2010).
[2]Performance Motion Devices Inc, Pro-Motion, Version 3.83,Lincoln, MA (2008).

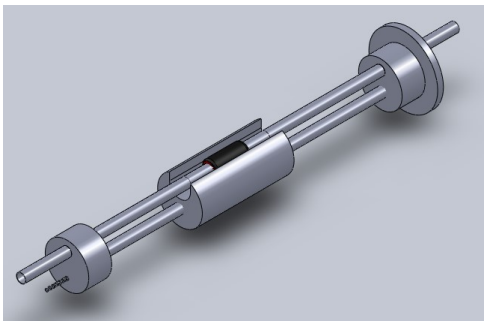

Figure 3: Original Pilot Rod Design

of the sample oscillator are recorded. Then by using the pilot rod's calibration data, the reactivity effect of the sample can be determined by matching the positions of equilibrium. The closed loop oscillator is used to measure small reactivity samples so the absorber in the pilot rod must necessarily have a low worth so that adequate resolution can be achieved.

The overall goal of this project is to prove that measuring small reactivities with the open loop can be just as precise as the closed loop method. The limiting factor in the determination of reactivities for samples this small is the reactor noise [11]. One of the most important aspects of the closed loop oscillator's uncertainty limit is the calibration of the pilot rod, so much effort has been taken in the calibration of the pilot rod (fully documented in Reference [12]). To characterize the pilot rod absorber's reactivity at multiple locations two period measurements were taken at multiple positions along the rod stroke. Cadmium was chosen as the neutron absorber for the pilot rod.

The pilot rod was designed previously by a senior design group at ISU in 2009 [8]. Their system consisted of a graphite cylinder with a hole bored through to accommodate the oscillation rod holding the sample container (black cylinder in Figure 3).

The oscillating rod is attached to a 35.56 cm lead screw driven by the linear actuator. To keep the sample container from scraping along the graphite during oscillation, two stabilization rods at the bottom of the graphite were added and polyethylene plug supports were placed at the ends of the assembly. This entire assembly was then inserted into the beam port of the AGN-201 for use.

Unfortunately due to the stress caused by sliding the assembly in and out of the reactor for each experimental run, the joint where the graphite and stabilizing rod meet came apart after only a few months of use. Another problem encountered while performing the first startups with this assembly was a loss of 24 cents of reactivity; much less than design's estimated 10 cent loss. A loss 24 cents of excess reactivity to the reactor would make operations during the warmer months impossible due to the negative temperature coefficient of the reactor.

Due to these issues, a new design using a graphite cylinder was devised. Most

Figure 4: Graphite Cylinder

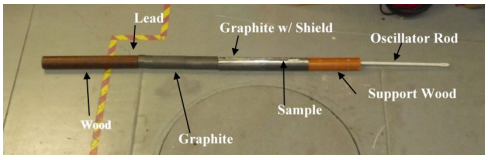

Figure 5: Oscillator Pieces

of the reactivity loss incurred in the previous design was due to the removal of a large majority of the graphite neutron reflector from the normal beam port configuration. To minimize the amount of reflector removed from the beam port, the new design extended the graphite boundaries into the wood section of the original configuration; this is accomplished using three pieces of graphite. Two pieces of graphite are solid graphite sections measuring 45 cm in length together and 10 cm in diameter; these occupy the southern half of the beam port with 10 cm of lead and wood to fill the rest of the beam port. The oscillator assembly occupies the northern half of the beam port with another piece of graphite with a U-shape along its axis. The U-shape is covered by a thin sheet of aluminum to prevent damage to the graphite cylinder by the moving absorber container. This is shown in Figure 4 with the shield attached. The graphite cylinder with the shield meets the two solid cylinders in the geometric center of the beam port. Figure 5 shows all of the individual pieces that are inserted into the beam port laid on the laboratory floor before insertion.

The absorber container made of PVC was created to hold six 2.54 cm diameter cadmium disks; effective height for all six disks is 2.54 cm. This sample container is attached to the oscillating rod, also made of PVC, with a screw and nut. The system was designed so a new absorber container can be attached without having to remove the oscillating rod by only switching absorber containers.

