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Oscillation Experiments in Sub-critical Systems in Support of Cross-section Measurements

by

David Coll Segarra

A dissertation

submitted in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy in Nuclear Science and Engineering

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Oscillation experiments in sub-critical systems in support of cross-section measurements

Dissertation abstract- Idaho State University (2021)

Pile oscillators have been used for many years to cause small perturbations in a nuclear reactor and study some properties associated with the reactor itself and with the sample being oscillated. A sample oscillating in and out of a reactor core can be used to determine its reactivity worth through inverse kinetics (open-loop technique as described in Imel, et al., and it has been shown that cross-sections can be also calculated from the reaction rates with low uncertainties using perturbation theory techniques. Thermal cross-sections have been the object of study for many years and are well verified, both experimentally and through modeling. However, fast fission cross-sections for the next generation of advanced reactors have much higher uncertainties, with little experimental data to verify the values. Decreasing these uncertainties can help reduce future design costs and provide larger margins of safety.

There has been interest in recent years to construct a large fast neutron sub-critical assembly to provide a platform for conducting measurements of various parameters including cross-sections. This assembly would be driven by a relatively modest neutron generator (e.g., D-T); the impetus is the belief that this could provide valuable data without having to construct an actual fast critical reactor with its substantial costs.

However, most (if not all) of the perturbation/oscillation measurements in the past have been performed in a critical system. We are trying to answer the following questions in this study: 1) can meaningful measurements be conducted at sub-critical, 2) if so down to what level of sub-criticality, and 3) down to what level of source strength? In this dissertation we describe our

experiments in our AGN-201 reactor at critical and sub-critical (to about k=0.96) and our experiments in our Sub-Critical Assembly (maximum of around k=0.90).

Key Words: Oscillations, reactivity, inverse kinetics, perturbation theory, subcritical, MCNP, ANSIN

1. Introduction

The pile oscillator method was first proposed by E.P. Wigner[4] in 1945 to study reactor properties, and in 1948 the first experiments using a pile oscillator were conducted by Hoover et al.[5]

In 1957 P. Schmid[6] in Switzerland measured reactivity experimentally with low uncertainty in the SAPHIR subcritical reactor by analyzing transient behavior.

In 1966 P. Skjerk Christensen[7] performed a few experiments with oscillators in a homogeneous reactor to study properties of different materials.

Pile oscillators are still in use today. In France this method has been used recently by Gruell et al.[8] and Geslot et al.[9] at the Minerve reactor in Cadarache to study properties of different materials by measuring reactivity changes around the samples being oscillated.

Previous work has been done using oscillators to obtain absorption cross-sections of materials. It usually involves complicated methods that compare changes in neutron population of an absorber being oscillated in a reactor with a sample of known cross-section also oscillating in the same reactor at the same time. The work proposed here offers a more direct way to obtain absorption cross-sections from experimental data.

The limit of detection is given by the reactor noise[10] as described by Cohn in 1960, for whom the fluctuations in neutron population can be treated as a "noise equivalent source".

2. Purpose

The purpose of this work is to demonstrate the use of the research reactor and the subcritical assembly to provide nuclear data (specifically reaction rates and cross-sections) for different materials at different levels of sub-criticality that can be applied in the future study of materials for advanced reactors. We are most interested in determining the lowest level of sub-criticality at which we can perform meaningful measurements. For that purpose, an oscillator is used to oscillate a small absorber in and out of the reactor or the SCA to create changes in neutron population that can be used to calculate changes in reactivity and, ultimately, cross-sections.

As mentioned previously the University of Tennessee is interested in this work, since they are in the process of constructing a large fast fission sub-critical assembly. Hence, this specific research project can be used as proof of concept for future studies for fast fission cross-sections data, reducing uncertainties and ultimately reducing reactor manufacturing costs.

This work has the potential of further collaborations with the University of Tennessee. It should also be noted that the oscillators can be used in our NE lab courses.

3. Theory

3.1 Inverse kinetics

Reactor kinetics (reactor dynamics) predicts the transient behavior of a nuclear reactor from its steady state. Transient behavior occurs in reactors if some properties in a steady-state reactor are modified[11]. These properties can be control rod motion, burnup, isotope production changes in temperature, environmental changes and accidents.

The point reactor kinetics equations are shown below (Equations 1 and 2). These equations can be combined and manipulated to get an expression for the changes in reactivity as a function of changes in neutron population over time. This leads to the inverse kinetics equation, and the process to obtain it is described below.

Starting with the point-kinetics equations:

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

$$\frac{dC_i}{dt} = -\lambda_i C_i(t_j) + \frac{\beta}{\Lambda} n(t) \qquad (Eq. 2)$$

$n(t) = reactor\ power\ at\ time\ t$

$\rho(t) = reactivity\ at\ time\ t$

$\beta = delayed\ neutron\ fraction$

$\Lambda = neutron\ generation\ time$

$\lambda_i = decay\ constant\ for\ precursor\ decay$

$C_i(t_j) = precursor\ density\ at\ time\ t$

$S = source\ strength$

Solving equation (1) for reactivity:

$$\rho(t) = \frac{dn(t)}{dt}\frac{\Lambda}{n(t)} - \frac{1}{n(t)}\sum_{i=1}^{6}\lambda_i C_i(t_j) + \beta \quad (Eq.3)$$

Using initial conditions in equation 2:

$$0 = -\lambda_i C_i(0) + \frac{\beta}{\Lambda}n_0 \quad (Eq.4)$$

$$C_i(0) = \frac{\beta}{\lambda_i \Lambda}n_0 \quad (Eq.5)$$

Multiplying both sides of equation (2) by $e^{\lambda_i t}$ after combining terms:

$$\frac{dC_i(t)}{dt} + \lambda_i C_i(t_j) = \frac{\beta}{\Lambda}n(t) \quad (Eq.6)$$

$$e^{\lambda_i t}\left(\frac{dC_i(t)}{dt} + \lambda_i C_i(t_j)\right) = e^{\lambda_i t}\frac{\beta}{\Lambda}n(t) \quad (Eq.7)$$

The first term of equation (7) can be rewritten as:

$$e^{\lambda_i t}\left(\frac{dC_i(t)}{dt} + \lambda_i C_i(t_j)\right) = \frac{d\left(C_i(t)e^{\lambda_i t}\right)}{dt} \quad (Eq.8)$$

Equation (7) can, then, be written as:

$$d\left(C_i(t)e^{\lambda_i t}\right) = e^{\lambda_i t}\frac{\beta}{\Lambda}n(t)dt \quad (Eq.9)$$

Now equation (9) can be integrated:

$$\int_0^t d\left(C_i(t)e^{\lambda_i t}\right) = \int_0^t e^{\lambda_i t'}\frac{\beta}{\Lambda}n(t')dt' \qquad (Eq.10)$$

Integrating the left side and moving the constants out of the integral in the right side:

$$C_i(t)e^{\lambda_i t} - C_i(0) = \frac{\beta}{\Lambda}\int_0^t e^{\lambda_i t'}n(t')dt' \qquad (Eq.11)$$

Replacing $C_i(0)$ calculated in equation (5):

$$C_i(t)e^{\lambda_i t} = \frac{\beta}{\lambda_i \Lambda}n_0 + \frac{\beta}{\Lambda}\int_0^t e^{\lambda_i t'}n(t')dt' \qquad (Eq.12)$$

Solving for $C_i(t)$:

$$C_i(t) = \frac{\beta}{\lambda_i \Lambda}n_0 e^{-\lambda_i t} + \frac{\beta}{\Lambda}\int_0^t e^{\lambda_i (t'-t)}n(t')dt' \qquad (Eq.13)$$

Now equation (13) can be used in equation (3) to give:

$$\rho(t) = \frac{dn(t)}{dt}\frac{\Lambda}{n(t)} - \frac{1}{n(t)}\sum_{i=1}^{6}\lambda_i\frac{\beta}{\lambda_i\Lambda}n_0 e^{-\lambda_i t} + \frac{\beta}{\Lambda}\int_0^t e^{\lambda_i (t'-t)}n(t')dt' + \beta \quad (Eq.14)$$

Finally, equation (14) becomes the inverse kinetics equation:

$$\rho(t) = \frac{dn(t)}{dt}\frac{\Lambda}{n(t)} - \frac{1}{n(t)}\sum_{i=1}^{6}\beta_i\left[n_0 e^{-\lambda_i t} + \lambda_i\int_0^t e^{-\lambda_i (t'-t)}n(t')dt'\right] + \beta \quad (Eq.15)$$

For this work, readings from the detectors were discretized, so the inverse kinetics equation had to be discretized to be used with the available data:

The differential term in equation 15 becomes:

$$\frac{dn(t)}{dt} = \frac{3n(t) - 4n(t-1) + n(t-2)}{2\Delta t} \qquad (Eq.16)$$

While the integral term can be discretized in the following way:

$$\int_0^t e^{-\lambda_i(t'-t)} n(t')dt' = H(t) = H(t-1)e^{-\lambda_i \Delta t} + \frac{n(t) + n(t-1)e^{-\lambda_i \Delta t}}{2}\Delta t \qquad (Eq.17)$$

Giving the following version of equation (15):

$$\rho(t) = \frac{3n(t) - 4n(t-1) + n(t-2)}{2\Delta t}\frac{\Lambda}{n(t)} - \frac{1}{n(t)}\sum_{i=1}^{6}\beta_i\left[n_0 e^{-\lambda_i t} + \lambda_i\right] H_i(t) + \beta \qquad (Eq.18)$$

3.2 The oscillator technique

Pile oscillators have been used for many years to cause small changes in reactivity in a reactor core. In 1963 Bennett and Long in their paper "Precision Limitations in the Measurement of Small Reactivity Changes"[12] showed that using an oscillator as a way of producing small reactivity changes reduces the uncertainty in reactivity calculations down to the pile noise. They also showed that the transfer function associated with an open loop has a gain equal to the inverse of the frequency at low frequencies at critical.

Pile noise was already mentioned before (Cohn 1960)[10]. It was found that the uncertainty associated with reactivity measurements can be calculated with the following equation:

$$\sigma(t) = \frac{5.1 * 10^{-6}}{\sqrt{Wt}}$$

Where $\sigma(t)$ is the standard deviation in reactivity at time t, t is the time in seconds and W is the average reactor power in watts.

From this equation one can see that increasing either power in the reactor or time of measurements the uncertainty in reactivity calculations can be reduced.

3.3 Perturbation theory

Perturbation theory is used to calculate the effects on reactivity caused by the introduction of a small sample in a reactor. Research reactors are a good example; researchers performing experiments in the reactor usually introduce detectors or other pieces of material that cause small changes in the flux around the perturbed place.

For one-group theory the adjoint flux (ϕ^+) and the forward flux (ϕ)are equal, and so we can write:

$$\Delta\rho = \frac{\int_V \left[\left(\nu\delta\Sigma_f - \delta\Sigma_a\right)\phi^2 - \delta D(\nabla\phi)^2\right]dV}{\nu\int_V \Sigma_f\,\phi^2 dV} \qquad (Eq.19)$$

If the change is in absorption only:

$$\Delta\rho = \frac{\int_V [(-\delta\Sigma_a)\phi^2]dV}{\nu\int_V \Sigma_f\,\phi^2 dV} = -\frac{\delta\Sigma_a\int_V [\phi^2]dV}{\nu\int_V \Sigma_f\,\phi^2 dV} \qquad (Eq.20)$$

Solving for the absorption cross-section:

$$\delta\Sigma_a = -\frac{\Delta\rho\nu\int_V \Sigma_f\,\phi^2 dV}{\int_V [\phi^2]dV} \qquad (Eq.21)$$

But $\delta\Sigma_a$ is the absorption cross-section of the sample, Σ_{ap}, and the integral in the denominator is over the volume of the perturbation or sample

$$\Sigma_{ap} = -\frac{\Delta\rho\nu\int_V \Sigma_f\,\phi^2 dV}{\int_{Vp}[\phi^2]dV_p} \qquad (Eq.22)$$

If the perturbation is very small the following approximation can be used:

$$\delta\Sigma_{\mathrm{a}} = \Sigma_{\mathrm{ap}} V_P \delta(\mathrm{r} - \mathrm{r}_0) \qquad (Eq.23)$$

$$\Delta\rho = -\frac{\Sigma_{ap} V_p \int_{Vp} [\phi^2] \delta(\mathrm{r} - \mathrm{r}_0) dV}{\nu \int_V \Sigma_f \phi^2 dV} \quad (Eq.24)$$

$$\Delta\rho = -\frac{\Sigma_{ap} V_p \phi^2(r_0)}{\nu \int_V \Sigma_f \phi^2 dV} \qquad (Eq.25)$$

Solving eq. 14 for the cross-section of the perturbation:

$$\Sigma_{ap} = -\frac{\Delta\rho\nu \int_V \Sigma_f \phi^2 dV}{V_p \phi^2(r_0)} \quad (Eq.26)$$

3.4 Previous work at ISU

Previous work has been done at Idaho State University over the past few years. The open loop oscillator was a senior design project from 2009. Other features and improvements have been added over the years by other senior design project teams and graduate students performing research using the equipment.

In 2013 Ben Baker demonstrated in his dissertation the equivalence between open and closed loop to measure reactivities on the AGN-201 reactor. The work was published in 2015[1].

In 2019 Sultan Sharif worked with the oscillator open loop technique to determine the reactivity worth of an oscillating neutron source in the AGN-201 reactor[3]. Two sources were analyzed, a radium-beryllium source (RaBe) and a californium 252 source (Cf-252). The change in reactivity caused by the addition of the RaBe source in the reactor core was calculated by difference in control rod height and was determined to be -8.7 cents. To analyze the Cf-252 source, perturbation theory was used. The reactivity change caused by this source was determined to be -9.92 cents.

4. Materials and methods

4.1 materials

4.1.1 AGN-201 reactor

The Aerojet General Nucleonics 201 (AGN-201) reactor at Idaho State University (fig. 1) is a 5W thermal reactor (zero electrical power) that is used for research and training. The core consists of a mix of UO_2 powder enriched at <20% and polyethylene. It has four control rods that are used to control the neutron population in the core. The control rods, unlike most commercial reactors, contain fuel.

