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Mohamed Lamine Benzerga

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DEMONSTRATING THAT AN OPEN LOOP SYSTEM COULD BE IMPLEMENTED IN A FAST REACTOR

by

Mohamed Lamine Benzerga

A Thesis

submitted in partial fulfillment

of the requirements for the degree of

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Mohamed Lamine Benzerga find it satisfactory and recommend that it be accepted.

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Abstract

This thesis covers the fundamentals of applying the open loop technique to determine the reactivity of small worth samples in a fast reactor in which the reactivity is inferred from the recorded power history using inverse kinetics. This thesis shows that there is no fundamental difference between a thermal reactor or 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 10^3 Hz which is much lower than our sensing ability (5×10^5 Hz). Therefore, the limiting factor is on the perturbation side rather than on the sensing side. This thesis also determines that the linear actuator is the most effective option to use in a fast reactor oscillator by using a decision matrix. After that, a design recommendation was given for an experimenter to conduct small sample oscillations in a fast reactor.

Chapter 1: INTRODUCTION

The open and closed loop reactivity oscillation systems are two types of mechanical systems that are employed in small-sample reactivity measurements in a nuclear reactor to yield an understanding of the relationship between the measured reactivity effect and the properties of the sample. The closed and open loop techniques have long existed but to our knowledge had not been implemented on the same system for the purposes of direct comparison until a study was done at ISU over the last 5 years. The results obtained have shown that both techniques can attain the same level of uncertainties, but at high frequency, the open loop is preferred (Baker, 2013). The open loop technique, inherently simpler than a closed loop, would allow integral reactivity worth measurements in a fast spectrum for minor actinides research. This is very important for the development of advanced nuclear system designs. The timeline of the whole project is shown below:

- 2009 Senior design project built open loop infrastructure
- 2010 Senior design project built closed loop infrastructure
- 2011 Adam Langbehn and Tony Riley added to the project
    - Adam Langbehn assigned to determine prompt neutron generation time with the use of a 1/v absorber (Langbehn, 2013).
    - Tony Riley assigned to calibrate the follower system (Riley, 2013).
- May 2011: Benjamin Baker completes his M.S. thesis using noise methods to determine the prompt neutron decay value (Baker, 2011).
- December 2013: Benjamin Baker completes his PHD dissertation .

- 2012 Aryal Harishchandra added to the project
  - Assigned to design an open loop system for the Advanced Test Reactor – Critical (ATR-C). Later changed to show that a stronger fundamental mode is required and the ATR-C is not a good choice of reactor to implement the system (Harishandra, 2014).

The work to date in this project is summarized in two key references (Baker & Imel, 2013) and (Baker & Imel, 2014).

In a nuclear reactor, fission is caused by the absorption of a neutron that makes the nucleus unstable due to the unbalance numbers of particles in the nucleus. This weakens the nuclear forces holding the particles, and therefore the nucleus splits into two or more less massive stable fragments (daughters). Additionally, the splitting of the parent's nuclide is followed by the creation of two or more neutrons from the initial fission with energy larger than 2 MeV along with gamma rays. The prompt neutrons released can now each induce fissions in other fissile or fissionable nuclei. This series of events is known as a chain reaction. The chain reaction is described quantitatively by the symbol k, which stands for the multiplication factor.

$$k = \frac{\text{number of fissions in one generation}}{\text{number of fissions in preceding generation}}$$

The reactor is said to be critical when k =1, which means that the number of neutrons in one generation is equal to the number of neutrons produced by the preceding generation. If k is less than 1, the number of fissions decreases and the reactor is said to be subcritical. If k is greater than 1, the number of fissions increases from one generation to another and the reactor is said to be supercritical.

Understanding the kinetics of nuclear reactors requires the use of the concept named reactivity. Reactivity is generally denoted by the lower case Greek letter rho (ρ). Rho is a unit-less quantity that describes the change of multiplication inside the reactor from generation to generation. Reactivity can also be perceived as the departure of the multiplication from the critical state. The equation below is the basic definition of reactivity.

$$\rho = \frac{k - 1}{k}$$

Reactivity can be expressed in decimal, percentage, or pcm (per cent mille) of $\frac{\Delta k}{k}$. Reactivity in the nuclear industry is often expressed in term of the delayed neutron fraction β with units of dollars or cents.

The point kinetic kinetic model is used in this study to illustrate the dynamics of nuclear reactors and more precisely we are using the model to determine reactivity uncertainty at noise levels. The point kinetics equations are given below (Hetrick, 1993).

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta}{\Lambda} n(t) - \lambda_i C_i(t), \qquad i = 1, \dots, 6$$

Where n (t) = neutron density or power
ρ (t) = reactivity
C_i(t) = precursor concentration for group i

β = delayed neutron fraction
β_i = delayed neutron fraction for precursor group i
λ_i = delayed neutron decay constant for precursor group i
Λ = neutron generation time (seconds)

From the first chain-reacting pile known as CP-1, experimenters realized that the most direct and reliable technique to measure the effect of various sample materials such as uranium, graphite, or aluminum is by inserting a sample through the pile and observing its effect on the multiplication of the neutrons sustaining the chain reaction (Foell, 1972). Nowadays, with better equipment and development, it is possible to study a wide range of materials and reactor parameters with diversity in experimental conditions. Small sample reactivity measurements are performed by using a mechanical system that oscillates a sample in and out of the core since reactivity, and hence multiplication, is perturbed. There are two types of methods we studied to analyze the period output functions after the reactor is perturbed: closed and open loop.

The closed loop method (often referred to as the reactivity oscillator method) is a method that tries to maintain the power at a constant level by changing position of a control rod as a sample is oscillated in and out of the core. Prior to employing this method, this “follower” rod must be well calibrated to relate its’ positions to reactivity. The follower rod consists of an absorber that maintains the reactor at a critical state while the sample is oscillated through the reactor core. The reactivity worth of the unknown sample is determined by using the differences in reactivity determined from the position of the follower rod. Figures **1** and **3** illustrate the dynamics of the closed loop and open loop oscillator method. It needs to be noted that in both Figure **1** and **3** that the perturbation is caused by a square waveform that perturbed the reactor system.

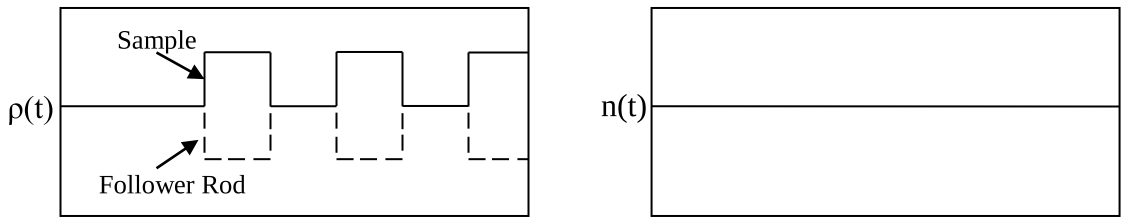

Figure 1: Closed Loop Oscillator Method (Baker, 2013)

To further illustrate the difference between an open loop and a closed loop, Figure **2** and Figure **4** shows a simple schematic of each method.

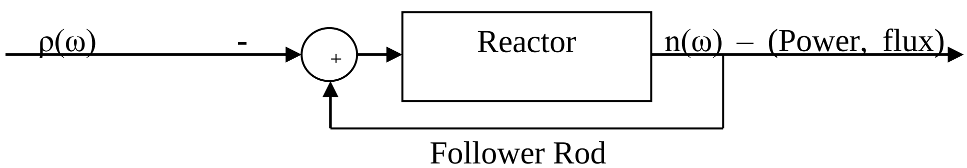

Figure 2 : Closed Loop Schematic

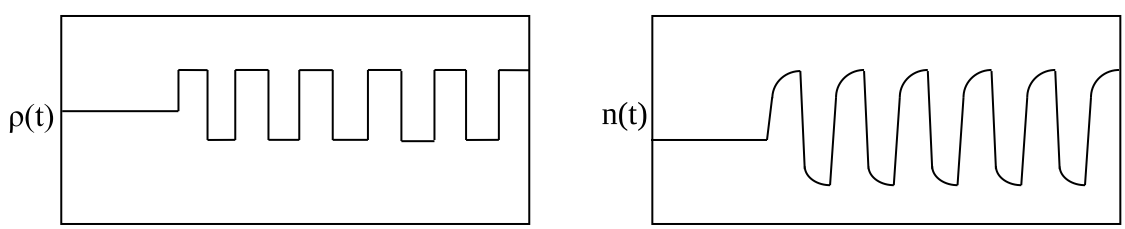

Figure 3: open loop reactivity input and power history

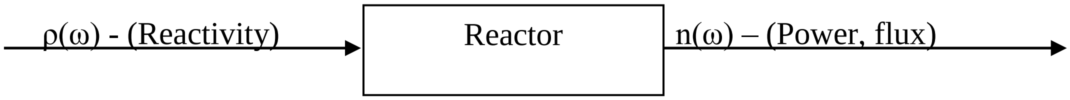

Figure 4 : Open Loop Schematic

As shown in Figure **4,** the reactivity input enters the reactor core without feedbacks from the output (power, flux, etc). Contrary to Figure **4**, Figure **2**, which demonstrates the closed loop mechanism, does provide feedbacks to the input reactivity from the output.

During the course of five years, graduate students at Idaho State University have been working on comparing methods of measuring very small reactivities limited by the noise level. This project began in 2008 and this thesis will be the last one of the oscillation group. This thesis consists of conceptually designing an open loop system for a fast reactor assembly such as MASURCA, located at the Cadarache Laboratory in southern France. The MASURCA reactor is a 5 KW design devoted to the studies of neutron characteristics of fast reactors, and development of measurement techniques (CEA, 2014). The MASURCA reactor has a flux level up to 10^{11} neutrons/cm^2 sec (CEA, 2014). The core materials of the MASURCA reactor are contained in cylinder rodlets and are wrapped into tubes having a square section (10 x10 cm) and approximately 3 meters in height (CEA, 2014). MASURCA had its first criticality in 1966. The MASURCA facility has been dedicated to research in support of the PHENIX, SUPERPHENIX and EFR (European Fast Reactor) projects until the mid 90's. Currently, the development of Generation IV nuclear systems is a priority research in France. The MASURCA facility will be performing future programs to determine "the representativeness of the spectral conditions and the sodium void reactivity effects of the future sodium fast reactor studied” (Fougeras et al, 2005). The MASURCA facility is scheduled to have a refurbishment next year to improve the measurements quality and also to comply with the new antiseismic regulation. The picture below is a cross section of the MASURCA facility. The implementation of the open loop system at the MASURCA facility would enable them to determine integral cross section response in a fast neutron spectrum for many transuranic isotopes which will crucial for characterization of fuel for future development of fast reactors.