The opposite end of the oscillating rod is connected to the lead screw on the linear actuator. Support for this rod is given by a piece of wood the same diameter as the access port with a hole bored through for the oscillating rod

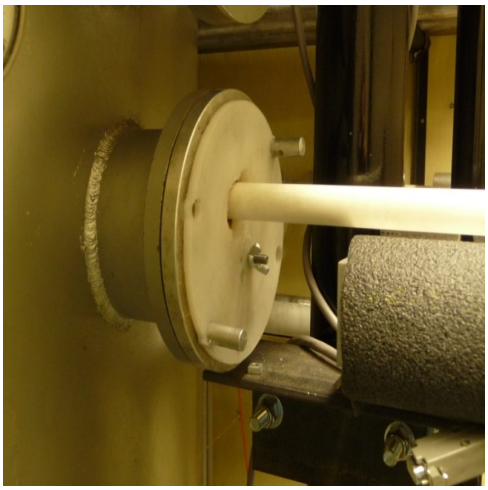

Figure 6: Oscillator Mounting

to rest on. The oscillating rod was cut so that the sample was located at the center of the beam port when the linear actuator was at its maximum stroke 35.56 cm.

The assembly is then attached to the reactor tank in the same way for each use to ensure the assembly is in the same location for each measurement (Figure 6).

The most important aspect of this system is the synchronization of measurements taken by the neutron detector with the positions of both the sample and pilot rod oscillators. To ensure the same timing for all of these measurements, LabView was used to control the oscillators and sample the current from the neutron detector. To control the oscillators, a LabView program was used.

Upon power-up, the controllers must be set with the correct initial parameters for optimum function. This process is accomplished using the Pro-Motion software due to the complex nature of the optimization and is done while the reactor is being brought to power. After the initial parameters are set, the controller will keep these until they are changed by the user. Using this feature the LabView program was written to assume the controller is initialized prior to its calling.

Each oscillator has two basic features; single move to position and oscillation. The single move feature allows the user to specify desired position to move the oscillator to and this command is then reinterpreted into cycles per second for the controller. The oscillation command is the single move command sequence followed by a looping command checking if the commanded position has been reached. Once the command position is reached, the second specified position is set and the process continues until the operator ends the oscillation. There is also the option to allow the oscillator to wait at the ends of each oscillation for a given dwell time. The oscillation function is usually used by the sample

oscillator and different wave forms can be produced by adjusting the dwell time. (With no dwell time the sample induces an approximate sine wave in the power while square waves can be produced using dwell times greater than one second).

For the closed loop system the pilot rod must follow or offset the power change from the sample oscillator. To accomplish this task, the current from the pico-ammeter is recorded and averaged over a Δt of 0.1 seconds. This current is compared to the previous current measurement. If the current is increased or decreased, then the pilot rod is moved closer to or further from the reactor core a fixed distance of 0.254 cm respectively. (A series of single position moves) The program continues to attempt to follow the open loop's induced power changes until ended by the user. This is a very simple control scheme and could be optimized or a more robust scheme could be implemented; however, this was not the scope of this work and is left for further study.

For calibration, the reactor was put on a positive period and then the sample was moved from its position in the beam port to the out of core position. Only positive periods were used because negative periods are bound by the longest delay group constant, 80 sec. A second drawback to negative periods is the amount of measurement time to reach 1% uncertainty in the period is much larger than for positive periods. To accomplish positive periods the sample is moved to the position of interest then the reactor is brought to critical. Then when the sample is moved to the least reactive position, the neutron absorber will not be as effective and the power will increase.

In Reference [13], a method is developed to determine the amount of time needed to wait until the observed power trace is within a desired uncertainty percentage of the asymptotic period, T. We can write the power as:

$$P(t) = \sum_{i=1}^{7} A_j^{s_j t}$$

with

$$A_j = (1-\rho)\frac{\Lambda + \sum_{i=1}^{7} \frac{\beta_i}{s_j+\lambda_i}}{\Lambda(1-\rho) + \sum_{i=1}^{6} \frac{\beta_i \lambda_i}{(s_j+\lambda_i)^2}}$$

In the above equations, s_j are the roots of the in-hour equation, Λ is the generation time, β_i are the delayed neutron fractions, and λ_i are the precursor decay constants.