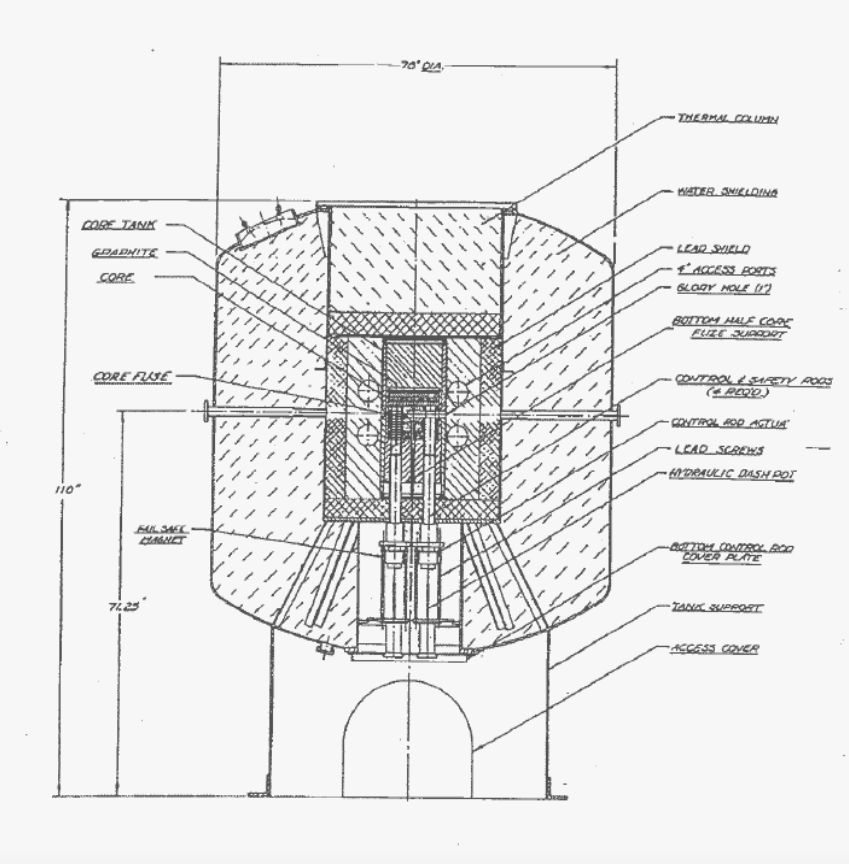

Figure 1 Schematics of the ISU AGN-201 reactor

There is an aluminum tube that runs from the outside of the system (both sides) and goes through the center of the core (glory hole). It also has four beam ports that can be used to introduce experiments in the system. However, these beam ports do not go through the core (see fig. 1 above)

The personnel required to operate the reactor include a reactor operator (RO) and a certified observer (CO) on site, and a senior reactor operator (SRO) on call.

There are three detectors, two BF_3 filled ion chambers and one BF_3 filled proportional counter. For this research work, data was collected from one of the ion chambers, and more specifically, channel 3 (see fig. 2 below)

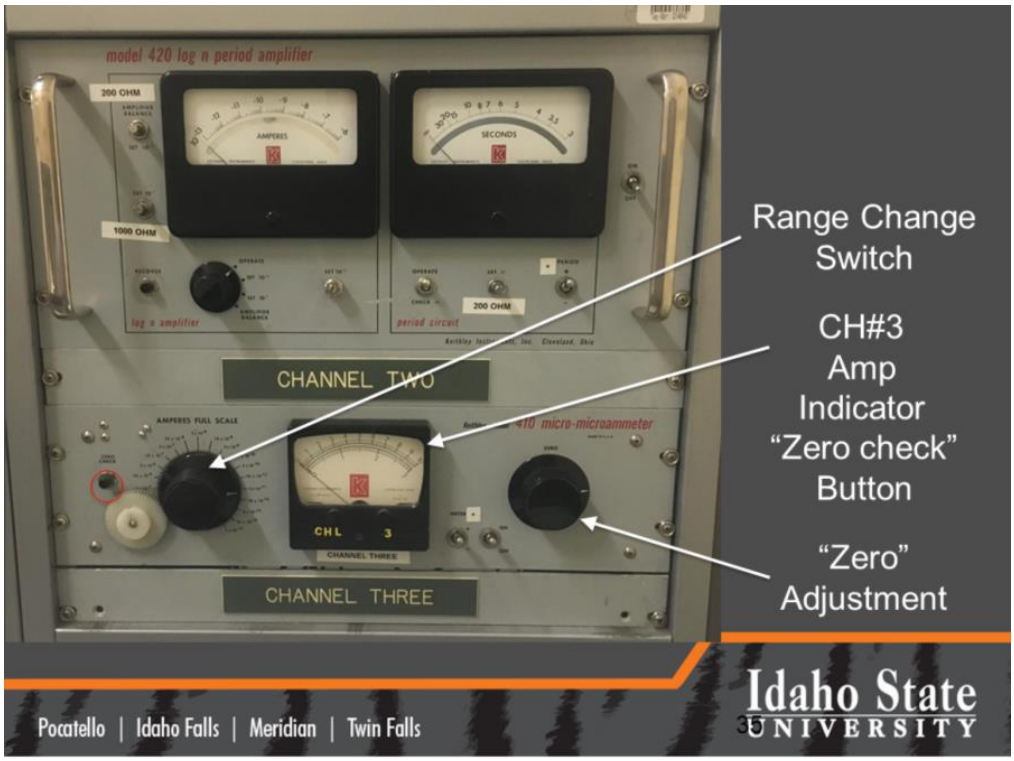

Figure 2. Channel #3 in the reactor console

Channel 3 has a range change switch that alternates ranges between 0-3 and 0-10 for fine adjustment of the desired power. The output of the detector goes to a chart recorder that stores the data and shows the trending on a screen (Fig. 3 below)

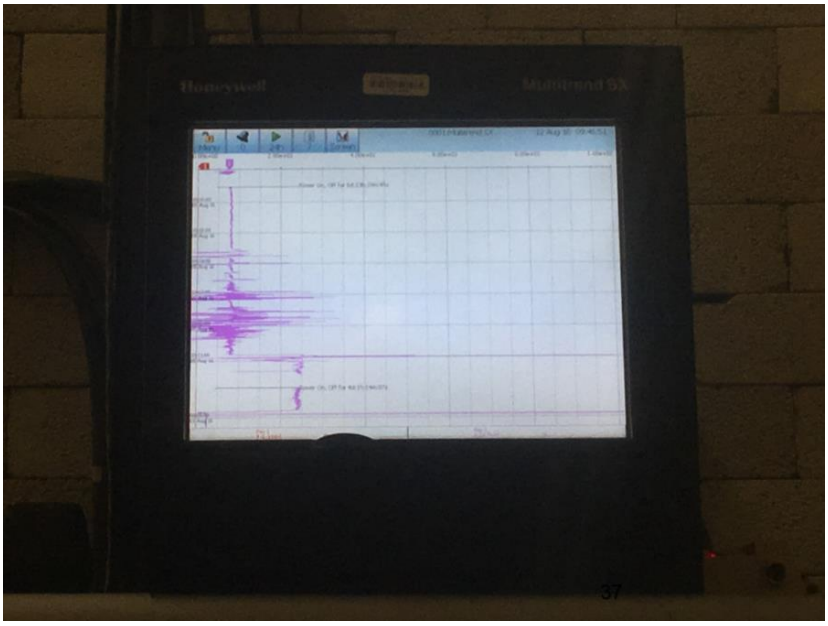

Figure 3. Chart recorder screen on the reactor console

Data from the chart recorder is discretized, one measurement is taken every 20 ms. The range is divided in 0-100% of power at that scale, no matter if it is the 0-3 or the 0-10 range.

4.1.2 SCA assembly

The subcritical assembly (SCA) at the Idaho State University (fig. 4) is a low enriched uranium assembly that uses water as a reflector. It has a total 150 fuel plates available that yield a subcriticality level of about k=0.86.

Figure 4 The ISU subcritical assembly (SCA)

The fuel plates are a uranium and aluminum mixture, with the uranium enriched to 19.8 wt%.

On the bottom of the assembly there is a thermal column composed of 95 graphite blocks.

There are three He-3 detectors, detectors one and two located in the opposite sides outside of the tank, a few inches from the surface, and detector 3 located in the thermal column.

Figure 5 Instrumentation electronics of the SCA

4.1.3 Oscillator

The oscillator consists of a linear actuator driven by a motor with an ION 500 motor drive controller. The controller is connected to the computer through a USB port and the system is run with the Pro-Motion software.

Figure 6 The oscillator system. Motor, actuator and controller

4.1.4 Data analysis

The main data source for this work was the AGN-201 chart recorder in console. The data provided was then analyzed for inverse kinetics with MATLAB. MATLAB would also analyze the peaks, find the mean of the peaks and provide standard deviations (figure 7)

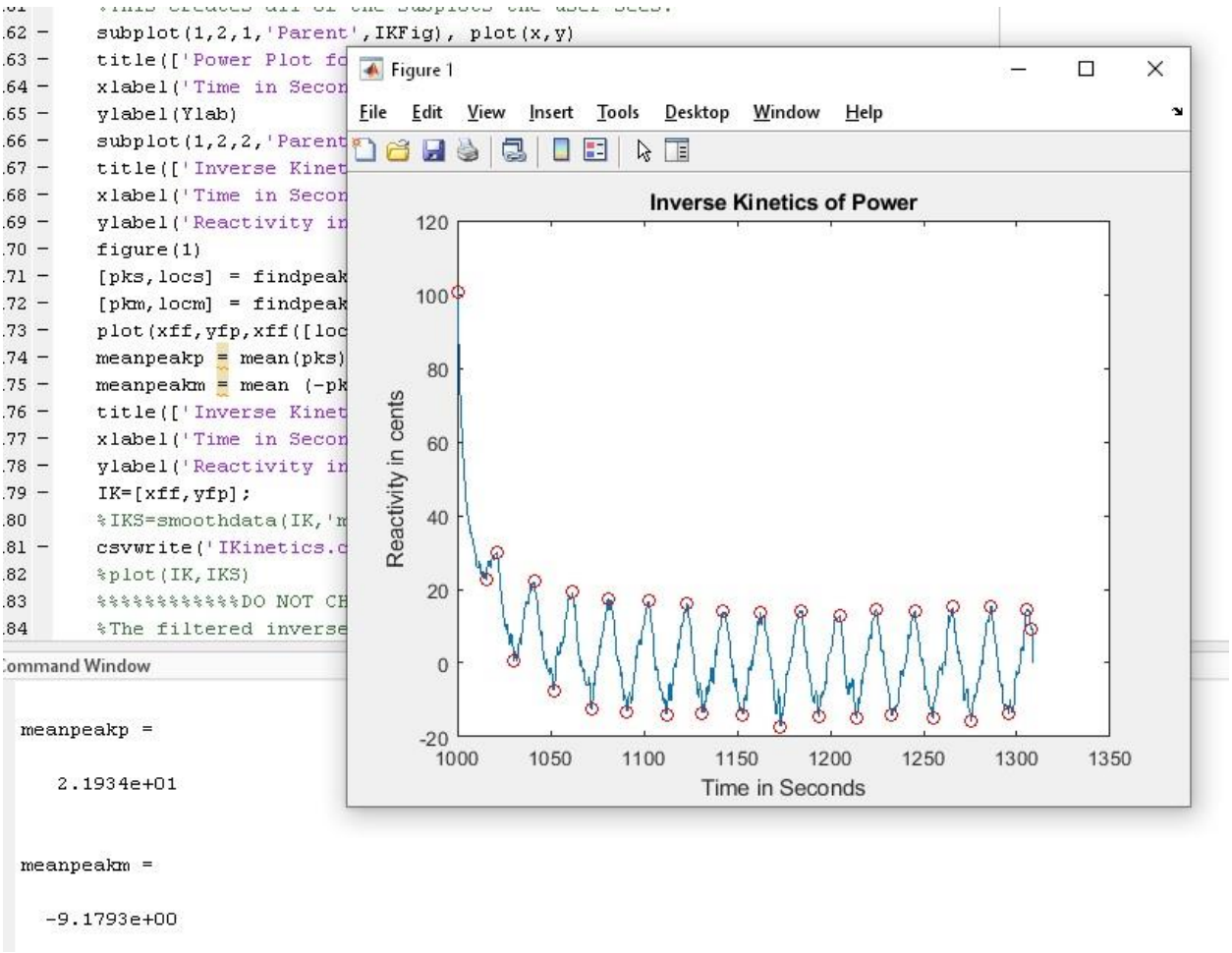

Figure 7 MATLAB sample graph. Finds peaks and calculates mean and standard deviation

Mathematica was used to calculate cross-sections using one group perturbation theory.

LabView was used to read data from the LND detector.

4.1.5 Detector

The detector used was an LND (LND Inc., Oceanside, NY) model 50329 non-compensated (does not discriminate gamma radiation) boron lined neutron detector. These detectors work by creating a current signal caused by the absorption of neutrons by the boron-10 isotope, according to the following nuclear reaction:

$$^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He \qquad (Eq. 27)$$

This model comes standard with an internal Am-241 source, which provides a steady current of around 10^{-11} A. This specific detector did not have the mentioned internal source.

Figure 8 LND detector

The detector had two connectors, one for high voltage (HV) and one for signal. The high voltage connector was connected to a HV power supply and the signal was sent to a picoammeter

(figure 9). The output from the picoammeter was sent to a computer and analyzed with LabView.

Figure 9 Picoammeter model 6485 from Keithley

The detector was initially tested on a table by using the CF-252 source in close contact. It was observed that the signal was not strong enough, so paraffin blocks were used around the detector. With these blocks a weak signal of around 2 pA was observed in the picoammeter (figure 10 below).