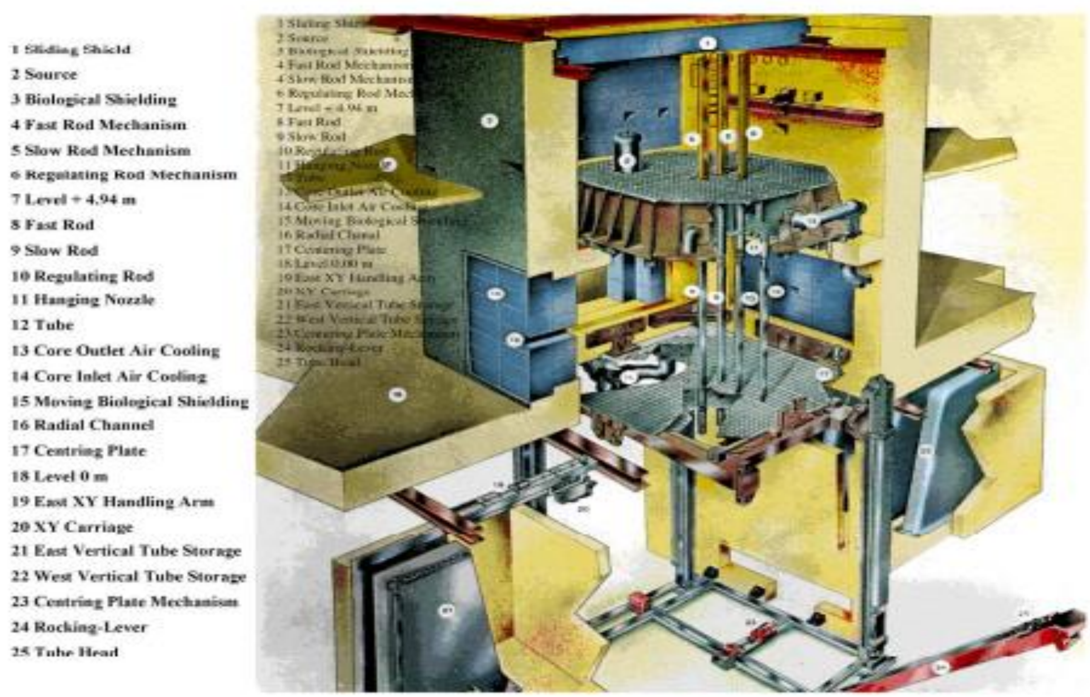

Figure 5: MASURCA Facility (IEEE, 2014)

1.1 Statement of Problem

The main goal of this thesis is to conceptually design a system to measure small worth samples using the oscillator technique for integral physics measurements in a fast spectrum reactor. The sample is oscillated in and out of the core and analyzed through readily applicable techniques (the asymptotic period measurement, the pile-oscillator method, and the power history method). Due to the extremely small reactivity changes, the high precision is an important criterion for this type of measurements. Therefore, acquiring premium efficiency and convenience of the measurement technique is essential for this special class of reactivity measurements. Numerous methods have been utilized to perform small-sample reactivity measurements but only a few were able to attain uncertainty in measurement down to the noise level: asymptotic method, power history method, pile oscillator method, and the closed loop method (pile oscillator method using automatic reactivity compensation (autorod)).

The space dependent kinetics model will be ignored in this thesis since we are assuming that the fundamental mode dominates throughout the course of the transient (Foell, 1972). There are two important concepts in this thesis that need to be understood: reactor noise and reactor drift. As (Foell, 1972) described it, reactor noise is manifested as random fluctuations in reactor power. As the oscillator techniques rely on imposed periodic fluctuations in reactor power, one cannot see those fluctuations if they fall below the noise level. If a complete stability could be integrated into the reactor system, all the drifts would be eliminated and the reactivity precision would be only limited by the reactor noise.

Reactor drift is primarily due to the temperature feedbacks and rarely to the barometric pressure. The effect of reactor drifts could be eliminated by correcting data and uncertainty would therefore only be limited by the reactor noise.

There have been methods that show theoretically that uncertainties in a measurement to the noise level can be obtained. The methods as mentioned above are: asymptotic period method, power history method, pile oscillator method and reactivity oscillator method. According to (Foell, 1972), the asymptotic period method was the first and most direct method of determining reactivity measurement of a reactor from insertion of a test sample. The asymptotic period method is a special solution to the point kinetics when a constant reactivity is inserted. The outcome of the power will consist of a single exponential after transients die off. The in-hour equation and inverse kinetics could both be employed to determine reactivity from the measured exponent. However, this technique is inconvenient due to the long waiting time for a single measurement. This technique is not practicable for acquiring reactivity uncertainty at noise levels but is often employed in the calibration of the control rod.

Another technique often used when measuring small reactivity changes in the nuclear reactor is the power history method. The power history method uses the inverse kinetics equation to determine reactivity from the power history. Inverse kinetics is derived from the point kinetics equation and has been crucial in small reactivity measurements since it can solve for reactivity as a function of time.

Another method that is used to measure and determine small sample worth uncertainty down to noise level is the pile oscillator technique. The pile oscillator technique was first introduced by (Wigner, 1945) during the time of the Manhattan

Project and later developed by (Weinberg & Schweinler, 1948). This technique is a method where a sample is oscillated in and out of the core; consequently the neutron flux get modulated between regions of high and low neutron flux. The pile oscillator is initiated by a periodic reactivity waveform that perturbs the reactor such that the power output is also a periodic function. The waveforms are created mechanically by either a linear or a rotary actuator. The reactivity from the open loop technique is investigated by two methods: inverse kinetic and harmonic analysis.

Chapter 2: Theory

2.1 Reactor Noise

Reactor noise has been investigated extensively in the early days of reactor research (Thie, 1963). Later, Frish and Littler were the first to work together to predict the fluctuations associated with sample reactivity measurements using the noise theory in a paper titled "Pile Modulation and Statistical Fluctuation in Piles" (Frish & Littler,1954). Furthermore, (Cohn, 1960) expressed the fluctuations in the reactivity measurement as a noise equivalent source in a paper titled "A Simplified Theory of Pile Noise". Cohn also represented the uncertainty due to reactor noise in the same paper. As stated by Foell , reactor noise is the random fluctuation of reactor power (Foell, 1972). Additionally, reactor noise is the theoretical limitation on how well the reactivity of a sample can be known because it is crucial for the experimenter to eliminate extraneous effects that may mask the true reactivity worth of the sample. Frisch and Littler were the first to use noise theory to investigate fluctuations associated with sample reactivity measurements (Frish & Littler, 1954). Later, a paper expressed a spectral noise equivalent source in terms of reactivity and is shown below by Equation (**1**) (Cohn, 1960).

$$\langle|\rho|^2\rangle = \frac{2l}{n}\left[\frac{\overline{\nu(\nu-1)}}{\bar{\nu}}\right] \qquad \text{Equation } (\mathbf{1})$$

Where n = the total number of neutrons in the reactor

ρ = reactivity

l = the prompt-neutron lifetime

ν = the average number of neutrons, both prompt and delayed produced per fission

Additionally, (Cohn, 1972) generated a variance expression for the generating time t of the spectral density of equivalent reactivity fluctuations shown below by Equation (**2**)

$$\sigma^2(t) = \frac{l}{nt}\left[\frac{\overline{\nu(\nu-1)}}{\bar{\nu}}\right] \qquad \text{Equation } (\mathbf{2})$$

The parameters in (**2**) are the same as in (**1**) with the exception of the time t. The bracket quantity $\frac{\overline{\nu(\nu-1)}}{\bar{\nu}^2}$ is 0.60 for U-235 and 0.66 for Pu-239 fast systems (10). The term $n/_{l\bar{\nu}}$ in (**2**) is the total fission rate in the reactor and is often noted as F. The fission rate could be changed to reactor power by applying appropriate variable for the desired system (fast or thermal). Equation **(3**) below illustrates the minimum uncertainty that could be obtained in a reactor system.

$$\sigma(t) = \frac{\text{Constant}}{\sqrt{Wt}} \qquad \text{Equation } (\mathbf{3})$$

From the above equation, higher power and longer times are the only two things that can improve the uncertainty of a measurement. As the power goes up, measurements get more precise since the uncertainty goes down. Typically, experimenters would want to go to as high of a power as possible to reduce the time for the target uncertainty. However, as the power is kept high, there can be feedback effects that start to interfere (e.g., temperature feedbacks, which could affect the experiment and mask the true worth of the test sample reactivity under study).

2.2 Reactor drift

Reactor drift occurs when the reactivity changes due to effects other than those introduced by the test specimen under study (Foell, 1972). The drift is often due to temperature effects and poor conductivity of reactor materials. This has been shown in numerous experiments when measuring reactivity worth of unknown samples on the AGN-201 reactor (Baker, 2013). Due to drift in the experiments, data have to be corrected before applying the harmonic analysis for the open loop techniques.

2.3 Inverse Kinetics

The inverse kinetics equation gives the experimenter the ability to determine the reactivity of an oscillating sample under study as function of time. We start with Equation (**4**)

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta}{\Lambda} n(t) - \lambda_i C_i(t), \quad i = 1, \dots, 6$$

Equation(**4**)

Where: n (t) = neutron density or power
ρ (t) = reactivity
$C_i(t)$ = precursor concentration for group i
β = delayed neutron fraction
β_i = delayed neutron fraction for precursor group i
λ_i = delayed neutron decay constant for precursor group i
Λ = neutron generation time

The system is assumed to be starting at rest and the initial conditions are determined by setting the derivative terms equal to zero. The initial conditions are:

$$C_i(0) = \frac{\beta_i n_0}{\Lambda \lambda_i}$$

Equation (**5**)

where n_0 is the initial power level.