Noting the ordering of the s_j roots, s_1 is the positive root which yields the asymptotic reactor period, T. So the uncertainty of s_1 is then related to how long until s_2 has decayed away so only s_1 contributes. We can derive the desired uncertainty using the following relation:

$$\Delta\sigma = \frac{A_2}{A_1} = \frac{s_2 - s_1}{s_1} e^{(s_2 - s_1)t}$$

The above equation gives a relation between a desired uncertainty (say 1%) and t, the time it will take before that uncertainty is reached, based upon the s_1 and kinetic parameters of the problem. This methodology was implemented for the AGN-201's specific generation time and β and a 1% uncertainty was

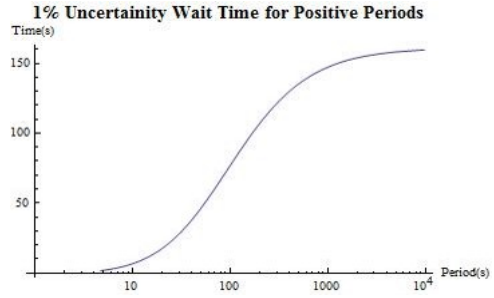

Figure 7: Uncertainty Wait Time for Positive Periods

desired.

In Figure 7, it can be seen that for fast periods (100 seconds or less) the asymptotic period is approached in less than one minute and for longer periods (greater than 1000 seconds) only 160 seconds are required. The periods encountered in this study ranged from 300 seconds to 10,000 seconds; A wait time of 300 seconds was chosen to provide enough data after the 1% uncertainty value to make confident fits to the data. Next the current output from the pico-ammeter is used as a representation for the P(t) in the above equation. Using a Mathematica[3] program the power trace is broken up into the initial five minute period measurement (300 sec) and then the second period measurement of five minutes due to the change in position. The period measurement can only fit the asymptotic period, T so the power trace is:

$$P(t) = P_{inititat} e^{t/T_{initial}} + P_{move} e^{t/T_{move}}$$

If the natural log is taken of the power trace data then the slope of the resulting fit line, α, gives the reactor period by:

$$T = 1/\alpha$$

The reactivity for that period can be determined for both the initial period and the sample move period. The total period recorded in the power trace measurement also consists of the initial period as well. It can be shown that if the initial reactivity is subtracted from the overall observed reactivity, the estimate for the sample is obtained.

$$\rho_{sample} = \rho_{move} - \rho_{initial}$$

The sample, using a power trace method, was moved in one cm increments through the beam port and each position was repeated 20 times to ensure the measurements followed a normal distribution. This resulted in 420 individual

[3]Wolfram Research, Inc., Mathematica, Version 8.0, Champaign, IL (2010).

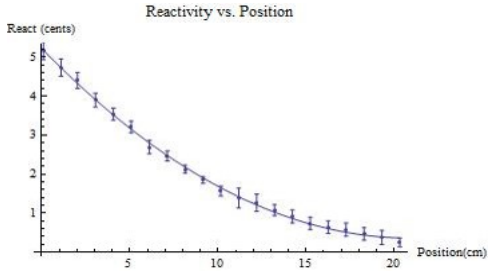

Figure 8: Calibration of Pilot Rod

measurements.

We show the final calibration results of the pilot rod in Figure 8. In that figure, the y-axis is the geometric center of beam port 4 and the error bars represent 1%, or one standard deviation from the mean. The data were fitted to a parabola with the result below:

$y = 5.129 - 0.464x + 0.011x^2$

where y is in cents and x is in cm from the geometric center of the beam port.

Due to time constraints, 20 measurements were viewed as the best sample set to see how repeated measurements were distributed (each measurement took 10 minutes totaling 70 hours of measurement time).

For the reactivity oscillator designed for ISUs AGN-201 reactor, the pilot rod has been calibrated with one cm resolution for its profile through the beam port (see Figure 8). With these calibration data obtained, experiments began using the closed loop oscillator.

Reactor Parameters Measurements

In this phase, two very important reactor parameters, the effective delayed neutron fraction β_{eff} and the generation time Λ, were determined for our AGN-201 reactor. Several methods were used to determine α, the prompt neutron decay constant from which the ratio of β_{eff}/Λ can be obtained easily. These methods were: Rossi-Alpha, Feynman-Alpha, Bennett Variance, Zero-Count Probability, and Power Spectral Density (PSD). All of these methods were performed using the same raw data, which consisted of times in which pulses occurred (i.e. time-stamped data). In addition, a Monte Carlo (MCNP) calculation was performed to determine β_{eff} and Λ. These methods were compared and contrasted to determine the best parameter values with the least uncertainties. This work is thoroughly documented with full citations in Reference [14].