Figure 10 Detector setup with paraffin blocks

The typical signal observed in the computer for this specific setup was:

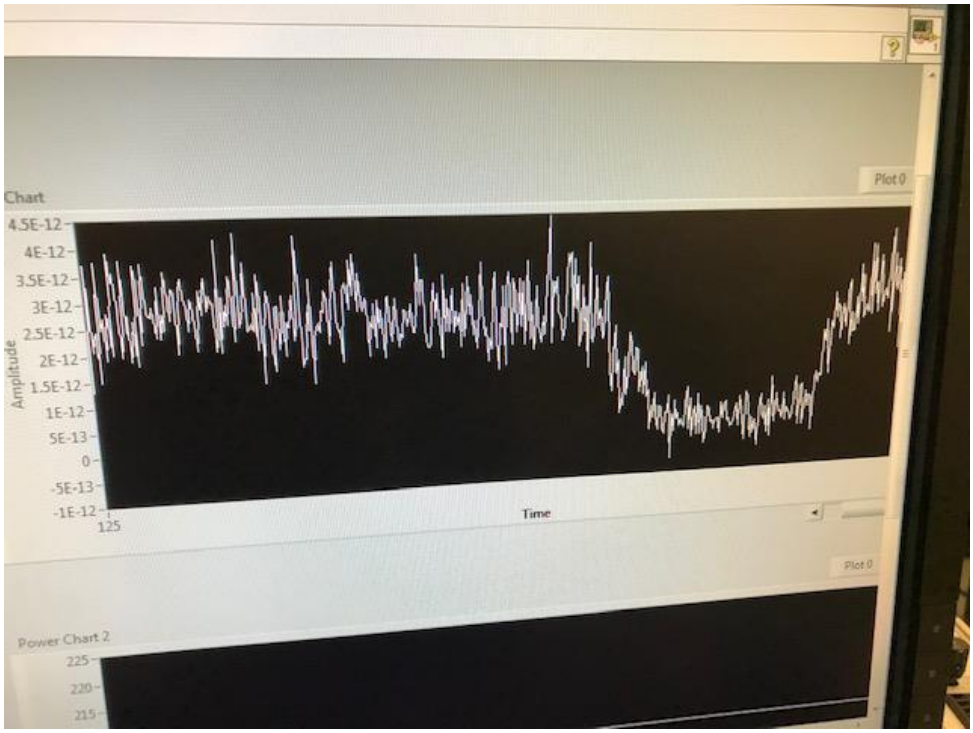

Figure 11 Signal from the LND detector. The abscissa is the time in seconds and the ordinate represents the magnitude of the current of the detector

4.2 Methods

4.2.1 AGN experiments

Several experiments were performed on different dates. The starting point was to corroborate recent experiment results in Sultan Sharif, M.S. master's thesis[3]. These initial experiments used the Cf-252 source as the oscillating sample.

The next series of experiments focused on oscillating absorbers with the reactor operating at critical. The absorbers were chosen based on availability in the lab. The first choice was cadmium since it has a large absorption cross-section and it was expected to give good results even with low neutron population. The second absorber was stainless steel since it is the cladding material of the Cf-252 source. The other two absorbers used were indium and gold, both of well-known cross-sections.

The last set of experiments were a repetition of the absorber oscillations but with the reactor subcritical.

Experimental procedure

The experimental procedure followed in all experiments was as follows:

The reactor operator would operate the reactor following the usual startup procedure. All initial safety checks, channel checks, interlock checks and rod drop test were performed, and then the reactor would be brought to critical at 10 mW. From there some modifications in power or operation mode could be added to the normal operation.

Some experiments were performed with the reactor critical, some at the beginning of operations without any rod inserted, some with two safety rods only inserted, and some with one or both control rods partially inserted. At the end of the experiments the reactor operator would follow the standard reactor shutdown procedure and the experiment materials were completely removed from the reactor system.

Data was extracted from the chart recorder and saved in a pen drive for future analysis.

4.2.1.1 Experiment #1 11/11/2019

Experiment 1 was a continuation of Sultan Sharif's work. The purpose was to corroborate his work with the Cf-252 source and to become familiar with the procedure and materials available.

The first part of experiment 1 consisted of oscillations of the Cf-252 source in the reactor without any rods in, which is equivalent to the lowest subcriticality level available of about k=0.96. The reactor console power was turned on and without inserting any rods the Cf-252 source was oscillated at 1 inch/s, 2 inches/s and 0.5 inches/s (about 0.0625, 0.125 and 0.3125 Hz) for about five minutes each. Data was collected from the chart recorder and analyzed. The first step was to read the file to see the full graph from the full experiment.

Selected portions from the data file were then analyzed using an inverse kinetics code (see Appendix A). Although this initial experiment has all the data analyzed in one single shot (figure 12), in latter experiments the curve was cut into portions to separate each oscillator speed.

The second part of experiment 1 consisted of oscillating the same Cf-252 source but this time with the two safety rods inserted, which would be the equivalent of an intermediate level of subcriticality of about k=0.98 (figure 13)

From the graphs below the reactivity change was found to be:

$$\rho_{no\ rods} = 10.25 \pm 0.31\ \ cents$$

$$\rho_{two\ SR} = \ 9.99 \pm 0.99\ \ cents$$

These numbers are consistent with Sultan Sharif's results of $\rho_{critical} = \ 9.92\ \ cents$

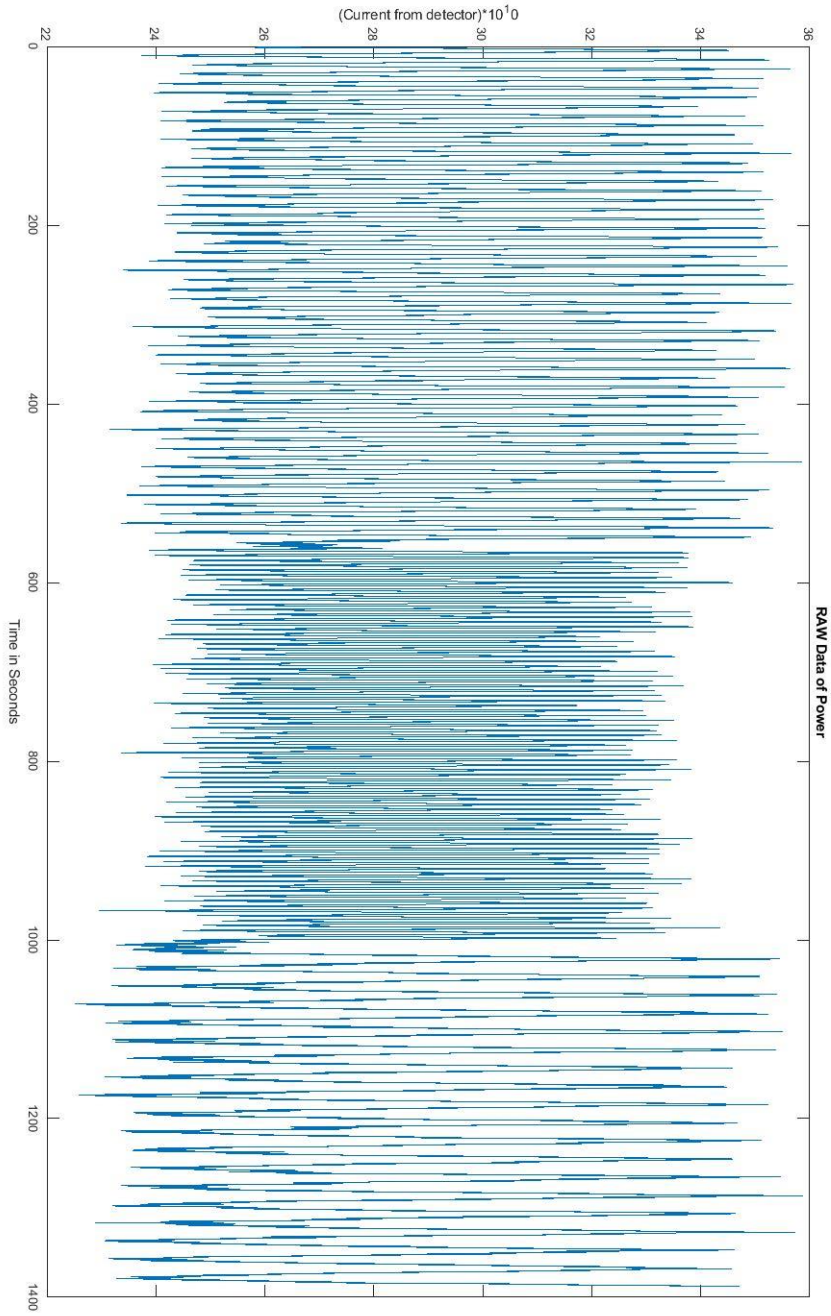

Figure 12 Oscillations of Cf-252 source with no rods inserted

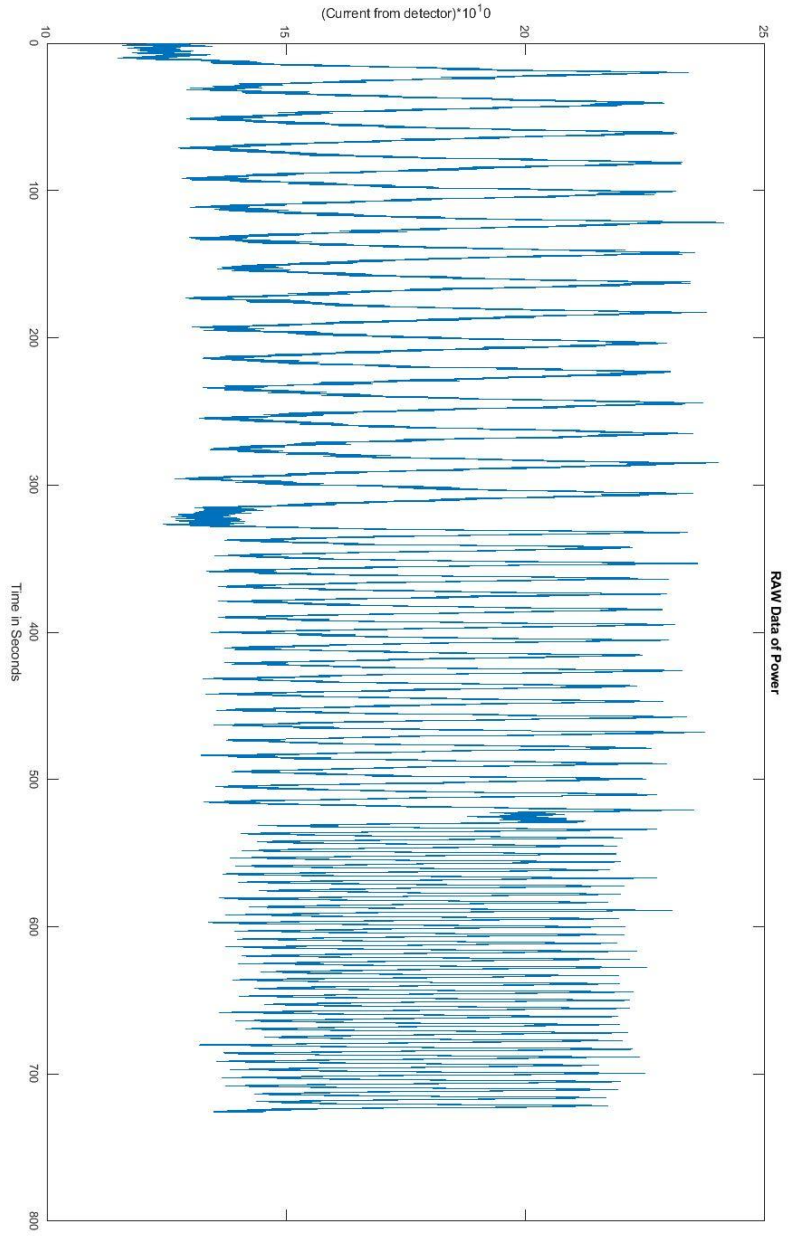

Figure 13 Oscillations of Cf-252 source with two safety rods inserted

4.2.1.2 Experiment #2 11/15/2019

Experiment 2 was a repetition of Experiment 1 but with a more accurate position of the oscillator to stop exactly at the center of the core at the end of the oscillation.

Part one was the oscillations with no control rods inserted (fig. 14) and part two consisted of the oscillations with the two safety rods inserted (fig. 15).

One can tell from the power graph that the range of the oscillations is about three times the range from Experiment 1. This implied that the range used was the 0-3 range in the console. The data from the chart recorder converts the 0-3 scale in the console into 0-100% of the range, so the results obtained in this experiment were divided by 3 since the scale used was 0-3.

The overall reactivity change obtained, as a full peak to peak distance was:

$$\rho_{no\ rods} = 21.22 \pm 2.60\ \ cents$$

$$\rho_{two\ SR} = \ 15.69 \pm 2.63\ \ cents$$

These are quite different from Experiment 1. The inconsistency was attributed to the change in the range of motion of the oscillator. These initial experiments used the full length of the oscillator to move the samples in and out of the core. The sample would start all the way out and travel past the edge of the core in the first setup.