The precursor concentration equation is a first order differential equation and can be solved using the integrating factor technique.

The result is shown in Equation (**6**)

$$C_i(t)e^{\lambda_i t} - C_i(0)e^0 = \frac{\beta_i}{\Lambda}\int_0^t e^{\lambda_i t'} n(t')dt' \qquad \text{Equation}(\mathbf{6})$$

Equation (**6**) can be solved for the precursor concentration, $C_i(t)$, and the initial conditions are applied.

$$C_i(t) = \frac{\beta_i n_0}{\Lambda\lambda_i}e^{-\lambda_i t} + \frac{\beta_i}{\Lambda}\int_0^t e^{\lambda_i(t'-t)}n(t')dt' \qquad \text{Equation}(\mathbf{7})$$

The reactivity can then be solved from Equation (**4**).

$$\rho(t) = \frac{dn(t)}{dt}\frac{\Lambda}{n(t)} - \frac{\Lambda}{n(t)}\sum \lambda_i C_i(t) + \beta \qquad \text{Equation}(\mathbf{8})$$

Substituting the precursor concentration from Equation (**7**) into Equation (**8**) gives result to Equation (**9**) which is one form of the inverse kinetics equation.

$$\rho(t) = \frac{dn(t)}{dt}\frac{\Lambda}{n(t)} - \frac{1}{n(t)}\sum_{i=1}^{6}\beta_i\left[n_0 e^{-\lambda_i t} + \lambda_i\int_0^t e^{\lambda_i(t'-t)}n(t')dt'\right] + \beta \qquad \text{Equation}(\mathbf{9})$$

2.4 Open Loop (Pile Oscillator)

The open loop method from a control system perceptive is to perturb the system and observe the output without any feedback control. Figures (**3**) and (**4**) introduced earlier illustrated schematically the open loop method, which consists of oscillating a sample between two regions inside the core. The oscillating process of the sample alters the neutron population based on the type of sample employed in the experiment. For instance, an absorber used as a sample will decrease the neutron population. Additionally, the change of neutron population is directly proportional to the reactor power. The open loop techniques are capable of attaining results down to the noise level and its' uncertainty is equivalent to the closed loop method as proven (Baker, 2013). The open loop technique is analyzed using the inverse kinetics equations or harmonic analysis. Note that the inverse kinetics equations can be applied to any power history and reactivity could be inferred from it as long as the initial conditions are known, i.e., a periodic reactivity is not required. It should also be pointed out that the pile oscillator is an open loop technique but mainly analyzed using the harmonic analysis (Fourier analysis and Fourier transform).

2.5 Transfer Function

The ratio of an output of a physical system to a signal input of a system (reactivity) in the Laplace domain can be expressed using the transfer function. If the input is X(s) and the output is Y(s) then the transfer function H(s) would be represented by Equation (**10**).

$$H(s) = \frac{\text{Laplace transform of output}}{\text{Laplace transform of input}} \qquad \text{Equation } (\mathbf{11})$$

Below is a block diagram illustrating the transfer function process for an open loop control system.

Figure 6: Transfer Function Diagram

2.6 Zero power Transfer Function

Measurements in reactors involving a reactivity change are investigated using the kinetics equations. However, reactivity oscillations are performed at low power (no feedback) so feedbacks from temperature will not obscure the reactivity effect on the sample (Foell, 1972).Additionally, perturbations of higher magnitude (above first order) are ignored (linearization).

A derivation is performed below.

The perturbation is assumed as follows:

$$n = n_0 + \delta n$$
$$\rho = \rho_0 + \delta\rho$$
$$q = q_0 = \frac{-\rho_0 n_0}{\Lambda} \qquad \text{Equation } (\mathbf{12})$$

$$c_i = c_{i0} + \delta c_i$$
$$I.C. \;\; c_{i0} = \frac{\beta_i n_0}{\lambda_i \Lambda}$$

Use the above equation and substitute them in the kinetics equations (**4**) yields Equation (**13**)

$$\frac{d(c_{i0} + \delta c_i)}{dt} = \frac{\beta_i}{\Lambda}(n_0 + \delta n) - \lambda_i(c_{i0} + \delta c_i) \qquad i = 1 \ldots 6$$

If the terms are expanded, we obtain (remember that the unperturbed quantities are constants):

$$\frac{d(\delta n)}{dt} = \frac{\rho_0 n_0 + \delta\rho n_0 - \beta n_0 + \rho_0 \delta n + \delta\rho\delta n - \beta\delta n}{\Lambda} + \sum_{i=1}^{6} \frac{\beta_i n_0}{\Lambda} + \sum_{i=1}^{6} \lambda_i \delta c_i + \frac{-\rho_0 n_0}{\Lambda}$$

$$\frac{d(\delta c_i)}{dt} = \frac{\beta_i n_0 + \beta_i \delta n}{\Lambda} - \lambda_i \delta c_i - \frac{\beta_i n_0}{\Lambda} \qquad i = 1 \ldots 6 \qquad \text{Equation } (\mathbf{14})$$

We cancel common terms and assume that $\delta\rho\delta n$ linearization is negligible because it is second order in perturbations, which yields

$$\frac{d(\delta n)}{dt} = \frac{\delta\rho n_0 + \rho_0 \delta n - \beta\delta n}{\Lambda} + \sum_{i=1}^{6} \lambda_i \delta c_i$$

$$\frac{d(\delta c_i)}{dt} = \frac{\beta_i \delta n}{\Lambda} - \lambda_i \delta c_i \qquad i = 1 \dots 6$$

Equation (**15**)

Take the Laplace transform of the two equations to obtain

$$s\delta N(s) = \frac{\delta R(s) n_0 + \rho_0 \delta N(s) - \beta\delta N(s)}{\Lambda} + \sum_{i=1}^{6} \lambda_i \delta C_i(s)$$

$$s\delta C_i(s) = \frac{\beta_i \delta N(s)}{\Lambda} - \lambda_i \delta C_i(s) \qquad i = 1 \dots 6$$

Equation (**16**)

Solving for $\delta C_i(s)$ and substituting in the power equation yields:

$$\delta C_i(s) = \frac{\beta_i \delta N(s)}{\Lambda(s+\lambda_i)}$$

$$s\delta N(s) = \frac{\delta R(s) n_0 + \rho_0 \delta N(s) - \beta\delta N(s)}{\Lambda} + \sum_{i=1}^{6} \lambda_i \frac{\beta_i \delta N(s)}{\Lambda(s+\lambda_i)}$$

Equation (**17**)

The ratio of $\delta N(s)/(n_0\, \delta R(s))$, is the zero-power transfer function. It is also normalized by dividing by n_0. Note that the denominator is the in-hour equation as defined in kinetics textbooks (Hetrick, 1993).

$$H(s) = \frac{\delta N(s)}{\delta R(s) n_0} = \frac{1}{s\Lambda - \rho_0 + \beta - \sum_{i=1}^{6} \frac{\beta_i \lambda_i}{(s+\lambda_i)}} \ \{Normalized\ T.F.\}$$

A generic plot of the zero-power transfer function is illustrated in Figure **7**. As can be seen, there are three distinct regions. At low frequencies the delayed neutrons contribute. In the plateau delayed neutrons cannot respond.

The first part of the transfer frequency consists of prompt and delayed neutrons which are affected by the signal. As the frequency gets higher the average delayed neutrons start losing pace and can't keep up with the signal, explaining the plateau. It needs to be noted that some delayed neutrons do keep up with the prompt neutrons in the plateau region. As the frequency keeps getting larger, the average population of prompt neutrons cannot keep up but some do which explains the decrease of the transfer function

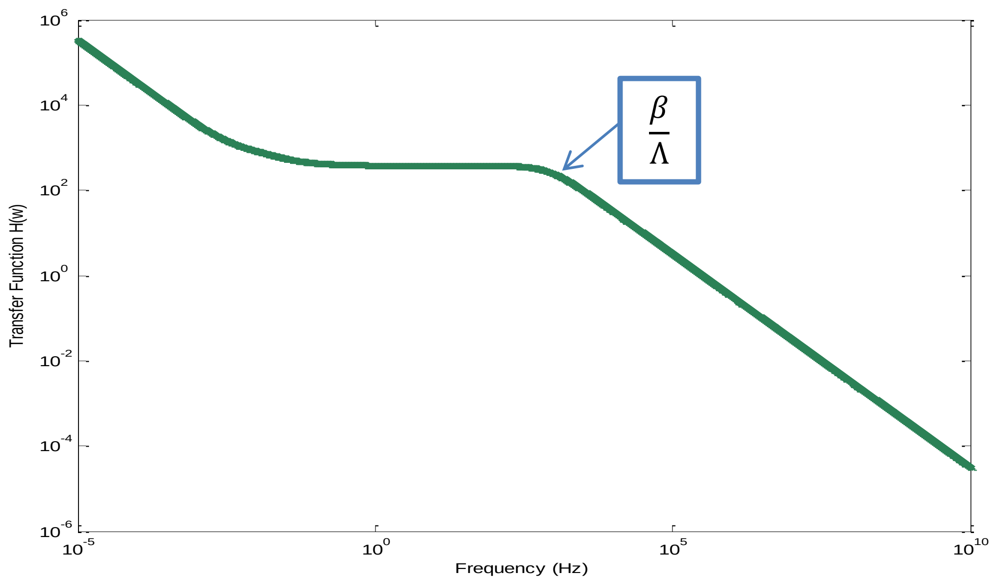

Figure 7: Zero-Power Transfer function Plot

2.7 Fast Reactors

In fast reactors, the neutrons inducing fissions have an average energy of several hundred KeV compared with an energy of less than 1 eV in thermal reactors. Fast reactors are types of nuclear reactors where the chain reaction is sustained by fast neutrons. Moreover, fast reactors use no moderator to slow down neutrons like thermal reactors but do use fuel richer in fissile material. In the fast fission as well as in thermal fission, neutrons are born in the MeV region with an average energy of 2 MeV. These fissions neutrons will decrease in energy through scattering events such as inelastic collisions with fuel and structural atoms. In fast reactors, the generation time is on the order of 10^{-7} to 10^{-9} seconds contrary to thermal reactors where the generation time is on the order of 10^{-3} seconds. As can be seen from Figure 7, the delayed neutron fraction (β) and the generation time (Λ) dictate the position (in frequency) of the end of the plateau (called break frequency). The ratio of $\frac{\beta}{\Lambda}$ is quite different for thermal versus fast reactors. On the other hand, for example, a plutonium fueled fast reactor would have $\beta\sim$ 0.003 as opposed to $\beta\sim$ 0.007 for a uranium reactor. This would actually tend to lower the break frequency. However, the differences in generation times are much more important. Fast reactors have generation times of fractions of a microsecond, while thermal reactors have times in the order of milliseconds. Thus, the fast reactor break frequency is normally much higher (as much as three decades) in a fast reactor. Fortunately with modern electronics we can design our acquisition system with sufficient time resolution.