The method of recording the time-stamps of pulses from three He3 detectors was performed with the reactor operating at 100 μWatts. Thirty runs of $1X10^6$ pulses were collected per detector and analyzed using noise analysis methods. The data from each run were able to be used to perform each method listed

above.

The prompt neutron decay value α value was determined from the results of the noise methods. The Zero- Count Probability method was disregarded because of the high uncertainties obtained compared to the other methods. Spatial effects were present in most results with the major exception of the Rossi-Alpha method. An averaged α value was determined using the Rossi-Alpha, Bennett and PSD results. The Feynman results were omitted because the Bennett method was chosen to represent the variance techniques, and the Bennett results had the smallest standard deviation out of the variance methods. The Rossi-Alpha value was determined to be $\alpha = -119.7 \pm 4.16\ sec^{-1}$. We evaluated the individual β_i by parameter fitting to the measured transfer function, and obtained $\beta_{eff} = 0.00747 \pm 0.00007$ from the sum. The credibility of the β_{eff} value was greatly increased because Busch et. al. [15] experimentally determined β_{eff} and obtained a consistent value. The neutron generation time was then inferred from the α value and β_{eff}. The result is $\Lambda = 62.4 \pm 2.17\ \mu sec$.

One of the more interesting consequences of this phase was the realization that the total uncertainty in an inverse kinetics measurement could be minimized by the proper selection of the frequency of oscillation. This was published in Reference [4]. The effect arises because of the different time constants of the delayed neutron precursors. We began by demonstrating that the total uncertainty in a reactivity measurement by inverse kinetics can be obtained by using the discretized partial derivatives, i.e., the discretized values are equivalent to those obtained by continuous partials. We then studied the specific contribution of each parameter $(\beta_i, \lambda_i, \Lambda)$ to the total uncertainty in a simulated reactivity insertion. From this, we noted the very different time behavior of calculated uncertainties due to each parameter following a ramp insertion of reactivity.

For example, the contribution of uncertainty in group 1 parameters builds up relatively slowly (hundreds of seconds); those due to group 2 are faster and larger in magnitude. This is simply due to the different time constants of group 1 and 2, and the fact that the magnitude of β_2 is greater than β_1. We noted that the uncertainty due to generation time (Λ) is insignificant for this type of insertion (ramp).

The behavior that we saw led us to realize that an oscillatory reactivity insertion, with the frequency chosen to emphasize the short term behavior could lead to reduced overall uncertainty. Thus, we performed simulated sinusoidal insertions at different frequencies. In this case, we found that the uncertainty in the neutron generation time actually dominated the overall uncertainty at high frequencies (above the cutoff frequency of the reactor transfer function). This is a sharp contrast to the result obtained from a ramp insertion. At low frequencies, the precursors dominate. The optimum frequency in the case of assuming equal 10% uncertainties was found to be in the range of 1 to 10 hz, which (not surprisingly) corresponds to the plateau of the transfer function for our AGN-201 reactor. For this range, the overall uncertainty is actually reduced by a factor of four (compared to the ramp) as shown in Figure 9. In fairness, we should mention that the differences are not as great when we use our actual uncertainty data from the AGN-201, but the minimization is still seen.

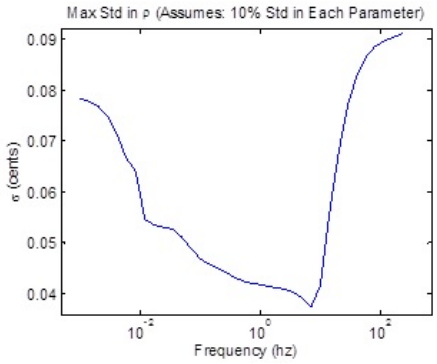

Figure 9: Uncertainty for Different Frequencies of Oscillation

Finally, in this phase we attempted to measure the generation time using the $1/v$ absorber technique (Reference [16]). It can be shown that the generation time can be related to the perturbation caused by a $1/v$ absorber as:

$$\Lambda = \frac{-\rho_p \int_V \psi^+ \psi dV}{\int_p \psi^+ N_p \sigma_{a,p}(v_0) v_0 \psi dV}$$

where ρ_p is the reactivity caused by the $1/v$ absorber, ψ^+ and ψ are the adjoint flux and forward flux respectively, N_p is the number density of the perturbing absorber, $\sigma_{a,p}(v_0)$ is the microscopic cross-section of the perturbing absorber at some reference speed, and v_0 is the reference speed. While the theory is straightforward, application to an experiment is difficult. In particular, we noted that determining the actual number density in our small samples was almost impossible. Thus, our results had a large uncertainty attached to them.