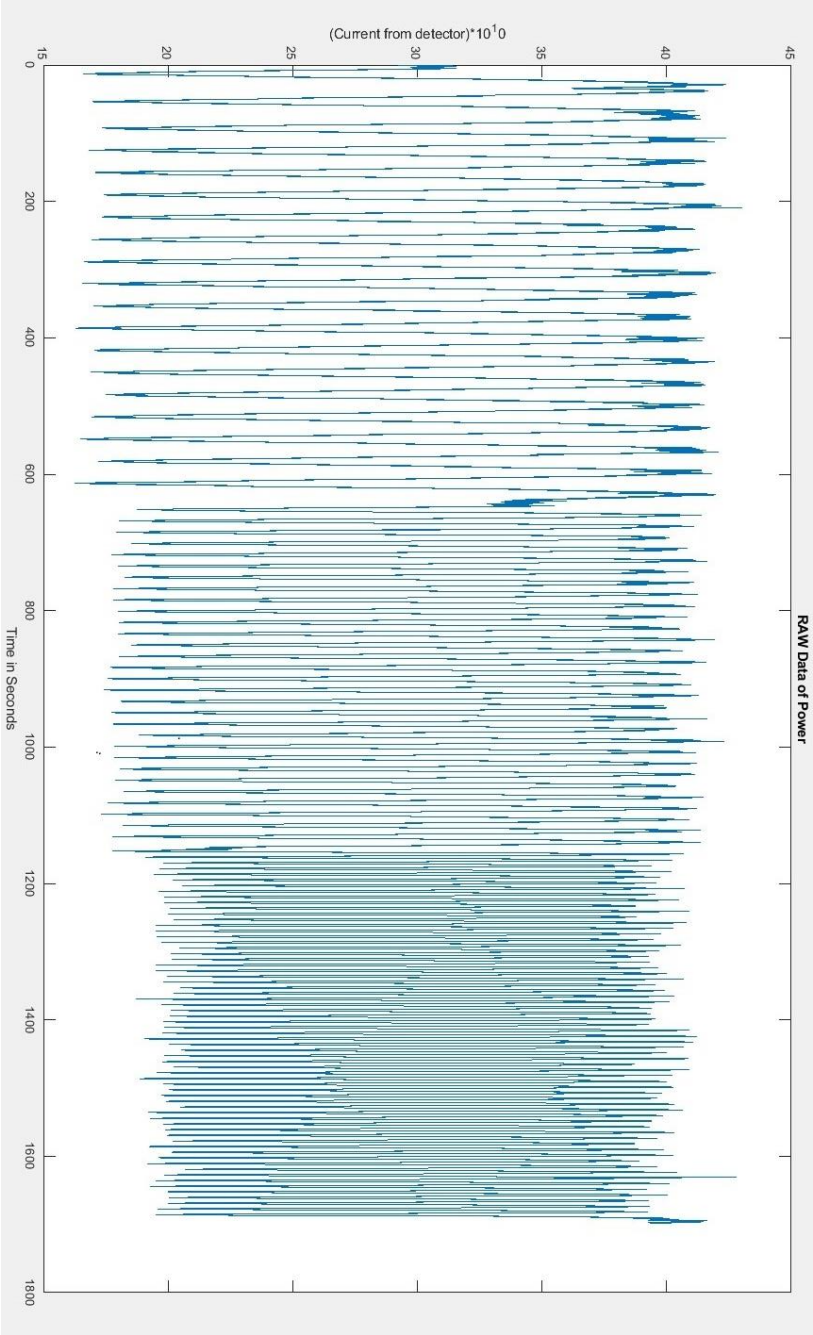

Figure 14 No control rods. Oscillations at 0.5, 1.0 and 2.0 inches/s

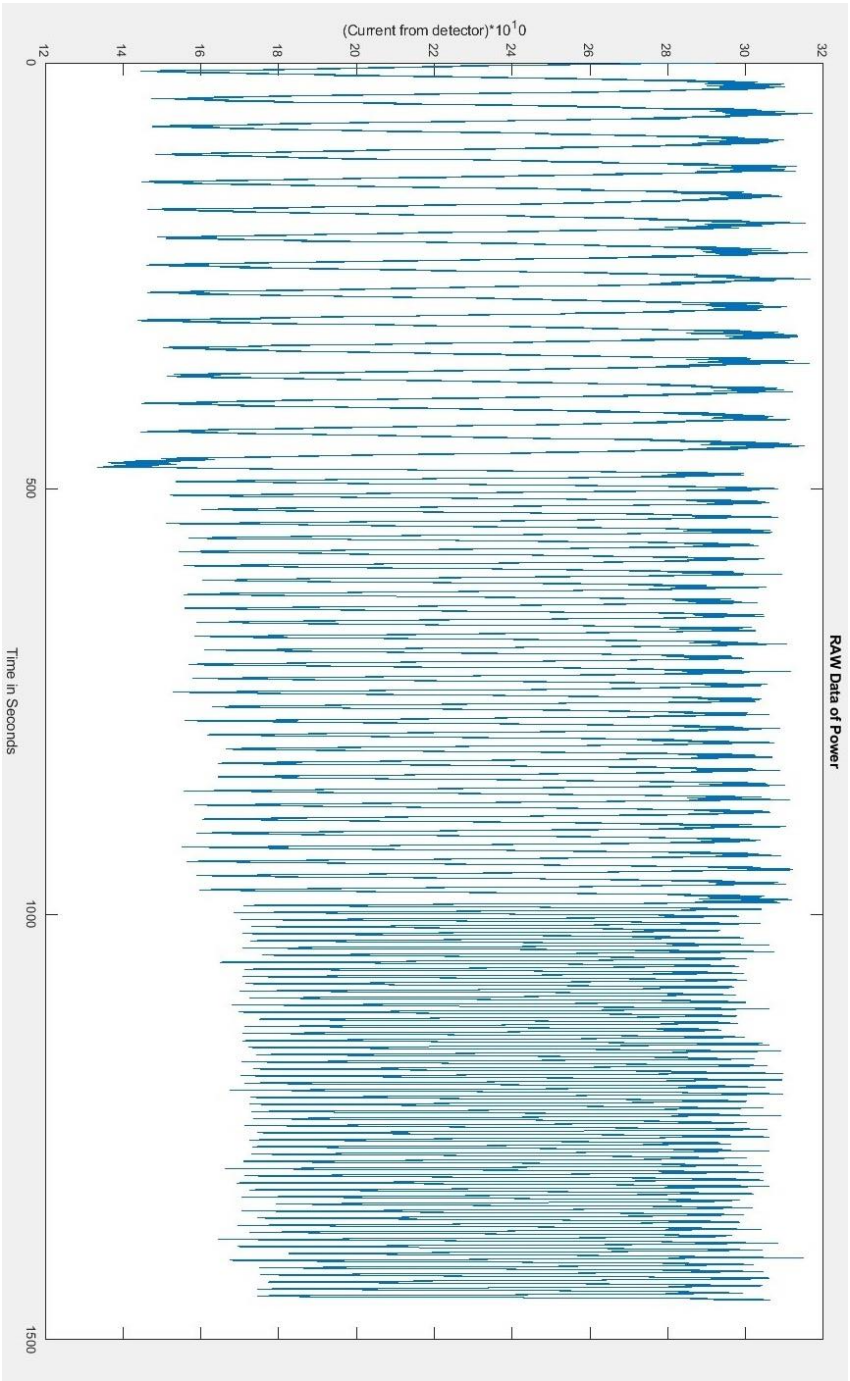

Figure 15 Two safety rods. Oscillations at 0.5, 1.0 and 2.0 inches/s

4.2.1.3 Experiment #3 12/05/2019

After the inconsistency between the results of the first two experiments, another experiment was performed to determine the reactivity change by a simpler method. Experiment 3 consisted in a rough way to estimate the change in reactivity by compensating the effect with the manipulation of the FCR. This experiment was a preparation and setup of the technique for both the experimenter and the reactor operator for future experiments, so no real data was taken.

Experiment 5 later in this paper shows the results obtained by using this method.

Figure 16 was used for this purpose and shows the change in reactivity as a function of the control rod position.

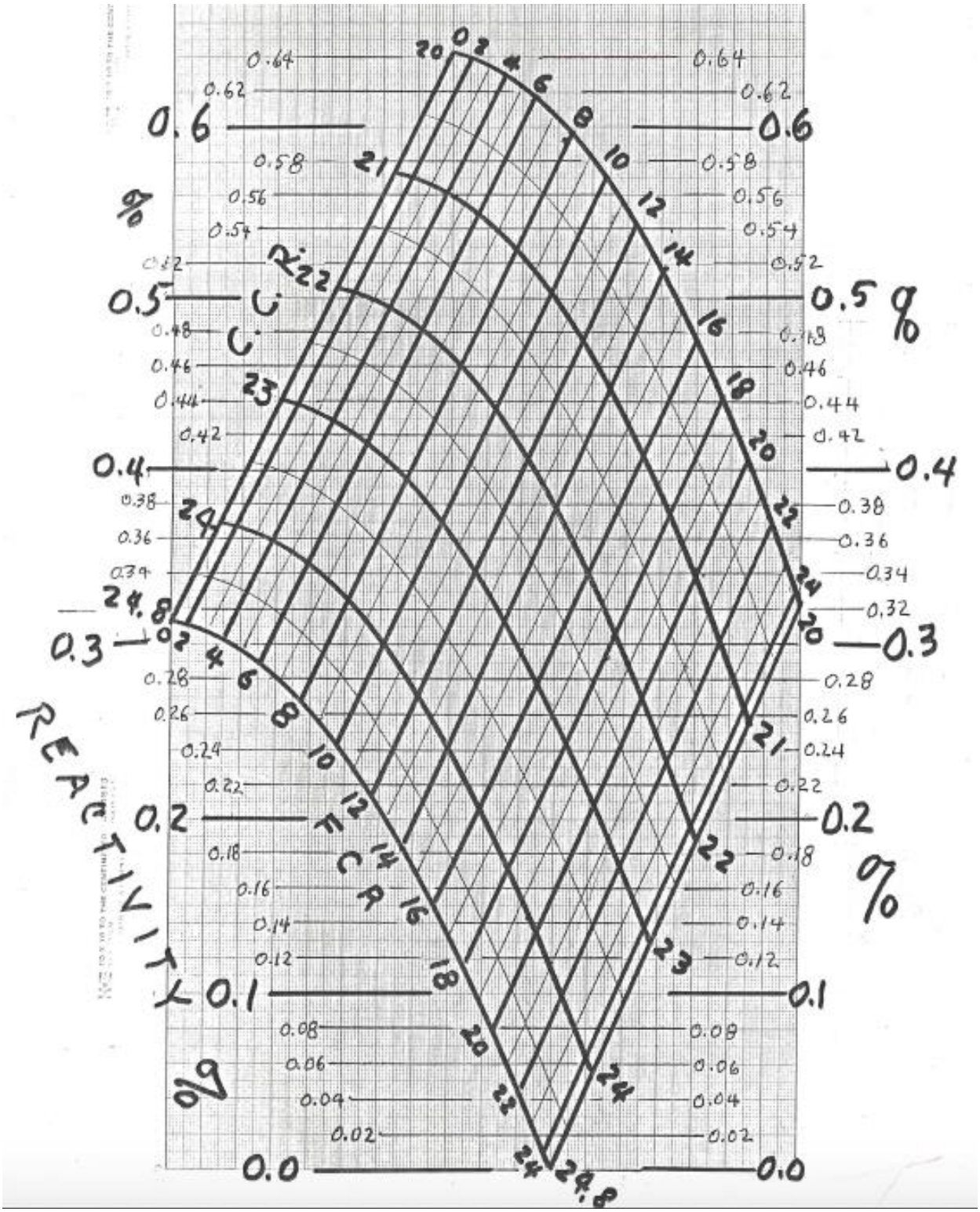

Figure 16 % reactivity based on control rod insertion

4.2.1.4 Experiment #4 02/07/2020

Experiment 4 was the first experiment where an absorber was oscillated instead of a neutron source. The cladding of the Cf-252 was made of stainless steel 304L, per manufacturer specifications (Frontier Technology Corp., Xenia, OH) with a total weight of 12 g.

Two pieces of stainless steel were cut, one was the same length as the cladding in the source and the other was the same weight.

Figure 17 304L Stainless steel samples. Same length (left), same weight (right)

The behavior of the reactor power was different to what was seen until then. Power would drop over time, so the observations from this experiment helped setup the future absorber experiments.

The fact that the power was dropping with every oscillation suggested that the experiment needed to start at the top of the channel 3 scale range, at about 75-80% of the scale to avoid reactor scram, and let the oscillations run until the scale would reach the 20-25%. This would limit the number of oscillations but would avoid problems with changing scales or scramming the reactor.

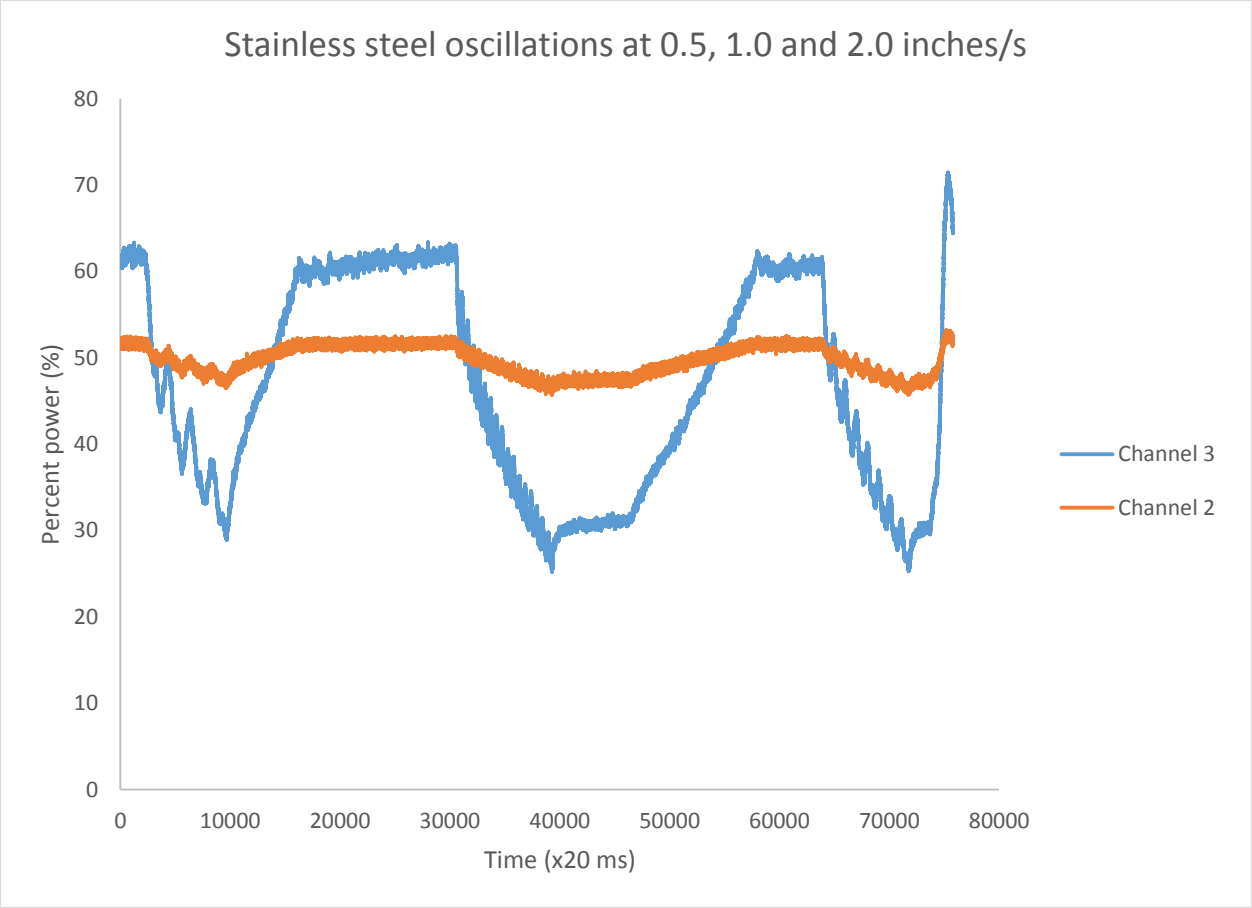

Figure 18 Sample absorber oscillations at different speeds. The range of the oscillator was 6 cm from the outside to the center of the core

The inverse kinetics analysis gave the following result:

$$\rho_{Stainless} = -11.20 \pm 0.46 \ \ cents$$

4.2.1.5 Experiment #5 02/28/2020

Experiment 5 consisted of the oscillations on the reactor of the Cf-source, the stainless steel cladding (absorber only) and a small sample of cadmium, followed by the reactivity estimation experiments with FCR compensation for the three samples.

The procedure followed for this and all the following experiments was as explained below.

The source was installed in the aluminum rod to oscillator, then it was pulled all the way out of the core. The reactor was brought to critical at 10 mW.

Samples were oscillated at 2-3 different frequencies in one of the 1-10 range scales in channel 3. For this experiment, the reactor was brought back to critical at 10 mW and the samples were moved to the center or the core. Reactivity change was compensated with the FCR to bring it back to critical.

The reactor was shutdown after each sample was analyzed and a new sample was placed on the oscillator. This process was repeated until all three samples were analyzed.