2.8 Detectors

2.8.1 Proportional Counter

We introduce some aspects of radiation detection, specifically proportional counters because the radiation detectors are the first part of the chain that makes up an oscillation system, either closed loop or open loop. Therefore, their characteristics such as dead time are very important. Operation of gas filled detectors is mainly based on the ionization of gas molecules inside the detector chamber. Radiation ionizes the fill gas inside the detector which produces ion pairs. The ion pairs migrate toward their respective electrodes due to the electrical field that the electrodes create. The charge collected on the anode creates a measurable pulse. “Proportional counter detectors are almost always operated in pulse mode and rely on the phenomenon of gas multiplication to amplify the charge represented by the original ion pairs created within the gas” (Knoll, 2010). These instruments are widely used to detect ionizing radiation. “Radiation detectors for which the total numbers of ions produced is proportional to the energy of the radiation are referred to as proportional counters” (Brey/Claver, 2012). Proportional counter detector design consists of an anode and cathode. The cathode is typically the outer housing of the detector, the anode a thin central wire. The characteristic generalized curve for a gas filled detector is shown in Figure 1.

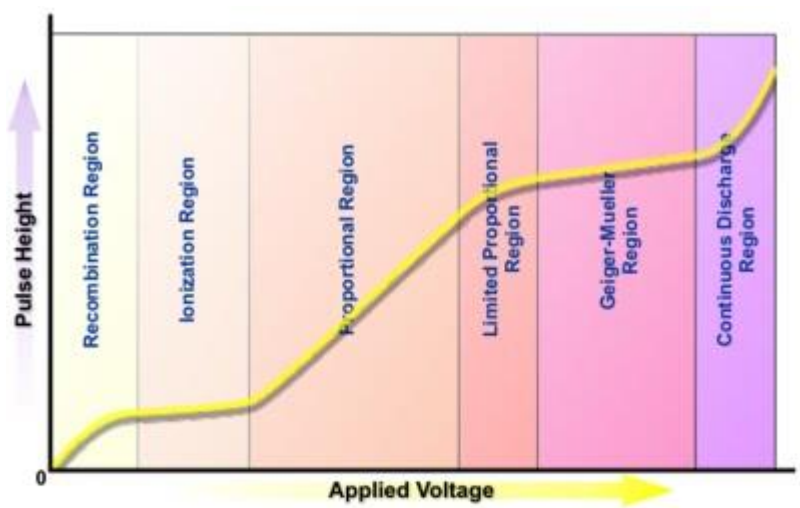

Figure 8: Six Regions Curve for gas filled detectors (Palvai, 2011)

Proportional counters are often used to differentiate between alpha and beta radiation. When operating a detector in the proportional region, beta and alpha radiations produce different size pulses that the detection system can differentiate between. The alpha and beta curves have two operating voltages in which they operate. The lower operating voltage corresponds to the alpha operating voltage and the higher operating voltage is the alpha/beta operating voltage. The optimum operating voltage of the alpha plateau is one-third of the way from the beginning of this plateau. The operating voltage for the alpha/beta plateau is one third of the way past the knee of this plateau.

Proportional counters are used for other applications such as the detection and spectroscopy of low energy X-radiation, as well as in the detection of neutrons (Knoll, 2012). Alpha radiation generates larger pulses than beta radiation at the same applied voltage due to the fact that alpha radiation creates a greater number of ion pairs generation than beta radiation. At the alpha plateau, all counts are from alpha particles; the contribution from beta particles is so small that they are implicitly discriminated (Brey/Claver, 2012). Increasing the applied voltage, beta particles start to be counted along with the alpha particles which results in the alpha/beta plateau. Unlike the case when using a Geiger-Muller system in which the "large output pulse from the detector make it unnecessary to use a preamplifier" (Brey/Claver, 2012), proportional counters use preamplifiers to increase the magnitude of the signal so it is not lost in the transmission. The magnitude of the output pulse for a proportional counter is in the millivolt ranges so both a preamplifier and amplifier are necessary to increase the magnitude of the output and provide pulse shaping.

2.8.2 Dead time

The dead time is the time after which an ionization event occurs when another ionization event cannot be detected. Dead time is related to the generation of a large number of ions pairs during the Townsend Avalanche. While electrons rapidly migrate to the anode, heavy positive ions form slow moving charge clouds which substantially reduce the electric field strength and the active region of the detector until they either recombine and are electrically neutralized or they migrate to the cathode. During some fraction of the migration time, the detector system is incapable of producing a second pulse of sufficient magnitude to exceed the detector's implicit discrimination.

Two methods are used to quantify the dead time: the oscilloscope method and the split source method. Using the oscilloscope method, the width of the output pulse of the detector is measured which represents an approximation of the detector dead time. This method is mostly employed in GM tubes but can be used for proportional counters operating in pulse mode in which information of individual events (amplitude, timing) is preserved.

The split source method involves the analysis of the radioactive material disk employed in the experiment and two blank halves. The blank halves are background halves used to keep consistent geometry in this method. These are counted for a certain period of time individually and in combination to obtain information of the variations in the observed counts under the prescribed counting conditions. At first, both halves of the source are counted and are given a value for the variable n_{12}. After that, one of the halves is removed without altering the geometry of the other one and the other source is counted to give the value of the variable n_{2}. It needs to be noted that whenever one of the source halves is removed, a blank half with the same geometry is put inside the detector. Lastly, the two half sources are removed and two blank halves are put in the detector and counted to give a value of the variable b. The counting time is the same for source combinations and the background. This method of calculating dead time works because the counting rate from the combined sources (source + blank halves) will be less than the sum of the two sources counted individually and therefore the dead time can be calculated from discrepancy assuming sufficient statistics.

$$\tau = \frac{[(n_1/T) + (n_2/T) - (n_{12}/T) - (b/T)]}{[2(n_1/T)\,(n_2/T)]} \tag{14}$$

n_1 = count using the first split source and a blank

n_2 = count using the second split source and a blank

n_{12} = count using both split sources together

b = count using both blanks

T = Period time in which counts were taken.

The split source method is more accurate than the oscilloscope method since it relies on quantitative results rather than visual inspection. However it should be noted that dead time is a function of count rate, so multiple source strengths, would be needed to cover a range.

There are two fundamental modes of dead time that need to be addressed. They are referred to paralyzable and nonparalyzable response. Detectors that are affected by paralyzable dead time, events that occur in the dead period are not counted and they extend the dead time by another period. However, in detectors affected by nonparalyzable dead time, events that occur during the dead period are still lost but don't extend the dead time. It needs to be noted that these two models are idealized models and actual detectors exhibit the combination of both. The dead time of the detector can also be extended by the associated electronics (amplifiers, preamplifiers, etc.). Therefore understanding the associated electronics and the modes arrangement of dead times is crucial for the experimenter to understand when analyzing data. A paralyzable detector can be corrected for dead time from the following equation (Knoll, 2012).

$$n = \frac{m}{1-m\tau} \tag{15}$$

n = true interaction rate

m = recorded count rate

τ = system dead time

For nonparalyzable detectors, the correction for dead time is determined from the following equation (**16**).

$$n = \frac{m}{e^{-n\tau}} \tag{16}$$

For low count rates, the paralyzable detector and nonparalyzable detector result in the same dead time as it can be seen from a Taylor expansion of equation (**16**).

$$n = m(1 + m\tau) \tag{17}$$

2.8.3 Efficiency

Detector efficiency needs to be taken into account since not all of the activity can be detected by the proportional counter. Detector efficiency yields a percentage of the total radiation that you could see with the detector. Detector efficiency is subdivided into two classes: absolute and intrinsic efficiencies. Absolute efficiency is defined by the following equation:

$$\epsilon_{abs} = \frac{pulses\ recorded}{radiation\ emitted\ by\ the\ source} \tag{18}$$

Absolute efficiencies are influenced by detector properties and the distance from the source to the detector (counting geometry). The intrinsic efficiency is defined by equation **19**.

$$\epsilon_{int} = \frac{pulses\ recorded}{radiation\ quanta\ incident\ on\ the\ detector} \tag{19}$$

The intrinsic efficiencies are dependent on detector characteristics relevant to the type of radiation detected. During these experiments, absolute efficiency is more of interest since it gives the percentage of neutrons radiation possibly seen in the detector.

Chapter 3: Design

3.1 Project Goal

We begin with the assumption that there is an interest in designing a system to perform integral reactivity physics measurements in a fast reactor such as the MASURCA facility. It would be far more straightforward to perform experiments of this type in a fast reactor instead of trying to mock-up a fast spectrum in a driven thermal reactor. If we could perform the experiments directly in the fast reactor, any concerns about coupling between a fast or a thermal zone would be alleviated. We have chosen to study the open loop here because of the simpler infrastructure. This leads to lower cost and less space taken within the reactor area, and it has been demonstrated that the open loop and closed loop methods are equivalent in their uncertainties and only limited by the noise level (Baker, 2013). Based on these results and conclusion, an open loop method is recommended for any fast reactor.

Before beginning the discussion on design, it should be noted that there is no fundamental difference between a thermal reactor or a fast reactor regarding kinetics behavior. The difference is one of time (or frequency) response as noted in the previous discussion. Thus, feasibility becomes primarily a question of whether we can design a detection system and an associated acquisition system with adequate time response.