The values obtained for Λ were much lower than predicted by other methods and calculations. If the experimental atom densities far exceeded the boundaries of perturbation theory, then the perturbed prompt neutron generation time would be much lower than a generation time calculated for a smaller atom density. A possible solution for this problem would be to find a more easily managed 1/v sample material. The perfect material would be a solid with a lower cross section to allow for a volume large enough for easy measurements of mass.

Applications to Other Systems

A simple method of determining small reactivity using an open loop oscillator technique was designed for the Neutron Radiography Reactor (NRAD) at the Idaho National Laboratory (Reference [17]. This technique was initially proposed for the Advanced Test Reactor (ATR-C, also at Idaho National Laboratory). However, it was found that ATR-C was not a good choice due to its complex geometry (effectively a clover-leaf with four lobes) and its characteristic

of having a very large coupling of the higher harmonics with the fundamental mode (small eigenvalue separation). However, an open loop method was found to be feasible to measure small reactivity worths in a simpler reactor such as NRAD.

NRAD is a TRIGA tank-type reactor, fueled with uranium-zirconium-hydride elements which give this type of reactor its very strong temperature feedback. To first order, being hydrogen moderated, NRAD will have a similar transfer function to the ISU AGN-201. Indeed, comparison of the transfer functions showed the feasibility and applicability of the open loop technique to measure reactivity of small samples. NRAD was found to have a spectrum with a slightly higher break frequency as compared to the AGN-201. After showing the fact that this technique could be used in NRAD, a simple oscillator design was also presented and can be found in Reference [17].

The final phase of this project briefly studied the application of the open loop oscillator technique in a generic fast reactor (Reference [18]). In that work, it was pointed out that there is no fundamental difference between a thermal reactor and a fast reactor regarding kinetics behavior. Additionally, transfer functions were generated for fast U-235 and Pu-239 fuel systems in which their break frequency is on the order of 1000 Hz which is much lower than our sensing sensitivity (500,000 Hz). Therefore in fast systems, the limiting factor is on the perturbation side rather than on the sensing side. That is, it is challenging to design a mechanical perturbation system (oscillator) that is able to operate up to the break frequency in a fast reactor. This is in contrast to a thermal system in which the break frequency is normally on the order of a few hertz. That being said, one can still operate on the plateau of the transfer function and use the open loop technique to determine small reactivity worths. In Reference [18], it was shown that the linear actuator would be the most effective option to use in a fast reactor oscillator using a decision matrix. After that, a design recommendation was given for the experimenter to conduct small sample oscillations in a fast reactor.

Conclusion

In this report, we have documented the support work that has gone into the project studying the equivalencies relative to uncertainties of the open and closed loop oscillator techniques as used to measure small reactivity worth samples. While the major conclusion of the project demonstrating the equivalency has been well documented in recent publications, we have never fully described the support work, and have taken advantage of this final report to do so.

We went to the beginning and described some aspects of the senior design projects that originally developed the apparatus to be used in our AGN-201 reactor. We then described in some detail the calibration of the pilot rod, as well as the measurement of the necessary reactor parameters such as β_{eff} and various λ_i. Finally, we briefly mentioned the transference of the open loop technique to other reactor systems. The full set of references including all the

theses is given.

Acknowledgment

The authors especially would like to thank the AGN-201 reactor operations crew for their support in running the reactor for the many hours required for this study. Acknowledgement is also given to the 2009 senior design team, Ben Baker, Eric Bonebrake, and Dan Jones, and the 2010 senior design team, Bryon Curnutt, Marcus Junod, Bruce Pierson, and Eric Pope.

Thanks also goes to the US Department of Energy for its support through the Nuclear Energy University Programs.

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