Starting with this experiment also and for all the following experiments, the oscillator was set to move between all the way out of the core to the center of the core only (about 6 inches one way).

Results are tabulated below:

Table 1 Experiment 5 reactivity estimated from oscillations

Sample	Time started	Frequency (inches/s)	Estimated reactivity IK
Cf-252 source	10:50	0.5	-14 cents
Cf-252 source	10:54	1.0	-14 cents
Cf-252 source	10:59	2.0	-14 cents
Stainless steel (short)	11:55	0.5	-8 cents
Stainless steel (short)	12:04	1.0	-8 cents
Stainless steel (short)	12:10	2.0	-8 cents
Cadmium	12:51	0.5	-18 cents
Cadmium	12:54	1.0	-18 cents
Cadmium	12:59	2.0	-18 cents

Table 2 Experiment 5 Rough reactivity estimates from FCR compensation

Sample	FCR initial position (cm)	FCR final position (cm)	Estimated reactivity (Reactivity curve)
Cf-252 source	13.76	19.18	-13 cents
Stainless steel	16.12	17.67	-2 cents
Cadmium	17.31	21.33	-10 cents

From this table it can be determined that FCR compensation yields a poor estimate of the reactivity worth of a sample probably because of the difficulty of obtaining a precise value for a given position using graphical data. Oscillations seem to be much more accurate or at least more consistent.

Cf-252 source analysis

Oscillations for each oscillator speed were analyzed individually. From the results a mean value with its standard deviation was obtained (table 3)

Table 3 Cf-252 source analysis

Cf-252				Total
	2s	1s	0.5s	
Mean	14.04	12.69	16.04	14.25
STD	0.83	2.18	3.19	2.07

$$\rho_{Cf-252} = 14.25 \pm 2.07 \text{ ¢}$$

Cadmium sample analysis

Oscillations for each oscillator speed were analyzed individually. From the results a mean value with its standard deviation was obtained (table 4)

Table 4 Cadmium sample analysis

Cadmium				Total
	2s	1s	0.5s	
Mean	-18.68	-17.45	-17.99	-17.91
STD	0.06	0.49	0.59	0.38

$$\rho_{Cd} = -17.91 \pm 0.38 \text{ ¢}$$

Stainless steel sample analysis

Oscillations for each oscillator speed were analyzed individually. From the results a mean value with its standard deviation was obtained (table 5). The 2 inches/s data points were too dispersed and were not used.

Table 5 Stainless steel sample analysis

Stainless steel			Total
	1s	0.5s	
Mean	-8.35	-9.21	-8.78
STD	0.64	0.54	0.84

$$\rho_{Stainless} = -8.78 \pm 0.84 \text{ ¢}$$

4.2.1.6 Experiment #6 28/05/2020

The experiments were started again after the COVID break. The purpose of this experiment is to measure reactivity changes of small samples in the most subcritical situation for the AGN-201, i.e. no rods inserted. At this time the old reactor console had been replaced by a newer one. Detectors did not seem to be working properly.

The LND detector was to be tested and see if it would give an acceptable signal to use in future experiments.

Part one

Part one of the experiment consisted in placing the detector as close to the core as possible and observe if there was a good signal. For that purpose, the graphite block in the center from the top of reactor was removed and the detector was placed in the hole. The detector was connected to the computer through the picoammeter and the specific LabView program for this setup was run. The RaBe source was placed in the glory hole and was moved back and forth. The same procedure was repeated with the CF-252 source (Fig. 19).

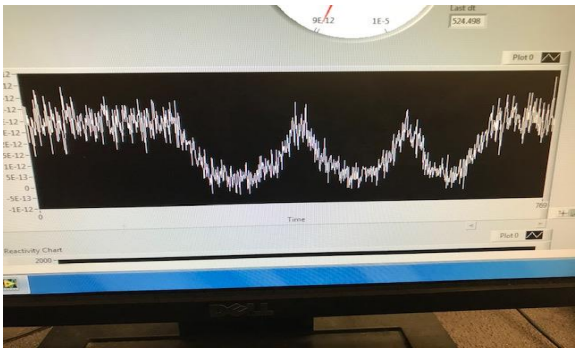

Figure 19 Manual oscillations of Cf-252 source. The abscissa is the time in seconds and the ordinate represents the magnitude of the current of the detector

The idea if everything went well was to oscillate an absorber (cadmium in this case) in the most subcritical situation in the reactor with a neutron source in the core to provide a steady flux of neutrons.

The signal was very noisy even when moving the source and no good data was obtained from this experiment. Readings from the LND detector were in the range of 2-3*10^{-12} with the RaBe source and 5-6*10^{-12} when oscillating the cadmium sample with the Cf-252 source (Fig. 20).

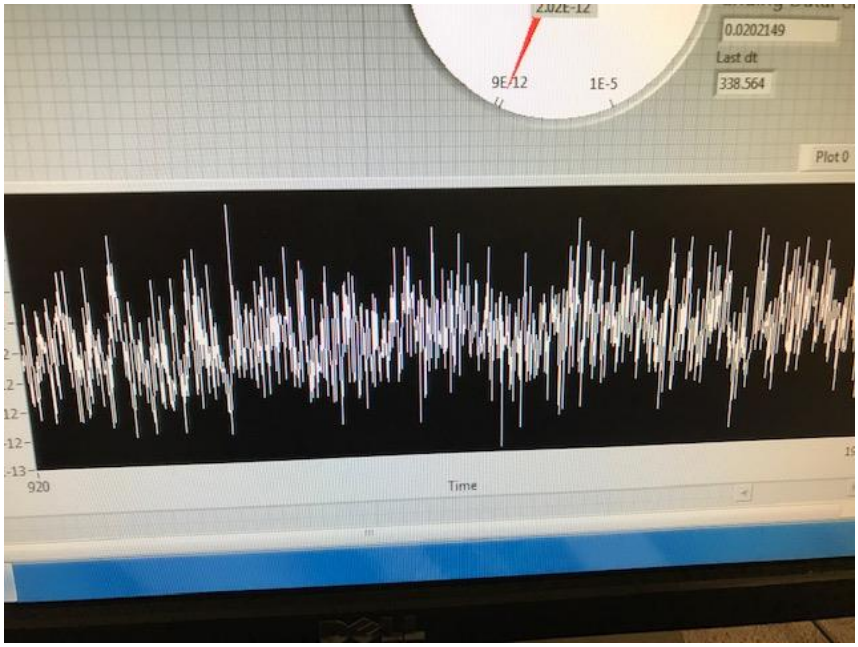

Figure 20 Oscillations of cadmium sample with no rods inserted. The abscissa is the time in seconds and the ordinate represents the magnitude of the current of the detector

The HV cable length did not allow the detector to be lowered as close as possible to the reactor core, so the experiment was scheduled to be repeated with the detector in full contact with the top of the reactor wall after the center graphite block was removed.

Part two

Part two of this experiment used the same setup as part one except that the LND detector was not used. The reactor console was turned on and the chart recorder graphs were observed while both neutron sources were oscillated manually.

Similar results as in part one were obtained. The signal was too noisy.

4.2.1.7 Experiment #7 06/02/2020

Experiment #6 data did not show good results. It was found however that the detector could be placed in the hole at the center graphite block that would put it closer to the core with the possibility of getting better data. A longer HV cable was used so the detector could be all the way down in the hole in direct contact with the base.

Results were still very noisy, although better than in previous experiment. Signal strength increased by 2x but was still very noisy.

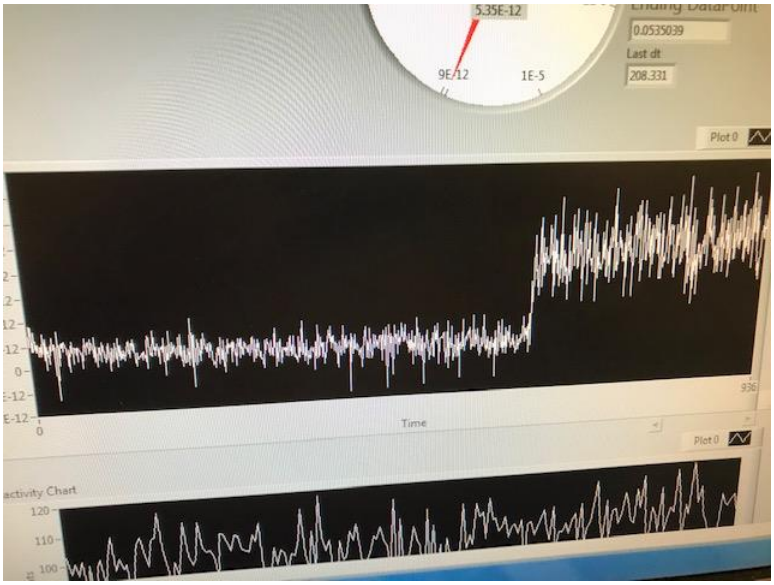

Figure 21 Sample graph with source out and in the core. The abscissa is the time in seconds and the ordinate represents the magnitude of the current of the detector

4.2.1.8 Experiment #8 06/04/2020

The next experiment consisted of oscillating a larger cadmium sample with the reactor at the most subcritical state with the RaBe source first and with the CF-252 second in the core.

The cadmium absorber had the following characteristics (fig. 22):

$Length = 5.0\ in\ (12.7\ cm)$

$Mass = 19.74\ g$

Figure 22 Cadmium sample used for this experiment

The reactor console chart recorder was used for this experiment since the LND detector had proven to be too noisy. Oscillations could be seen in the chart recorder but once analyzed they still were too noisy.

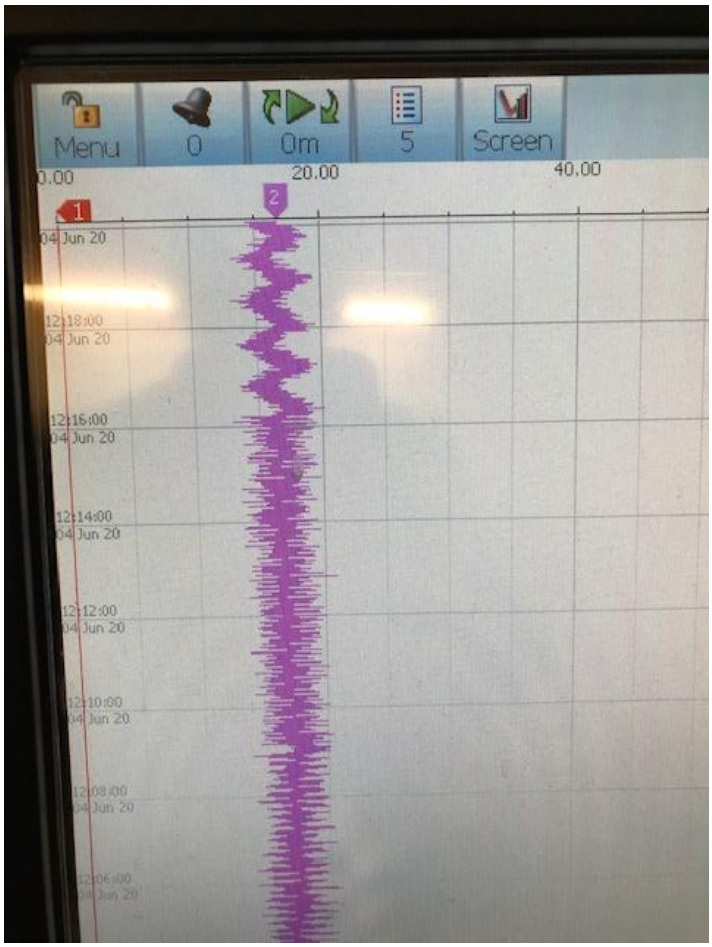

Figure 23 Oscillations in channel 3 of large cadmium sample with no control rods

The bottom and central part correspond to the 1.0 and 2.0 inches/s speeds. The top portion of the graph corresponds to the 0.5 inches/s speed. It was analyzed through the inverse kinetics code (fig. 24 below) and the following results were obtained:

$$\rho_{Cd} = -21.07 \pm 2.92 \text{ ¢}$$

Since the sample is considerably larger than the one used in experiment 5, it was expected to obtain a greater change in reactivity.

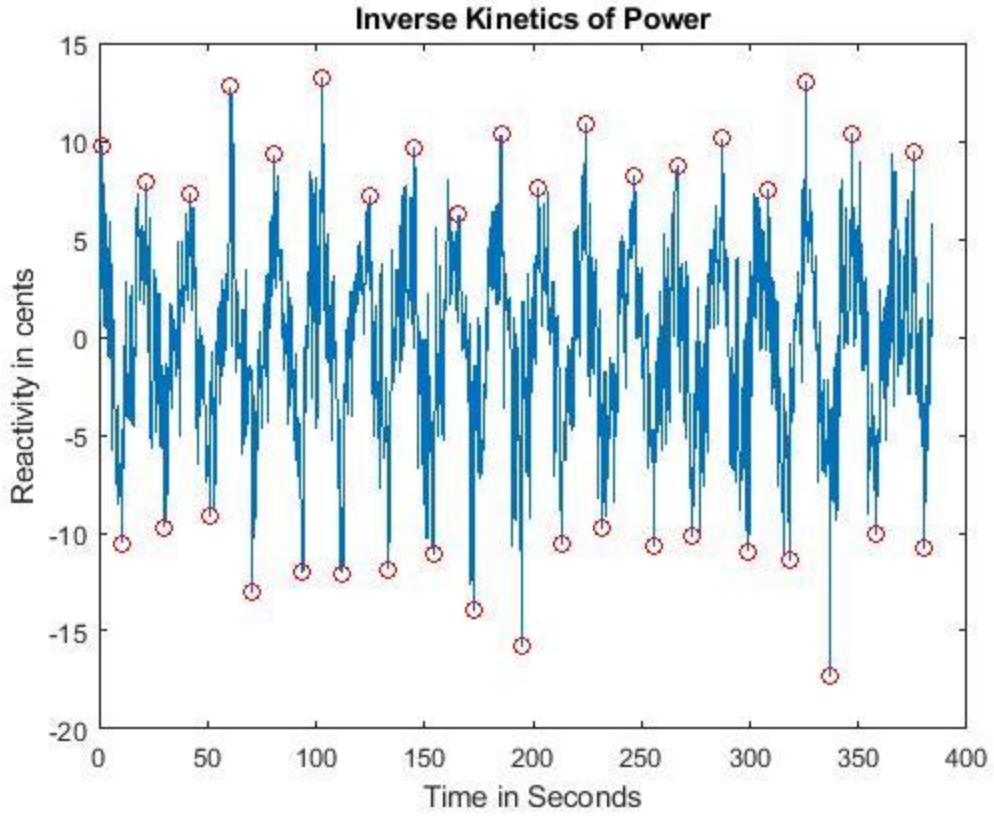

Figure 24 Cadmium sample oscillations with no control rods

Figure 24 shows the combination of the Cf-252 as the neutron source with the slowest speed of 0.5 inches/s.