3.1.1.1 Limiting Factor

Several instruments are required to perform reactivity measurements. These instruments include a detector, amplifier, data acquisition system (DAQ), actuator, controller and recording software such as Labview™. A typical detector employed in this type of experiment is a gas filled detector (proportional counter, ionization chamber). The detector detects the power/ flux level and sends signals to an amplifier. Recording software will either register pulses or current as a function of time. On the mechanical side, an actuator is used to move a sample in and out of the core to perturb the reactor system. Position information (of the sample) must also be recorded. Demonstrating that an open loop technique works in a fast system, requires that one finds the limiting factor in the experiment in order to have a better understanding of the system that will be implemented in the reactor. Different pulse detectors were looked at and analyzed to become more familiar with the sensing side of the system. One microsecond was taken as the rise time to illustrate the limiting factor. The rise time put a limitation as how fast we can detect some sort of change. One microsecond implies a frequency response of 10^6Hz, half of that is $5x10^5$ Hz. Therefore, we should be able to see the frequency range of neutrons that are less than that using the transfer function that was generated for fast U-235 and Pu-239 fueled systems. The transfer functions are generated to show that the frequency spectrum for both type of systems differs only at the high frequencies. A Matlab^R code was developed utilizing the reactor parameters (betas, lamdas and generation time) for both U-235 and Pu-239 in a fast spectrum to show that the "knee" or break frequency was on the same order. Table **1** and **2** show the relevant values that went into calculation of the transfer functions (Hetrick, 1993) shown in Figure **8.** The break frequency on the fast transfer function for Pu-239 and U-235 is on the order of 10^3 Hz, which is much lower than our sensing ability (Figure **11**). This highlights the fact that the limiting factor will be on the perturbation side rather than on the sensing side.

Group No. (i)	Beta j	Lambda j	Beta (Delayed Neutron Fraction)	Neutron Generation life	Yield (Neutrons per Fission)
1	0.038	0.0127	0.0065	$5x10^{-7}$	0.000247
2	0.213	0.0317			0.0013845
3	0.188	0.115			0.001222
4	0.407	0.311			0.0026455
5	0.128	1.4			0.000832
6	0.026	3.87			0.000169

Table 1: Delayed Neutrons from U-235 Fast Fission

Group No. (i)	Beta j	Lambda j	Beta (Delayed Neutron Fraction)	Neutron Generation life	Yield (Neutrons per Fission)
1	0.038	0.0129	0.003	$5x10^{-7}$	0.000114
2	0.280	0.0311			0.00084
3	0.216	0.134			0.000648
4	0.328	0.331			0.000984
5	0.103	1.26			0.000309
6	0.035	3.21			0.000105

Table 2: Delayed Neutrons from Pu-239 Fast Fission

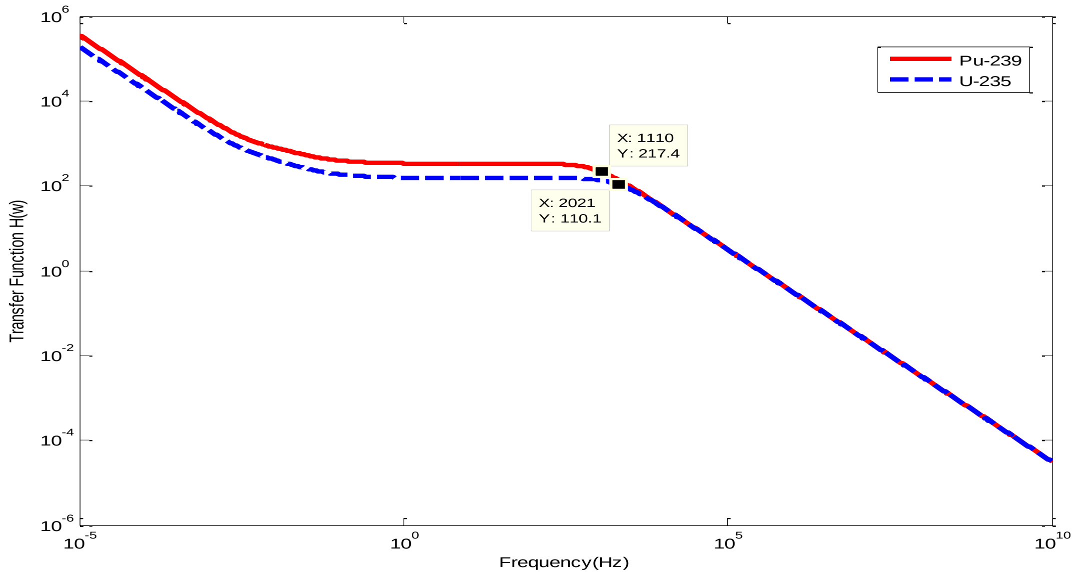

Figure 9: Uranium-235 & Pu-239 Transfer Function

Additionally, any oscillation method requires certain equipment such as a gas filled detector (ionization chamber, or proportional counter), motor control system, data acquisition system, preamplifier and amplifier. The mechanism of how fill detectors work is explained in the theory section under detectors. It needs to be noted that the detection system needed in a fast system will be different than in thermal system. Contrary to the use of BF_3 tubes for thermal neutrons, BF_3 tubes are rarely used to detect fast neutrons due to the low detection efficiency. Elastic scattering plays an important role in fast neutron detection. The fast incoming neutron, transfers some of its kinetic energy to the scattering nucleus and in general, the material used is hydrogen. Hydrogen is the most popular target nucleus used in fast neutron detection. The incident neutron colliding with hydrogen nucleus could transfer all its entire energy in a single collision contrary to heavy nuclei where only small fraction of the neutron energy can be transferred in collisions. Furthermore, other techniques have been used to detect fast neutrons not employing the scattering technique, but based on the Li-6 (n,α) and He-3 (n,p) reactions. Ionization chambers are widely used in the detection of neutrons in fast reactors such as MASURCA. Ionization chambers are coated with an isotope depending on what the experimenter wants to study or detect. Fission chambers are commonly used when gamma discrimination is required. The fission chambers are coated with fissile or fissionable material to detect incoming neutrons. It needs to be noted that the fission chambers are often employed for in-core detection to provide information on the spatial variation of the neutron flux. In-core detectors suffer from phenomena called burnup which is the decrease of the neutron sensitivity of about 50% after an exposure of a fluence of 1.71×10^{21} n/cm^2 (Knoll, 2010). A method that has shown to be effective in reducing the effects of burnup is to mix fertile and fissile material in the neutron-sensitive lining of the chamber (Knoll, 2010).The signal from the detector is sent to either a current amplifier or a pre-amplifier depending on the type of detector employed in the experiment. A pre-amplifier provides no pulse shaping but does terminate the detector capacitance quickly. Moreover, pre-amplifiers provide impedance matching to the detector and increase the magnitude of the signal so it is not lost in the transmission. Amplifiers are also employed in the experiment to shape the pulse, amplify the signal and provide noise filtering of the system. There are three modes of operation of radiation detection employed in the nuclear detection field. The three modes are: pulse mode, current mode, and mean square voltage mode (often referred by Campbelling mode). For the purpose of small sample oscillations, the pulse mode is almost always used. Pulse mode is employed when event rates are not high like in current and campbelling mode where event rates are so high and it becomes hard to discrimate between events. Operating in the pulse mode helps preserve information on the amplitude and timing of individual events, not possible in other modes (Knoll, 2010). Figure **9** below illustrates how the electronic system should be connected to perform oscillation experiments. A motor control system is utilized to control the motor in place for the mechanical or pneumatic system for sample oscillations. Moreover, the motor communicates with the software program to send position information. Software previously employed in the past by the oscillator group project are Labview™ and Pro-motion™ during their experiments on the AGN-201 reactor. The Pro-motion™ software has the ability to control the actuators and incorporate predetermined parameters in the motor controllers. The Labview™ types of software are employed in the experiment to record the power history data. For the experimental interest, it is recommended to start recording the power history after approximately 10 minutes to make sure that all the transients die off and the system is on a steady state condition. The frequency response of the signal is limited by the response speed of the DAQ, as well as the detector time response. Sometimes the signal has a logic pulse less than 5 V and the DAQ cannot record the signal. Therefore, it is recommended to use an Encoder box that raise the logic pulse up to 5 volts so the DAQ can record the voltage and send information to the computer program.