4.2.1.9 Experiment #9 06/10/2020

Initially it was thought that experiment 8 results could be meaningful, so a new set of experiments was scheduled. The goal was to keep cutting the sample in half until no further usable results were available.

The cadmium sample from previous experiment was cut in half (approximately) and experiment #8 was repeated with the new source.

The cadmium source had the following characteristics:

$$Length = 2\frac{5}{8}\ in\ (6.67\ cm)$$

$$Mass = 10.13\ g$$

Again, the optimum set up was oscillating at the slowest speed using the Cf-252 source. This time the reactivity worth of the sample was:

$$\rho_{Cd} = -17.95\ \pm 2.61\ ¢$$

Since the sample is considerably larger than the one used in experiment 5, it was expected to obtain a greater change in reactivity.

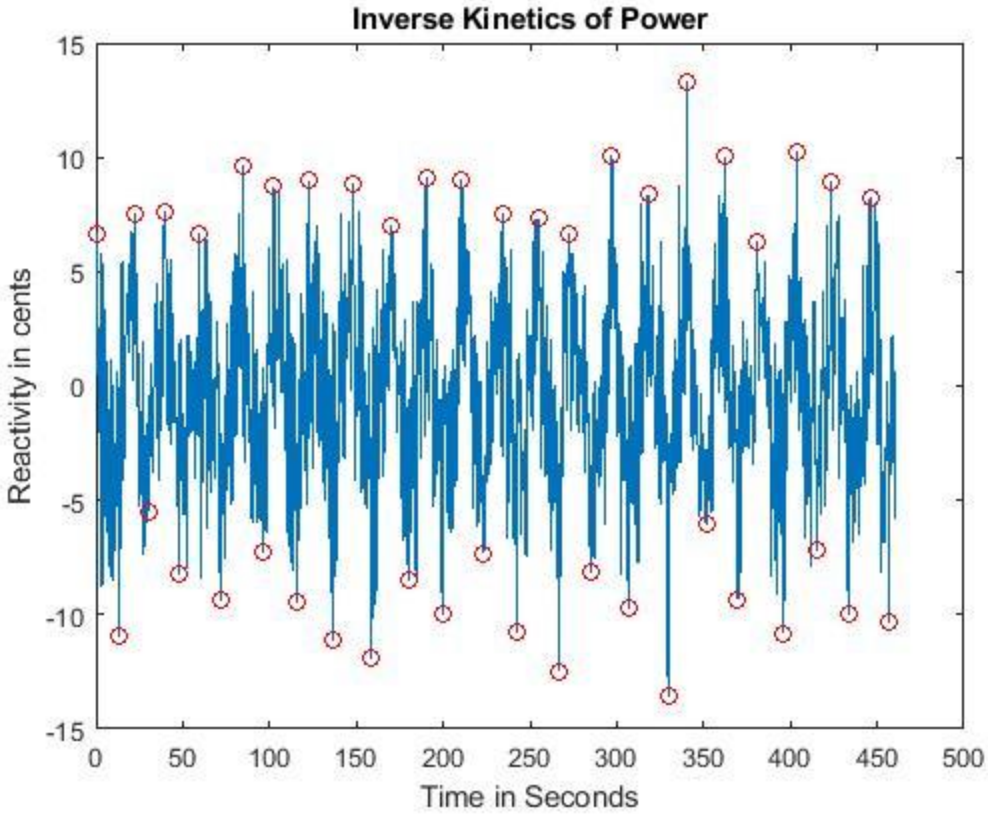

Figure 25 Cadmium sample oscillations with no control rods

At this point the reactor supervisor advised that the detector in channel two was not working properly and that the reactor in channel 3 could have some problems as well. Experiments of this kind were stopped for a few weeks.

4.2.1.10 Experiment #10 06/19/2020

One hour of reactor was available that day and there were a couple things that could be tested. Based on the data for the half Cd sample experiments, we wanted to test a single jump in reactivity, with the Cf-252 source in the center of the core and moving the sample to the center of the core and leave it there for a couple minutes.

Next test was based on the presumption that the Cd sample in direct (or almost direct contact) with the source in the center of the core may have an effect on the results. To account for this the source was pulled between one and two inches out from the center of the core to avoid close proximity with the sample. No differences were observed.

Results were:

Absorber out: 20.99

Absorber in: 18.27

Next we looked at the worth of the source using the promt jump (drop) approximation.

For one group the neutron power is given by:

$$n(t) = \frac{n_0}{\beta - \rho_0}\left[\beta e^{\left(\frac{\lambda\rho_0}{\beta-\rho_0}t\right)} - \rho_0 e^{\left(-\frac{\beta-\rho_0}{l}t\right)}\right] \qquad (Eq.\,28)$$

For $t = 0^+$after a jump or drop in reactivity the second exponential vanishes rapidly because of the $\frac{1}{l}$ term (the generation time is in the order of 100 ns) and the first exponential approaches 1.

Thus it can be written as:

$$\frac{n(0^+)}{n_0} = \frac{\beta}{\beta - \rho_0} \qquad (Eq. 29)$$

From equation 29 applying the values obtained from the experiment:

$$\frac{n(t)}{n_0} = \frac{18.27}{20.99} = 0.87 = \frac{\beta}{\beta - \rho_0}$$

$$(0.87 - 1)\beta = 0.87\rho_0$$

$$\rho_0 = \frac{(0.87 - 1)\beta}{0.87} = -0.0011 \approx -15\ cents$$

Comparing this number with the one obtained by oscillating a cadmium sample in and out of the reactor, it can be determined that the prompt jump approximation gives a good idea of the reactivity worth of a sample, so one would know what to expect before starting oscillation experiments.

4.2.1.11 Experiment #11 06/29/2020

Until now the LND detector had been placed in a hole on top of the reactor, based on previous experimenter's experience. Previous experimenters have used a detector in the top hole but at much higher power, with many more neutrons available.

For this experiment the detector was placed inside the beam port number 3 with the usual connections to the picoammeter and HV power supply. The LabView code was used to get the readings from the detector.

The purpose of this experiment was to test the detector signal by placing the detector closer to the core and operating the reactor at 10 mW.

The first part consisted of oscillating the initial small cadmium sample with the reactor critical at 10 mW to compare readings to the previous readings with the old console.

Placing the detector in one of the beam ports did not improve the quality of the signal. The significance is that there is a need for more power, a more efficient detector or better placement to obtain useful signals.

4.2.1.12 Experiment #12 08/28/2020

There was a two-month gap since last experiment due to reactor breakdown. One of the detectors was not working and that prevented operators from starting the reactor.

The small cadmium sample was oscillated with the reactor critical and with the reactor subcritical with the two safety rods inserted. (no CCR and no FCR).

The results from the reactor critical were in accordance with previous experiments results, so it was determined that the readings from channel 3 were good when the reactor is critical.

However, at subcriticality the readings were too noisy and they did not give any useful data.

4.2.1.13 Experiment #13 10/22/2020

In this experiment a small indium sample was oscillated in the reactor in its critical position at 10 mW power.

Sample weight = 1.34 g

Shape: “solid” cylinder about 1 cm long by 0.2 cm diameter. In reality the cylinder was made out of several small thin sheets pressed together (see figure 26)

Figure 26 Indium sample

From the reactivity graph it was estimated that the reactivity change due to the introduction of the indium sample was -12 cents.

Indium sample reactivity analysis

Oscillations for each oscillator speed were analyzed individually. From the results a mean value with its standard deviation was obtained:

$$\rho_{In} = -11.51 \pm 0.51 \text{ ¢}$$

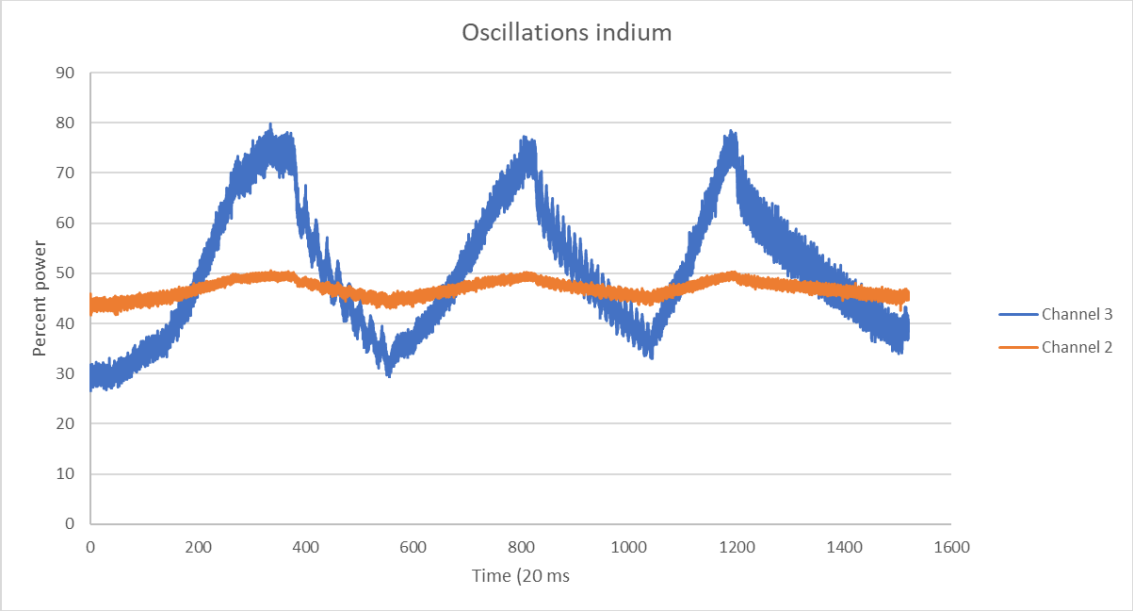

Figure 27 Raw data of indium oscillations showing amplitude of oscillations vs time in seconds

4.2.1.14 Experiment #14 11/06/2020

The same procedure in experiment 13 was followed but this time a small gold sample was used in the oscillations. The sample consisted of three gold foils available in the lab with a circular shape. They were all uneven so if stacked together there would be air in between the layers that could adversely affect the results. Air between the layers affects the effective density, creating a variable that is almost impossible to measure. The foils where stacked and folded in half to fit the oscillator rod.

Figure 28 Gold sample

Sample was oscillated at 0.5 inches/s, 1 inch/s and 2 inches/s (figure 29 below)

Sample weight=1.08 g

Diameter= 2.3 cm

Thickness= 0.5 mm

The initial estimate of the reactivity change from inverse kinetics was of about -7 cents.

Gold sample reactivity analysis

Oscillations for each oscillator speed were analyzed individually. Each peak was normalized and from the results a mean value with its standard deviation was obtained:

$$\rho_{Au} = -6.84 \pm 1.01 \text{ ¢}$$

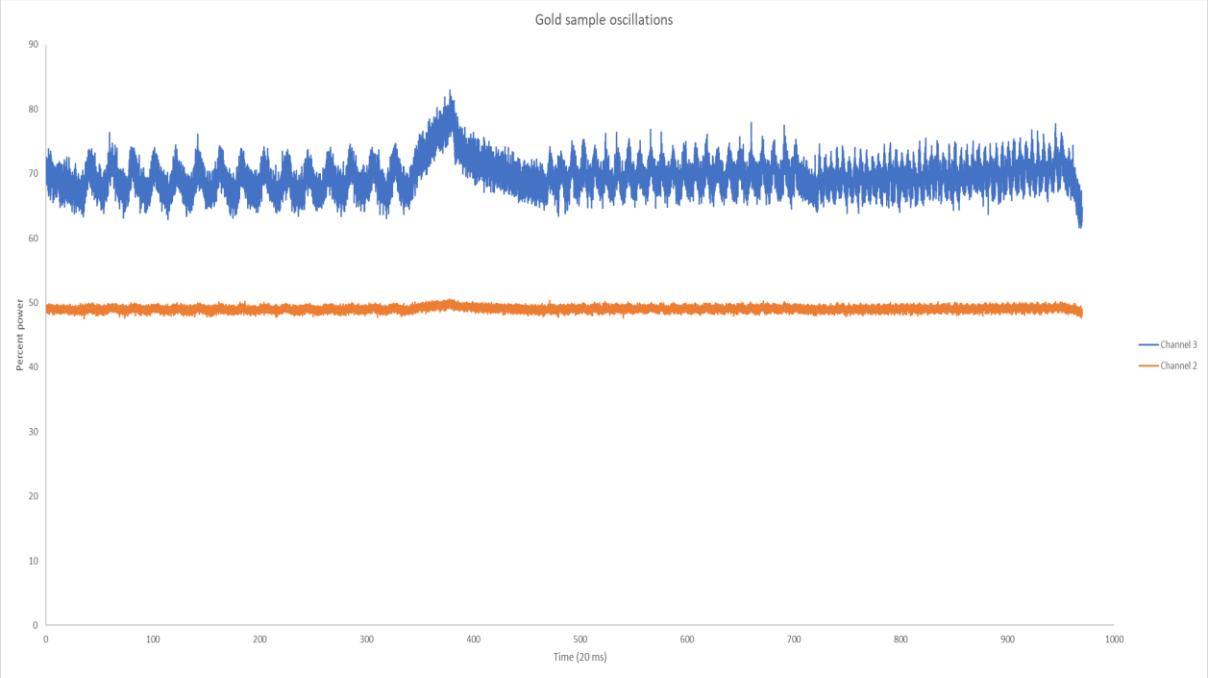

Figure 29 Gold oscillations showing amplitude of oscillations vs time in seconds

4.2.1.15 Experiment #15 11/17/2020

A new neutron source was available for experiments. The source was a 1 Ci americium-beryllium (AmBe) source with a neutron rate of about $2*10^6$ neutrons/s.

For this experiment all three available sources were used as follows:

- Cf-252 source in glory hole
- RaBe source in glory hole
- AmBe source in beam port #3

All combined gave about $2.5*10^6$ neutrons/s, giving a reactor power of 2 mW as read in channel 3 in the reactor console. The small cadmium sample was used as a sample to oscillate.

Figure 30 AmBe source in beam port 3

Small oscillations in power were noticed when the source was oscillated at the usual 0.5, 1.0 and 2.0 inches/s, but the oscillations were not distinguishable from the noise recorded without any oscillations going on. Several channel 3 different power ranges were tested, specifically 3mW, 1 mW, 300µW and 100µW by fully or partially pulling sources out.

It was concluded that with this setup it is not possible to obtain useful data for the purpose of this research.

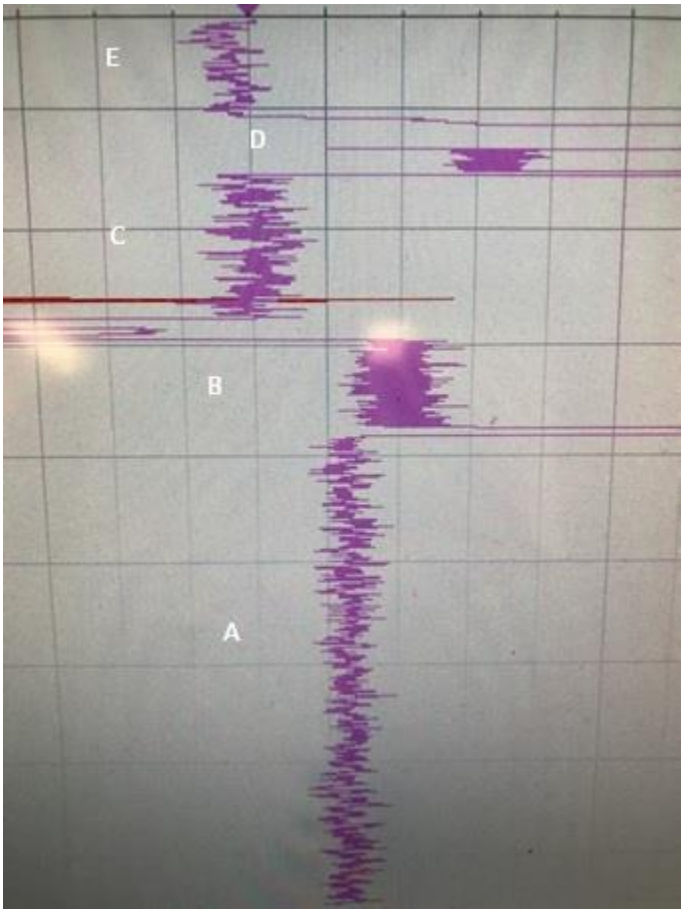

Figure 31 From bottom to top of graph: a) Oscillations in the 300µW range. b) Oscillations in the 1 mW range. c) Oscillations in the 100 µW range. d) 3mW range noise (similar to 1mW range oscillations). e) 300 mW range noise (similar to oscillations in the same range

4.2.1.16 Experiment #16 11/24/2020

Figure 32 shows the oscillations on the reactor power from the console from the large cadmium sample with two sources in the glory hole (first part of the graph) and with an additional source in the beam port #3 (the signal shows a noticeable rapid increase when the third source is placed.

No useful data was obtained from the ion chamber detector or from the small sample.

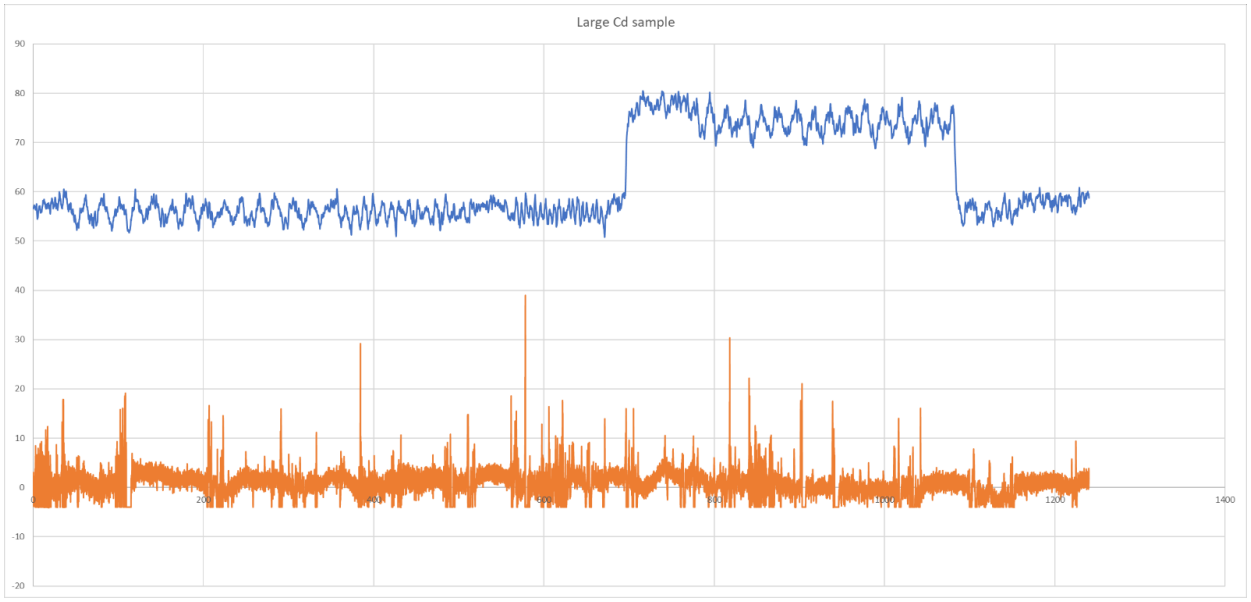

Figure 32 Experiment 16 oscillations of large cadmium sample

A quick look at the results from the inverse kinetics analysis give an approximate reactivity change of – 12 cents. The smaller cadmium sample gave a reactivity change of -18 cents, so it was expected a greater neutron absorption, and this result is not good.

Large sample is 5 inches long and about 20g.

Small sample is 0.7 inches long and 1.6g.

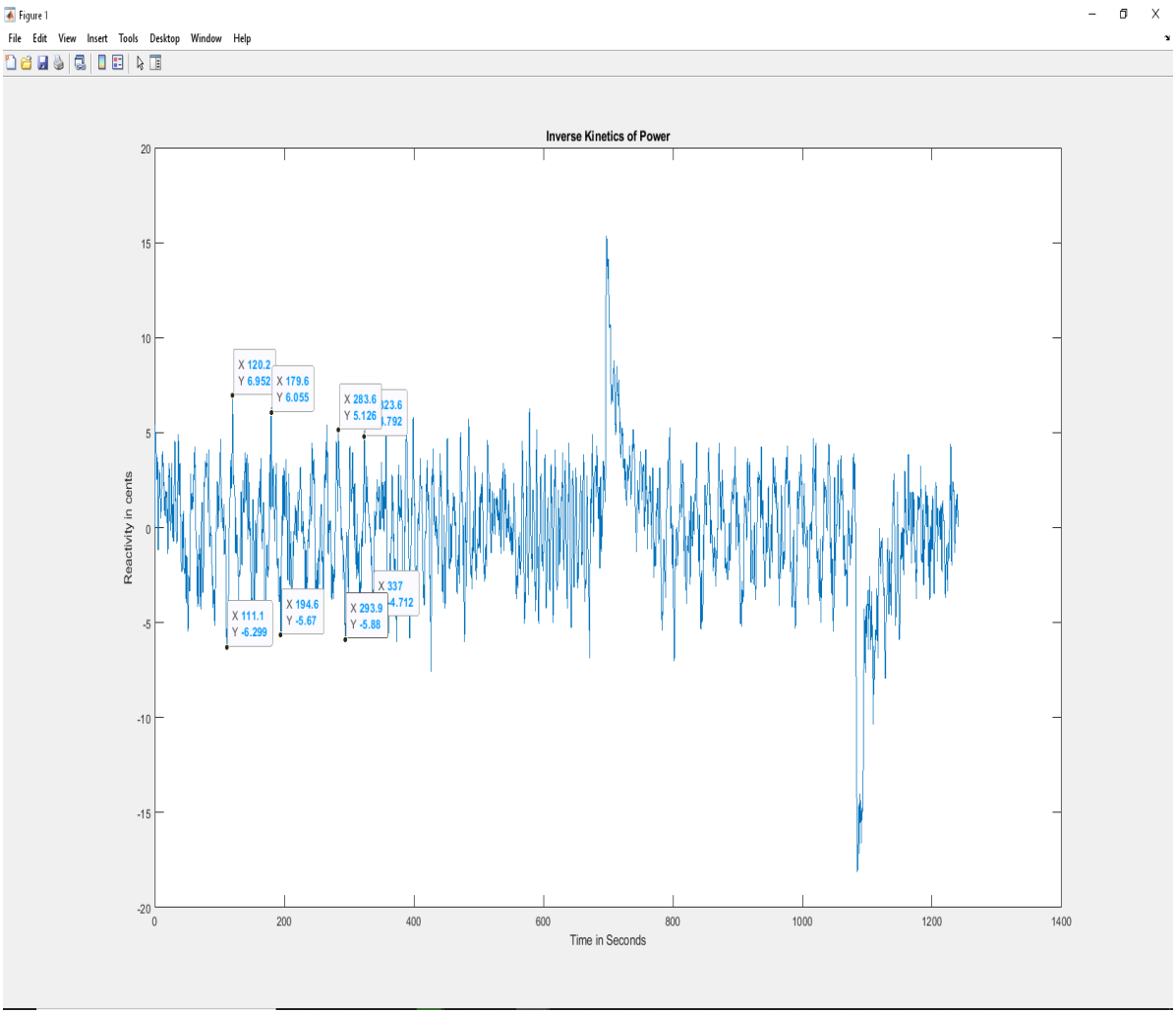

Figure 33 Estimated reactivity worth from graph

This concluded the series of experiments in the AGN-201 reactor.

4.2.2. Subcritical assembly experiments

Experiments in the SCA consisted in oscillating an absorber in and out of the core with all the plates in the assembly (150 plates). The initial thought was to add a support and attach the oscillator system to repeat experiments in a similar fashion as in the reactor. However, the detectors available at the SCA were proportional counters instead of ion chambers. The LND detector was tested to see if it would detect anything with that low neutron population. It was placed inside an aluminum can that had been previously used to accommodate detector 2 in the AGN-201 reactor (fig. 34)

Figure 34 Aluminum can attached to the SCA to hold the LND detector

The other three available detectors in the SCA assembly would give neutron counts instead of current, so the oscillator method could not be used with these detectors. Instead, counts would be taken without a sample in the assembly and then the counts would be repeated with a sample in the center. The difference in count numbers should give a change in reactivity according to equation xx below:

$$\frac{CR_1}{CR_2} = \frac{1 - K_2}{1 - K_1} \qquad Equation\ 30$$

Experimental procedure

The following procedure was followed every time the SCA was operated:

- Instrumentation was powered on and the three detectors were brought to the established voltage.
- Plates were put in the assembly in a rectangular shape.
- The assembly was filled with water.
- The external source (Cf-252) was placed in the center of the assembly.
- Experiments were started.

After the experiment, the water is pumped out of the SCA and all plates are removed, dried and placed back in the safety box.

4.2.2.1 Experiment 17 12/07/2020

The first experiment in the SCA was to test equipment and have an idea of the response that can be achieved from the available instrumentation. The standard procedure was followed to start the assembly. Once the 150 plates were set and the Cf-252 source was inserted in the center of the plate setup, count rates were taken for five minutes. Count rates were repeated for five more minutes to take an average. Next, a cadmium sample (large sample) was positioned in the center of the core close to the source. Count rates from the four detectors were taken twice for five minutes.

Results are in the following table:

	Det 1	Det 2	Det 3		Det 1	Det 2	Det 3
CR Empty	8008	14595	2623				
CR Empty	8013	14693	2599	Ave CR	8010.5	14644	2611
CR Cd sample	7960	14138	2477				
CR Cd sample	8111	14390	2484	Ave CR Cd	7960	14264	2480.5
				Dif.	50.5	380	130.5
				% dif.	0.630423	2.594919	4.998085

Table 6. Count rates in the SCA for 5 minutes without and with an absorber

The results showed some drop in the number of counts when the absorber was present, although hardly statistically significant. However, no change in neutron population was observed in the LND detector.

This initial experiment was not conclusive but it gave some hope that we could get some useful data and it set the basis for the next set of experiments.

4.2.2.2 Experiment #18 12/08/2020 to 12/10/2020

Experiment 19 consisted of counting twice for two hours in the SCA with different absorbers in the core. The first counts were with no sample.

Part 1

During days one and two, counts were taken for two hours once in the afternoon without a sample in the core (day 1) and once in the morning with no sample and once in the afternoon with cadmium sample in the core (day 2). Results are shown in table xx below.

A drop in the count rate was observed when counting in the morning which was constant for detectors 1 and 2, the two that are exposed to the air in the room. The difference it was attributed to changes in temperature.

Count number three was in the afternoon (higher temperature that specific day) with the cadmium sample in the core.

	Det 1	Det 2	Det 3
CR Empty (Afternoon day 1)	224001	239771	56017
CR Empty (Morning day 2)	215663	230251	56693
CR Cd sample (Afternoon day 2)	210574	242055	54387

Table 7 Count rates without and with an absorber in the core

Part 2

Day three experiment consisted in a repeat of counts with the cadmium sample in the core. A drop in the number of counts was observed, similar to the drop observed from day 2, but this time it was on detector 1 instead of detector 2 (see table 8 below)

	Det 1	Det 2	Det 3
CR Cd sample (Morning day 3)	232839	204797	55080
CR Cd sample (Afternoon day 3)	227378	202798	54645

Table 8. Count rates with a cadmium sample in the core

Another blank (no sample) count was done next day to make sure nothing had changed in the detectors configuration or location that would have caused the switch. It turned out that the counts with no sample gave a similar result as counts with sample from the previous day (table 9 below)

	Det 1	Det 2	Det 3
CR Empty (Afternoon day 4)	224001	239771	56017

Table 9 Count rate with an empty core

A summary of parts 1 and 2 combined is below:

	Det 1	Det 2	Det 3		Det 1	Det 2	Det 3
CR Empty (Afternoon day 1)	224001	239771	56017				
CR Empty (Morning day 2)	215663	230251	56693				
CR Empty (Afternoon day 1)	233539	204338	55310	Ave. empty	224401	224787	56007
CR Cd sample (Afternoon day 2)	210574	242055	54387	Uncert.	158	158	79
CR Cd sample (Morning day 3)	232839	204797	55080				
CR Cd sample (Afternoon day 3)	227378	202798	54645	Ave. Cd	223597	216550	54704
				Uncert.	158	155	78

Table 10 Summary of count rates for part 1 and 2 with analysis

After taking averages, the difference in neutron counts without and with an absorber is not conclusive. While detector 2 sees a significant drop in neutron count (8.5%), detectors one and three do not see any significant drop.