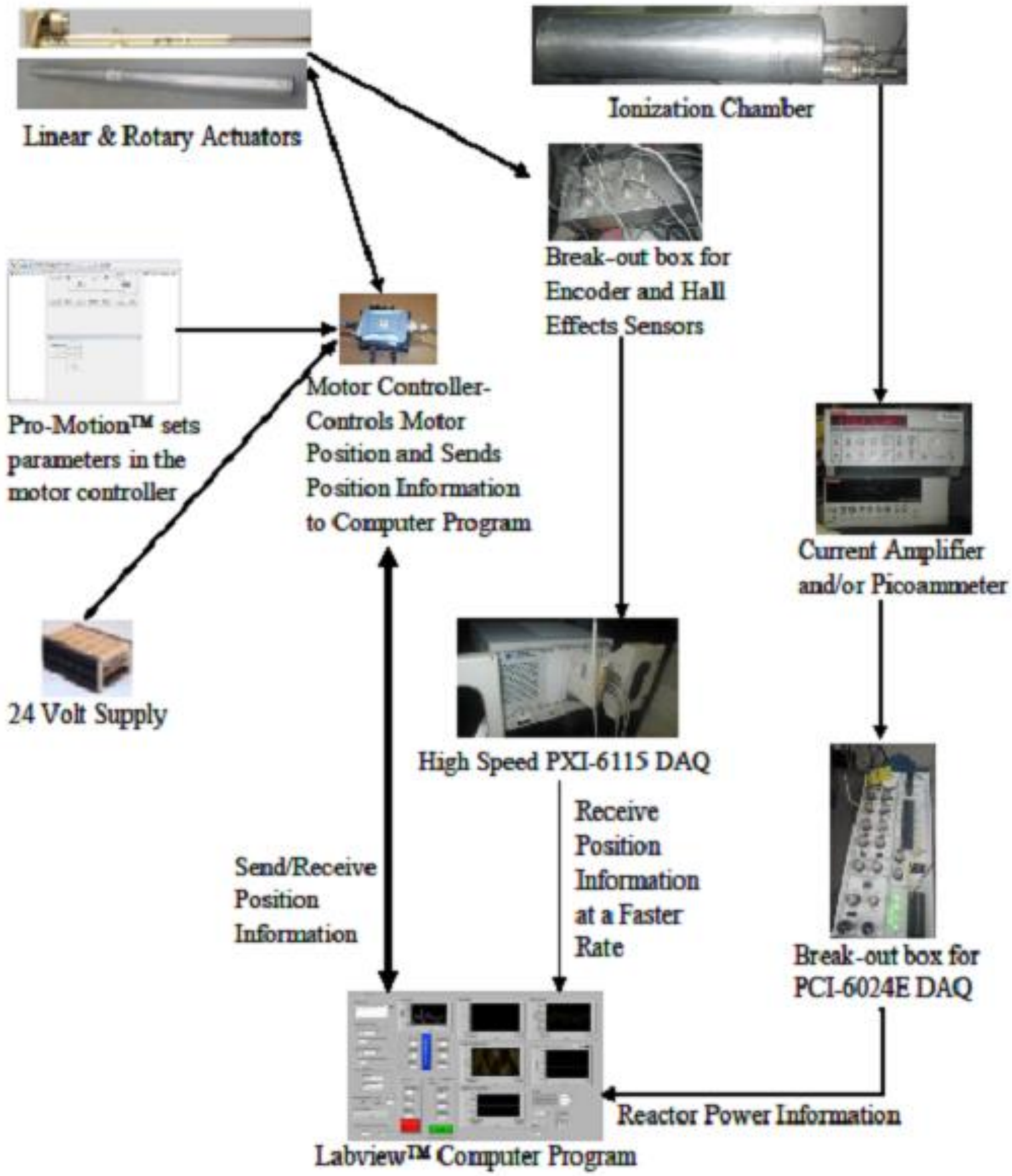

Figure 10: Control setup for the open loop

Below is a chart which shows that the detection side could sense the signal and the limiting factor is the mechanical/movement of the sample. The fastest motor possible that we found has a frequency of 10,890 Hz (Popular Science, 2009). The average frequency response from the detector and the amplifier for a fast reactor such as

MASURCA is 120 x 10^{-9} seconds (Assal et al, 2012). Clearly from the chart, the limiting factor will be how fast things can be perturbed or rotated (motor). As shown below, the frequency response of the detector modes and amplifier from MASURCA can be seen by the data acquisition which sample 100 million samples per second. This chart confirms that the limiting factor is on the mechanical side.

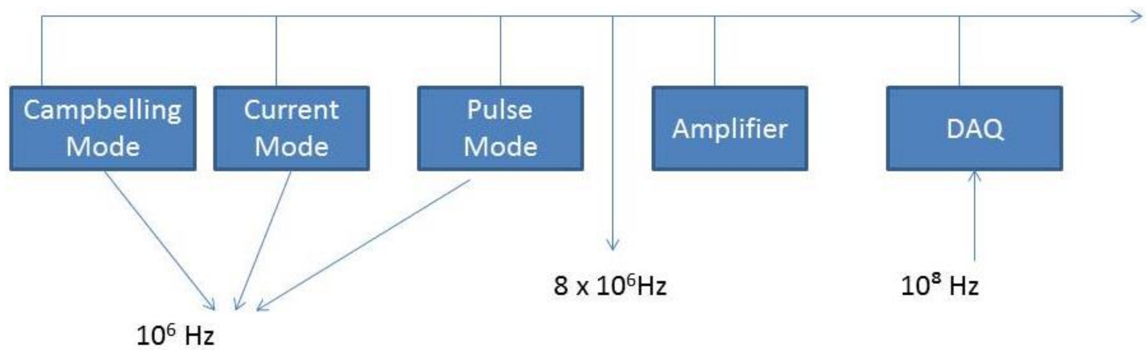

Figure 11: Frequency response of the electronic system

3.2 Project Constraints

Many possible systems can fulfill the goal of installing an oscillation experiment in a fast reactor. However, there are also numerous design constraints that need to be considered before a system could be effectively and wisely chosen. One constraint that is imposed on this problem is that there is only a very small amount of excess reactivity available. Thus, the solution cannot involve anything that will significantly lower the reactivity (e.g. air voids) and cause the reactor to become subcritical. Another constraint governing the scope of this problem is the amount of foundation space available near the core support assembly of the reactor core. The system must be able to fit in the area near the edge of the reactor core. An easily movable system versus a more or less permanent system is also another consideration guiding this problem. A movable system is needed so that fuel inspections or core changes, which are completed quite regularly, can be conducted with ease. A permanent system may hinder fuel inspections especially of those fuel assemblies near the edge of the core where the system is installed. As a result, the structure must be movable in order to reduce difficulties in fuel inspection or core changes. It would also be ideal to incorporate an assembly that can be easily maintained. This will reduce costs and likely improve production capabilities. Another major consideration that needs to be looked at in any design option is the safety of the system. Any precarious design option that might cause damage to the reactor core in some direct or indirect way must be eliminated. Considerations of safety include physical and nuclear stability. The system must be physically stable in that there is no way that it can wobble or fall causing damage to the reactor core. In addition, it must be stable in a nuclear sense in that it does not cause any significant transient behavior in the reactor core in terms of neutron flux and criticality. Moreover, possible systems will have to be analyzed to ensure that they do not cause an inadvertent supercritical state in the reactor or activate certain materials that may pose health risks. The last major limitation placed on the design of this system is that it should be financially feasible.

3.3 Design Possibilities and Description

Two choices of systems were analyzed: pneumatic systems and mechanical systems. Under each of these two systems, there are many different design possibilities.

3.3.1Pneumatic System (Rabbit)

Pneumatic systems are systems that are operated by gas (e.g., air) under high pressure. A rabbit design would work by creating a temporary vacuum inside of a tube which will cause the sample to be pushed down to the other end of the tube where the specimen can then be oscillated for a certain period of time. This tube would be completely free of water or liquid so the vacuum pressure created inside would push the sample from one end to another.

3.3.2 Mechanical System

1. Pulley System

A mechanical pulley system would work by attaching a sample holder to a mechanical pulley that can be remotely operated. In this way, the pulley would send a sample down into the core when specimen oscillation needs to be completed. Ideally, the mechanical pulley will be run by a motor outside of the reactor/coolant system to avoid design difficulties and increases in cost. Limit switches would need to be incorporated into this design to ensure that the samples reach the proper depth for oscillation. It should be noted that frequency repeatability and fidelity is a challenge with a pulley system.

2. Linear actuator

Linear actuators are mechanical designs used in a wide variety of applications in many industries. In this thesis, the linear actuator is chosen for fast reactor systems such as MASURCA .The linear actuator system consists of creating reactivity waveforms to perturb the reactor. The linear actuator is a mechanical system that is employed to produce a square reactivity waveform. The linear actuator oscillates the sample under study in a straight line through the core between two chosen positions points within reactor core. Figure **12** shows a picture of an ECT series linear actuator.

Figure 12: Linear actuator (Thompson, 2014)

A solid aluminum bar is attached to one end of the linear actuator so the sample can be moved in and out of the core. Driving the linear actuator is an electric motor that enables the actuator to move the samples inside the core of the reactor to the region of interest. Software such as Pro-motion™ or Lab-view™ can be used to control the motor controller, record the power history and position of the actuator. Prior to starting the experiment, one ought to wait for a certain amount of time to allow the system to stabilize to obtain a clean square reactivity waveform. Additionally, the inverse kinetics method requires a wait time before starting to save data to minimize transient effects.

3. Rotary actuator

The rotary actuator is another mechanical system used to perturb the reactor system periodically. In the rotary actuator the sample rotates near the core which yields a reactivity sinusoid delivered to the core. The power output of the system consists of the same sinusoid amplified by the average power level and magnitude of the transfer function. Additionally, the output sinusoid will be the input rotating frequency with a phase shift. When performing oscillations at frequencies larger than 1000 Hz, the rotary actuator is the desired option for determining the transfer function of a reactor. Moreover, the rotary actuator is used to perform small sample reactivity worths by attaching the sample under study inside a long cylindrical tube and supported inside a large aluminum tube that is meant to be used in the beam ports for measurement techniques. Figure **13** shows a picture of the rotary oscillator used in the AGN-201 experiments.

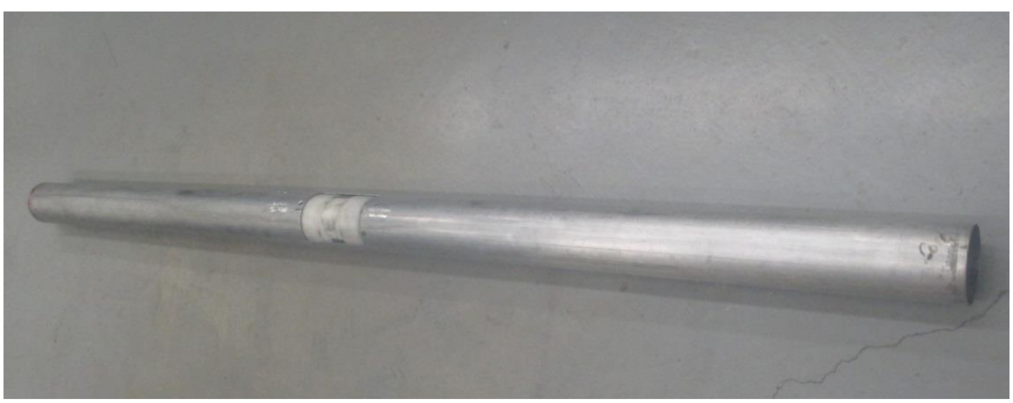

Figure 13: Rotary actuator

Prior to using the rotary actuator a neutron absorber sample such as boron is attached in order to create a clean looking sinusoid reactivity waveform. Additionally, wait time is required before starting the experiment to be as close to critical as possible to produce a stable waveform. Therefore, when saving data after a wait time, most of the transient will die off and the inverse kinetics would apply just as well.

3.4 Design Considerations and Choice

3.4.1 Rabbit System

The rabbit system was investigated extensively. For the particular rabbit system, two options are possible. The rabbit inlet could be placed in the reactor operator room, or it can be placed inside the reactor confinement room. In addition, safety mechanisms will be needed to prevent radiation contamination. Moreover, if the inlet is placed in the reactor operator room, shielding calculations will need to be completed to ensure that personnel are not getting exposed to significant amounts of radiation through the rabbit tube. If the inlet is placed inside the containment room, there will have to be a tight bend in the tube to facilitate the shielding that is on the platform. One concern of the rabbit system is safety. The rabbit system utilizes a vacuum which leads to large pressure differences. In addition, Argon-41 production in an air system becomes a major problem that must be handled with caution if the inlet is placed in the reactor operation room. Failure to monitor radiation release from the rabbit tube could lead to radiation contamination. However, this leads to additional design complexities along with increased costs. Another major drawback of this system is its installation cost. For the rabbit system to be implemented safely, it is estimated to cost around 4 to 5 million dollars. Some of this cost is due to sample handling difficulties that need to be overcome after sample oscillations. In addition, installing a system like this would affect the excess reactivity available which is needed to operate the reactor. If the whole system remains inside the confinement room, the bend in the tube that facilitates the platform shielding will make it complicated to complete fuel inspections. Related to this, there is very limited space available inside the containment room which is needed to hold all of the rabbit system equipment. If the whole rabbit system is moved for every fuel inspection, the operators run the risk of breaking the equipment. Figure **14** is a picture of the rabbit design generated on Autocad.

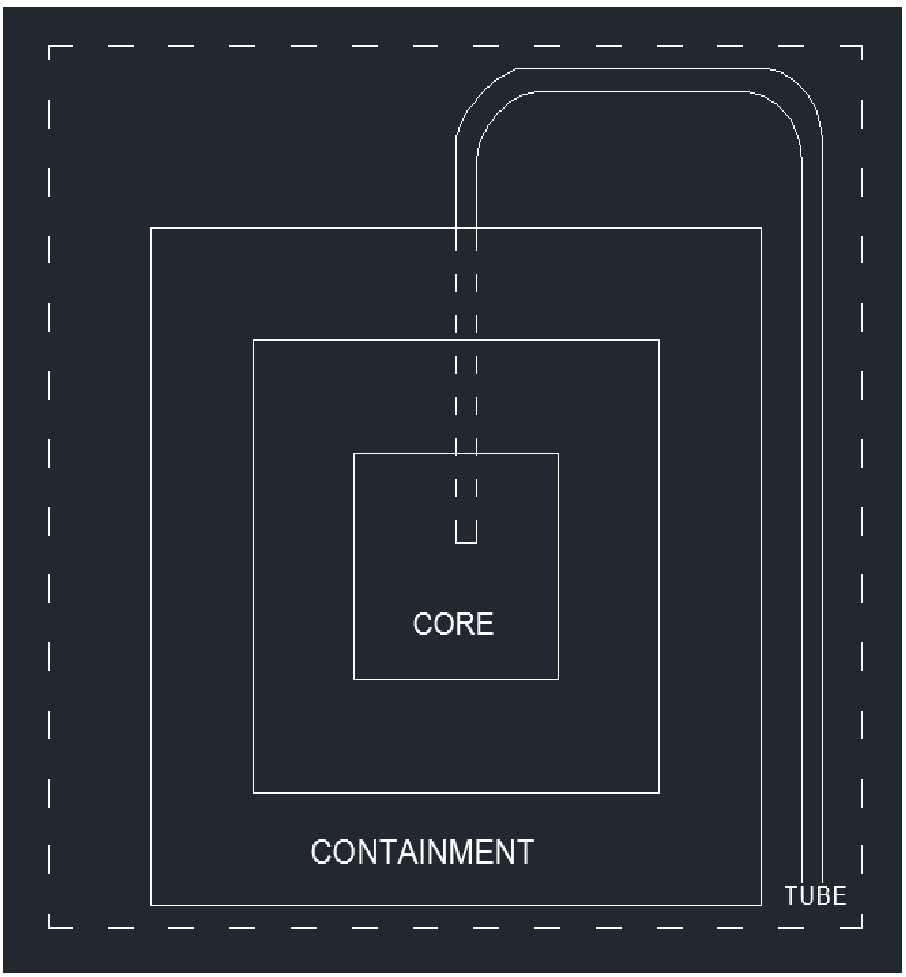

Figure 14: Rabbit system

3.5 Mechanical Pulley System

The advantage of this design is that it is simple and cheap to install. Furthermore, the installation of this assembly would not result in a significant reactivity loss, and the core is likely to remain stable during operation. Moreover, any mechanical failure of this system would need to be detected by the electronic control equipment which would increase the cost of the overall system. Another disadvantage of this system, it cannot be implemented in every fast reactor system due to the space availability. In a facility like MASURCA, the mechanical pulley system would be less effective since the glory hole is located on the side of the reactor and the mechanical pulley system works best when reaching from the top of the reactor tank such as the Neutron Radiography Reactor located at the Idaho National Laboratory.

3.5.1 Linear actuator

The advantage of this system is not only is it simple to install and affordable but also its convenience to meet the desired physics to determine reactivity using the inverse kinetics. Furthermore, the linear actuator is easily remotely adjusted to the desired range of frequency where the gain is reasonably high to perform the experiment. Additionally, linear actuators designed by Thompson offer multi-stop capabilities (+/- 0.013mm) and are very rigid yielding excellent position reproducibility. Moreover, the linear actuator requires less maintenance compared to pneumatic or hydraulics designs.

3.5.2 Rotary actuator

The advantage of the rotary actuator is its' capabilities to operate in a fast frequency range unlike other designs. However, to implement the rotary actuator in our AGN-201 reactor, the normal contents of the beam ports had to be removed for the rotary to be installed. The removing of the normal contents causes a large reactivity loss in core reactivity. This reactivity needs to be added back to perform the experiment. For example in the AGN 201 reactor, the reactivity loss is compensated by inserting a polyethylene tube inside the glory hole. This problem is facility dependent and may not be a problem in a facility with more excess reactivity available such as MASURCA. However, MASURCA does not have beam ports, so fuel would have to be removed. The problem with the rotary is that at low frequencies of few hertz, when performing sample oscillations to determine the transfer function, the voltage from the amplifier attenuates the signals to record the data (Baker, 2013).

Chapter 4: Decision Matrix

Shown next is a decision matrix which sums up all of the arguments presented previously. The main constraints of the project are shown here along with the possible systems. A value of zero indicates that the system does not meet the constraint at all. A value of one indicates that the system meets the constraint in a highly insufficient manner, which makes it a poor choice for that particular constraint. A value of two indicates that it only partially fulfills the constraint. A value of three indicates that it meets the constraint although it could be better. A value of four indicates that it meets the constraint almost perfectly. Last, a value of five indicates that it meets the constraint fully. Table **3** below summarizes the decision matrix.

	Rabbit	Pulley system	Linear Actuator	Rotary Actuator
Sample Oscillation (Hz)	4	3	4	5
Sampling time	5	5	5	5
Instrumentation Space	3	3	5	5
Movable System	3	3	5	4
Easy Maintenance	3	4	5	5
Ease of Analysis	4	4	4	3
Waveform Repeatability	4	3	5	5
Low Initial Cost	4	4	4	3
Sample Positioning	5	5	4	3
Total (out of 45)	**35**	**34**	**41**	**38**

Table 3: Decision Matrix of the Design Options

Overall, as can be seen from Table **3**, it appears that the linear actuator system will be the most effective option to use in fast reactor oscillator. The rotary actuator is also another good design; however, its initial cost, ease of analysis and sample positioning makes it less suitable compared to the linear actuator. The sampling frequency is one of the constraints that both linear and rotary actuator well satisfy. The sampling frequency is based on how often the experimenter wants to sample until the mechanically created waveform is seen. If the experimenter is studying high frequencies, the experimenter would need to sample faster and vice versa. For example a perturbation of the reactor with 100 Hz or 100 cycles per seconds corresponds to a period of 0.01 seconds. It would be up to the experimenter to decide how many samples would be needed within the waveform. If 50 data points is taken then the experimenter would need to sample every 0.0002 seconds which the period divided by the number of data points needed ($\frac{0.01}{50}$) . Therefore, the sampling frequency would be $\frac{1}{0.0002\ seconds}$ = 5000 Hz in order to get 50 samples per 0.01 seconds. It needs to be noted that the sampling frequency needs to be larger than the frequency at which the waveform is created to see what happens and collect data. Additionally, the sampling time is the time desired by the experimenter to sample until the collected data are satisfactory. Nowadays, abilities to record data far exceed how fast we actually rotate or do anything with it. An affordable DAQ could easily sample 100,000 samples per second. Another constraint analyzed is the ease of analysis of recorded data. The experimenter needs to be able to analyze the recorded data easily to determine the worth of the sample under study. When performing a rotary oscillator to perturb the reactor sinusoidally results in a sinusoid amplified by the reactor power and the magnitude of the transfer function. Determining reactivity, the experimenter needs the amplitude of the sinusoid and defining that amplitude is not as clear or straightforward as for square waves which have flat region with clear maxima and minima. Waveform repeatability is another important constraint used in the decision matrix. When performing these types of experiments, repeatability matters in terms of perturbing the reactor system. Linear and rotary actuators are mechanically stable and rigid system therefore they offer great stability and repeatability of waveforms to the experimenter. On the other hand, pulley system and rabbit offer less consistency in waveform repeatability. A pulley system uses rope or chain to drive the sample in and out of the core and it relies on the tension inside the rope/chain to keep the sample fixed in position. The rope or metal chains are not rigid bodies and cannot offer the same stability in repeatability of the sample as gears. Moreover, rabbit systems are little better than pulley system due the pressure difference created at the tube to send the sample in and out of the core. The problem that rises with the rabbit system, is when you use a different pressure difference, the same sample will not reach the same exact position as the pressure difference created previously. Additionally, bouncing of the sample can occur which would affect repeatability. The last constraint used in the decision matrix is sample positioning. Pulley, rabbit and linear all can oscillate in and out of the core whereas the rotary system can only oscillate within the reactor core in multiple regions. This makes it impossible for the experimenter to oscillate between the core and other regions such as the reflector region. It needs to be noted that the pulley and rabbit system can travel long distance within the core compared to linear actuator.

4.1 Design

Determining the reactivity of small worth samples would require the experimenter to have a linear actuator on the mechanical side to drive the sample in and out of the core. Preferably, one would use a linear actuator of the ECT series made by Thompson which gives the experimenter multi-stop capabilities (+/- 0.013mm) and the ability to work fast and accurately with an impressive range of precision. Additionally, a motor is required to control the actuator for the open loop system. Any DC brushless motor with a rated speed range of 2400 to 5500 RPM is recommended for this experiment. A motor control system is also needed to control the motor in place for the mechanical system for sample oscillations. An ION 3000 motor controller is recommended to be used due its' high performance motion control, network connectivity and power amplification. A computer program such as Pro-motion is recommended to be installed in the computer to preload parameters to the motor controller to avoid the experimenter to have to calibrate each time while performing the experiment. Moreover, the linear actuator needs to be connected to computer software such as Labview™ to send information of the position of the actuator to control the motor and record the power history. On the sensing side of this design system, a fission ionization chamber is recommended to be employed to detect the power/flux level and send signals to an amplifier to increase the magnitude of the output signal, provide pulse shaping and to supply a noise filtering for the system. Once the amplifier receives the signal, a Data Acquisition System (DAQ) is needed in order to sample the signal and convert the signal to digital values that can be processed, visualized by computer software, and to store measurement data. A recommended (DAQ) is PXI-6115 from National Instruments. This DAQ can sample up to 100 million samples per seconds which gives the experimenter the capability to detect the frequency response of other electronic components in the chain. A power supply is needed in this experiment to supply voltage to the motor controller and associated electrical components prior to starting the experiment. Table 4 below summarizes the components needed for this experiment.

Type Of Instruments	**Purpose**
Ionization fission chamber	To detect power & neutron density
Linear actuator	To drive the sample in and out of the core
Motor (DC brushless motor with speed range of 2400 to 5500 RPM)	To control the linear actuator
Motor Controller (ION 3000)	To control the motor
Pro-motion software	To preload parameters in motor controller
Current Amplifier and/or Preampfier and linear amplifier for pulse mode	To amplify the magnitude of the signal from the fission ionization chamber
Data Acquisition System (PXI-6115)	To sample the signal from the current amplifier and convert it to digital values
Computer Program (Labview)	To receive information of the position of the actuator to control the motor and record the power history.
Power supply	to supply voltage to the motor controller and associated electrical components

Table 4: Instruments and Purpose

Chapter 5: Conclusion

The open loop oscillation technique is a straight forward and simple method to determine small sample reactivity measurements in fast reactors. The sampling side showed that it far exceeds the capabilities of the mechanical perturbation of the reactor. Transfer functions for both U-235 and Pu-239 systems were generated using a Matlab code that illustrates that their break frequency is much smaller than our sensing ability. Therefore, the limiting factor is on the mechanical side rather than on the sensing side.

Two choices of systems were analyzed: pneumatic systems and mechanical systems. Under each of these two systems, there are many different design possibilities. Using a decision matrix, the linear actuator was shown to be the most effective mechanical design.

The open loop oscillation technique has been proven to reach the same level of uncertainty as the closed loop in thermal systems (Baker, 2013). This thesis demonstrated that the open loop technique is feasible in a fast reactor to perform small reactivity sample oscillations in which the reactivity in inferred from the power history using inverse kinetics.

Chapter 6: References

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Chapter 7: Appendices

7.1 Derivation of the Magnitude of Reactor Transfer Function

To begin the Laplace variable is replace with jω for frequency determination and the equation for the transfer function is simplified by combining the terms with β's and noting that β is the sum of the β_i's.

$$H(j\omega) = \frac{1}{j\omega\Lambda - \rho_0 + \sum_{i=1}^{6} \frac{j\omega\beta_i}{(\lambda_i + j\omega)}}$$

The next step is to take the magnitude squared of each side.

$$|H(\omega)|^2 = \frac{1}{\left|j\omega\Lambda - \rho_0 + \sum_{i=1}^{6} \frac{j\omega\beta_i}{(\lambda_i + j\omega)}\right|^2}$$

The summation term can then be multiplied by the complex conjugate to obtain a real valued denominator.

$$|H(\omega)|^2 = \frac{1}{\left|j\omega\Lambda - \rho_0 + \sum_{i=1}^{6} \frac{j\omega\beta_i}{(\lambda_i + j\omega)} \frac{(\lambda_i - j\omega)}{(\lambda_i - j\omega)}\right|^2}$$

$$|H(\omega)|^2 = \frac{1}{\left|j\omega\Lambda - \rho_0 + \sum_{i=1}^{6} \frac{\beta_i\omega^2 + j\beta_i\lambda_i\omega}{\left(\lambda_i{}^2 + \omega^2\right)}\right|^2}$$

The real and imaginary parts can then be grouped together.

$$|H(\omega)|^2 = \frac{1}{\left|\left(-\rho_0 + \omega \sum_{i=1}^{6} \frac{\beta_i\omega}{\left(\lambda_i{}^2 + \omega^2\right)}\right) + j\left(\omega\left(\Lambda + \sum_{i=1}^{6} \frac{\beta_i\lambda_i}{\left(\lambda_i{}^2 + \omega^2\right)}\right)\right)\right|^2}$$

It is convenient to define the following quantities for simplification.

$$A = \sum_{i=1}^{6} \frac{\beta_i \lambda_i}{({\lambda_i}^2 + \omega^2)}$$

$$B = \sum_{i=1}^{6} \frac{\beta_i \omega}{({\lambda_i}^2 + \omega^2)}$$

The magnitude squared for the denominator can be determined by taking the sum of squares for the real and imaginary parts.

$$|H(\omega)|^2 = \frac{1}{\big(\omega(\Lambda + A)\big)^2 + (\omega B - \rho_0)^2}$$

For the fitting algorithm ρ_0 was assumed to be zero and the equation simplifies to the final result for the magnitude of the reactor transfer function.

$$|H(\omega)| = \frac{1}{\sqrt{\omega^2((\Lambda + A)^2 + B^2)}}$$

7.2 Matlab Code for the transfer functions

```
function [ D phase] = TransferFunction( freq,rho,version)
%AGNTRANSFERFUNCTION Calculates the magnitude of the transfer function at a
%specified frequency


if isempty(version)
    disp('Warning you did not chose a version of parameters!!!')
   version = 1;
end


if version == 1
```

```
    % 1st Old version of parameters
    Beta=0.00745;
    % Duderstadt estimates
    Betaj=[0.038 0.213 0.188 0.407 0.128 0.026]*Beta;
    Lambdaj=[1/55.79, 1/22.78, 1/6.33, 1/2.18, 1/0.512, 1/0.08]*log(2);
    Gen_Life = 62.2E-6;

elseif version == 2
    % 2nd Old version of parameters
    Beta=0.00745;
    Betaj=[0.038 0.213 0.188 0.407 0.128 0.026]*Beta;
    Lambdaj=[1/55.72, 1/22.72, 1/6.22, 1/2.3, 1/0.610, 1/0.23]*log(2);
    Gen_Life = 62.2E-6;

elseif version == 3
    % Data from fit of Transfer Function 2013
    Lambdaj = [0.0135261,0.0296958,0.114594,0.299206,1.04434,5.43916];
    Betaj=[0.000283,0.001563,0.001835,0.002259,0.001183,0.000343];
    Beta = sum(Betaj);
    Gen_Life = 62.2E-6;

elseif version == 4
    % MCNP
    Beta=0.00745;
    Betaj = [0.03183 0.1657 0.1644 0.4575 0.1339 0.0464]*Beta;
    Lambdaj=[1/55.49365, 1/21.78519, 1/6.33547, 1/2.18564, 1/0.51208, 1/0.08016]*log(2);
    Gen_Life = 62.2E-6;
elseif version == 5
```

```
  % Very Old Parameters
  Betaj=[0.00024,0.00163, 0.00147, 0.00295, 0.00074, 0.00031];
  Lambdaj=[1/55.72, 1/22.72, 1/6.22, 1/2.3, 1/0.610, 1/0.23]*log(2);
  Beta=0.00734;
  Gen_Life = 7.499*10^(-5);

elseif version == 6
 %NO idea where this came from
  Betaj=[0.00028309,0.00156321,0.00183519,0.00225935,0.00118252,0.000343374];
  Lambdaj=[0.0135261,0.0296958,0.114594,0.299206,1.04434,5.43916];
  Gen_Life = 5.96103E-5;
elseif version == 7
  %this code is for U235 Transfer Function
  Beta = 0.0065;
   Betaj=[0.038,0.213,0.188,0.407,0.128,0.026]*Beta;
  Lambdaj=[0.0127,0.0317,0.115,0.311,1.4,3.87];
  Gen_Life = 5E-7;
 elseif version == 8
   %this code is for PU239 Transfer Function
    Beta = 0.003;
   Betaj=[0.038,0.280,0.216,0.328,0.103,0.035]*Beta;
  Lambdaj=[0.0129,0.0311,0.134,0.331,1.26,3.21];
  Gen_Life = 5E-7;
elseif version == 9
  %this code is for U233 Transfer Function
 Beta = 0.00267;
   Betaj=[.086,0.274,0.227,0.317,0.073,0.023]*Beta;
  Lambdaj=[0.0126,0.0334,0.131,0.302,1.27,3.13];
```

```
  Gen_Life = 5E-7;
end
  G = zeros(1,length(freq));
sums = 0;
for jj = 1:length(freq)
  for ii = 1:6
    sums = sums + Betaj(ii)/(Lambdaj(ii)+1i*2*pi*freq(jj));
  end
  G(jj) = 1/((1i*2*pi*freq(jj)*(Gen_Life+sums))-rho);
  sums = 0;
end
D = abs(G);
phase = angle(G);
end
```