Part 3

Based on the previous observed behavior and the changes in count drop among detectors and it was decided that counts should be taken immediately one after the other to avoid any changes in temperature in the room or any detector adjustments from turning on and off the power supplies.

Consecutive one-hour counts were taken next day with the following results:

	Det 1	Det 2	Det 3
CR Empty	114110	103442	25551
CR cadmium sample	115132	103628	25415

Table 11 One hour counts with and without sample in core

No appreciable drop in the number of counts was observed.

4.2.2.3 Experiment #19 12/16/2020

Just to make sure these results were conclusive the same experiment was repeated (Table 12 below)

	Det 1	Det 2	Det 3
CR Empty	117700	99692	25496
CR cadmium sample	117975	98809	25983

Table 12 One hour counts with and without sample in core

It was determined at this point that the data obtained from these experiments was worthless and some other approach had to be taken.

4.2.2.4 Experiment #20 12/17/2020

The new approach for this and following experiments was to use stronger sources. This experiment was a repetition of experiment 19 but with the AmBe source (1 Ci) in the center of the SCA core. Measurements were taken for one hour without and with an absorber. Results are shown below in table 13.

	Det 1	Det 2	Det 3
CR Empty	182665	188320	107604
CR cadmium sample	175412	171707	127397

Table 13 One hour counts with and without sample in core with AmBe source

The experiment was repeated a second time with the following results:

	Det 1	Det 2	Det 3
CR Empty	212984	194066	68200
CR cadmium sample	212680	185808	70492

Table 14 One hour counts with and without sample in core with AmBe source

Although detectors one and two see a significant drop in neutron count in the first set, detector 3 sees about the same neutrons. In the second part only detector two sees a drop, but it is a smaller drop compared to part one.

4.2.2.5 Experiment #21 12/18/2020

This was the last experiment in the SCA and concluded all the experiments for this work. This was a repetition of experiment 19 and 20 but with all three sources available in the center of the assembly yielding a total source strength of about

.

Figure 35 SCA with three sources

Measurements were taken for one hour without and with an absorber. Results are shown below in table 15.

	Det 1	Det 2	Det 3
CR Empty	262465	322912	67734
CR cadmium sample	261687	322716	67888

Table 15 One hour counts with and without sample in core with AmBe source

No significant drop in the number of neutrons was seen when an absorber was in the center of the assembly.

5. Modeling

5.1 MCNP modeling

An available model of the AGN-201 nuclear reactor was available in the department and it was used to simulate the effect of inserting a cadmium sample in the core. The MCNP code was run with 100,000, 500,000 and 1,000,000 neutrons per second. This was the equivalent of running the oscillator when the sample is all the way out of the core, where the high peak is seen in the oscillations curve. Then the code was modified and a cadmium sample of exact dimensions of the one used in the experiments was placed in the glory hole in the center of the core. That would be the equivalent of the low peak in the oscillations curve.

Results are tabulated below:

	Empty k	Cd sample k	beta	Ro (%)	Ro ($)	STD
100000 nps	1.00435	1.00332	0.0074	-0.00103	-0.13859	0.00025
500000 nps	1.00487	1.00336	0.0074	-0.0015	-0.20307	0.00011
1000000 nps	1.00458	1.00329	0.0074	-0.00128	-0.17353	0.00008

Table 16 Reactivity change from MCNP modeling

It takes about three days to run 1,000,000 nps, but one can see that with 1,000,000 nps the result is closer to the experimental value of -17.91 ± 0.38 ¢. Also, as expected, the uncertainty decreases as the number of neutrons increases.

5.2 ANISN modeling

ANISN is a one-dimensional transport theory code developed at LANL in the 1060's. Because it can model multigroup adjoint flux transport, it was used to find cross-sections through multigroup perturbation theory.

The model of the rector is spherical, with the cadmium in the center with radii from 0.28 to 0.30 cm, as used in previous calculations. The oscillator aluminum tube is also modeled as a thin shell of aluminum (0.3 to 1.0 cm). Then the core region starts and extends out to a radius of 12.5 cm. This is followed by a graphite reflector to 20 cm. A fixed source was placed in the interval just at the edge of the core; the source was high energy (14 MeV realizing that this will have no bearing on cadmium absorption). The reactor was assumed to have a mass of U-235 of 665 grams, per technical specifications. The uranium is 20 % enriched. The rest of the core material was polyethylene (C_2H_4). The Bugle 93 library was used, which has 47 neutron groups and 20 gamma groups, coupled. The important groups are 46 and 47 representing the energies below the cadmium cutoff, although group 45 was included just to confirm it does not affect the results. Both forward and adjoint fluxes were calculated. The equation for multi-group perturbation theory is a modification (or an extension) of equation 20 where it is not assumed that the adjoint flux is equal to the forward flux the addition of the adjoint flux:

$$\Delta\rho = -\frac{\delta\Sigma_a \int_V \phi^+\phi dV}{\nu \int_V \phi^+\Sigma_f\phi dV} \qquad (Eq.31)$$

For the term $\nu\phi^{+}\Sigma_f$ in the core we took the calculated ANISN fission rate, and just took the adjoint flux for the lower energy groups. A macroscopic cross-section was obtained of 156 cm^{-1} while Lamarsh gives a value of 114 cm^{-1} (a 25 % difference).

It should be noted that the value was adjusted for the difference in mass of cadmium that the 0.02 cm shell represents (about 0.5 gr) vs the actual sample mass (1.6 gr).

Plots of the fluxes in the cadmium shell show a great degree of self-shielding, which certainly invalidates a true perturbation analysis. However, this does demonstrate the methodology needed to extract cross sections from reactivity data. The cadmium sample was simply too absorbent. It should be noted that much better results were obtained by looking at a stainless steel sample, even with one group perturbation theory

Secondly, a calculation was performed in which the cadmium density was zeroed, which would be an assumption that self-shielding was not important. This severely underestimates the cross section (a value of 6 cm^{-1} is obtained, a 1,800 percent difference!)

6. Results

The first series of experiments were focused on familiarizing with the equipment and corroborating Sultan Sharif's work. Results are tabulated below:

	Experiment 1	Experiment 2
Cf-252 Reactivity change no rods	$10.25 \pm 0.31 \ \ cents$	$21.22 \pm 2.60 \ \ cents$
Cf-252 Reactivity change two safety rods	$9.99 \pm 0.99 \ \ cents$	$15.69 \pm 2.63 \ \ cents$

Table 17 Experiments 1 and 2 results

The lack of agreement in the two experiments was due to the fact that different rod oscillations travel positions were being tested. Experiment 1 is more in agreement with Sultan Sharif's reactivity of 9.92 cents (no uncertainty was provided). Based on these experiments a standard traveling length from out of the core to the middle of the core was established for future experiments.

Experiment 5 gave another result for the Cf-252 source, this time with the stablished oscillator travel length and with the reactor critical at 10 mW:

$$\rho_{Cf-252} = 14.25 \ \pm 2.07 \ ¢$$

Next series of experiments involved an absorber oscillating with the reactor critical at 10 mW. First absorber used was stainless steel, since it is the cladding in the Cf-252 source. A piece of stainless steel with the same weight as the cladding in the Cf-252 was oscillated and the reactivity worth was found to be $\rho_{Stainless\ long} = -11.20 \pm 0.46 \ \ cents$. Next experiment the

stainless steel sample oscillated was of the same length as the cladding in the Cf-252 source.

The reactivity worth was $\rho_{Stainless\ short} = -8.78 \pm 0.84$ ¢

Stainless steel	% in alloy	Atomic mass	percent atomic mass	abs x-s	Percent x-s
C	0.0003	12	0.0036	0.0034	0.00000102
Mn	0.02	54.9	1.098	13.3	0.266
P	0.00045	30.9	0.013905	0.18	0.000081
S	0.0003	32	0.0096	0.52	0.000156
Si	0.0075	28.1	0.21075	0.16	0.0012
Cr	0.18	52	9.36	3.1	0.558
Ni	0.08	58	4.64	4.43	0.3544
N	0.0001	14	0.0014	1.85	0.000185
Fe	0.71135	55.8	39.69333	2.55	1.8139425
		Total:	55.030585		
				Total x-s	2.99396552

Table 18 Stainless steel sample analysis

One group perturbation theory was run on this sample and the theoretical absorption cross-section was calculated from values from literature.

Theoretical thermal absorption cross-section calculation

From literature, the components of 304L stainless are: Carbon .03%, Manganese 2.00%, Phosphorus .045%, Sulfur .030%, Silicon .75%, Chromium 18-20.00%, Nickel 8.00-12.00%, Nitrogen-.10%, Iron- Balanced. This table and these calculations assume that the stainless steel has 71.135% of iron, which comes from balancing 18% of chromium and 8% of nickel. No information was provided by the manufacturer of the source about the exact composition of the cladding.

First thing calculated was the percent of mass for each component in alloy which gave a molecular mass of about 55 (it makes sense since the majority is iron)

The same procedure was used with the individual absorption cross-sections, to find a cross-section for stainless steel of 2.99 b.

One group perturbation theory was used to calculate the cross-section based on the results from oscillating the sample. A Mathematica code was written to perform the calculations (appendix B). The cross-section obtained this way was 2.34 b.

Knowing the real exact composition of the sample, a better estimate could have been calculated.

Next absorber and the one that was most used for the experiments was cadmium. The reactivity worth for the small sample of cadmium with the reactor critical at 10 mW was:

$$\rho_{Cd} = -17.91 \pm 0.38 \text{ ¢}$$

Based on this number, perturbation theory was used to determine the thermal absorption cross-section.

One group perturbation theory gave a value of:

$$\sigma_{Cd} = 147.38\ b$$

The procedure and data used in the Mathematica code is as follows:

From equation 21:

$$\Sigma_{ap} = -\frac{\Delta\rho v \int_V \Sigma_f \emptyset^2 dV}{\int_{Vp}[\phi^2]dV_p}$$

$\Sigma_f = 0.0762\ cm^{-1}$

$\nu_r = 2.4$

Flux for a cylindrical shape:

$$\phi\,(r,z) = Aj_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right)\ (used\ Ben's\ matlab\ code\ to\ calculate\ the\ integral)$$

R= 12.8 cm, H= 25.8 cm for reactor

innerR= 0.28cm, outerR= 0.30 cm H= 1.76 cm for small sample, assuming a cylindrical shape

$$V = \pi R^2 H$$

Case 1 (Using integral flux squared)

$$\Sigma_{ap} = -\frac{\rho\nu\int_V \Sigma_f\left(Aj_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right)\right)^2 dV}{\int_V A^2(j_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right))^2\,dV}\ (A^2s\ cancel\ out)$$

$$\Sigma_{ap} = -\frac{\rho\nu\int_V \Sigma_f(j_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right))^2 dV}{\int_V (j_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right))^2 dV\ \ (integral\ for\ sample)}$$

$$\Sigma_{ap} = -\frac{\left((0.1791\$ * 0.0074)(2.4)(0.0762)(1.789 * 10^3)\right)}{(0.0637)} = 6.85\ cm^{-1}$$

$$\sigma_{ap} = \frac{\Sigma_{ap}}{N} = 147.38\ b$$

Case 2 (using volume sample)

Using equation 26 and taking a point at the center of the reactor where flux is maximum:

$$\phi\,(0,0) = A$$

$$\Sigma_{ap} = -\frac{\rho\nu\int_V \Sigma_f\left(Aj_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right)\right)^2 dV}{V_p A^2} == -\frac{\rho\nu\int_V \Sigma_f\left(j_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right)\right)^2 dV}{V_p}$$

$$\Sigma_{ap} = -\frac{\left((0.1791\$ * 0.0074)(2.4)(0.0762)(1.789 * 10^3)\right)}{(0.095)} = 4.56\ cm^{-1}$$

$$\sigma_{ap} = \frac{\Sigma_{ap}}{N} = 98.15\ b$$

For both cases the calculation of the number of atoms is, with a sample mass of 1.6g:

$$N = \left(\frac{\rho N_a}{M}\right) = \frac{(8.65 * 6.022 * 10^{23})}{112.411} = 0.046 * 10^{24} atoms$$

The tabulated absorption cross-section for cadmium is 1250 b. This value is far from the values calculated using one group perturbation theory, so for cadmium, one group does not come with a good result. Multi group transport calculations were the next step.

Cadmium was further analyzed at different subcritical stages. Although it was possible to get a reactivity worth number, the numbers are not consistent with the reactivity worth found at criticality.

ANISN modeling gave a better approximation of the cadmium cross-section by using multi-group adjoint flux but it proved that cadmium is not a well-behaved absorber.

Next absorber studied was indium. Only thin sheets were available, so a few of them where stacked together and shaped into an irregular cylinder. The reactivity worth of this sample through oscillations was:

$$\rho_{In} = -11.51 \pm 0.51\ ¢$$

The calculated absorption cross-section using one group perturbation theory (appendix B) was:

$$\sigma_{In} = 55.52\ b$$

The literature absorption cross-section for indium[14] is 194 b. The problem with this sample is that there is air in between layers of indium sheets. Just a small reduction in the radius of the sample gets the value of the cross section much closer to the literature value.

Last absorber analyzed was gold. The same problem mentioned above in indium was also found in gold. Air spaces could be completely removed from between the layers.

The reactivity worth of the sample was found to be:

$$\rho_{Au} = -6.84 \pm 1.01 \text{ ¢}$$

The one group perturbation theory analysis (appendix B) gave an absorption cross-section of:

$$\sigma_{Au} = 27.60\ b$$

The literature value is 98.8 b.

Several SCA experiments were performed without any conclusive results. The fact that the LND detector could not be used because of not having enough sensitivity was critical in these set of experiments. Count rates were used instead. Count rates would change between morning and afternoon and this was attributed to temperature changes but sometimes there was no difference in count rates between having an absorber in the assembly or not. After several experiments it was determined that the results were not good for the purpose of this work.

7. Conclusions

From this work it can be concluded that it is difficult to obtain reactivity worth of samples even of the order of 10-20 cents at low levels of criticality and low source strength. This is in contrast with previous work that demonstrated reactivity worths of small cadmium samples could be obtained down to the fractions of one hundredths of a cent; however those results were obtained with the reactor critical and operating at much higher power levels (up to 3 watts). We attempted to demonstrate meaningful measurements at k=0.97, but for the most part the results were inconclusive and typical errors on the order of 10% for samples in the 10-20 cents reactivity range were found. It is not likely that increased fixed source levels would help because it is the multiplication that has to change at sub-critical levels. Our AGN with all control rods withdrawn has a shutdown worth of about 0.0325 (Δk), which leads to a multiplication of about 30.77. A 10 cents addition to the core would change the multiplication to 30.12 which goes a long way to explaining why our results were poor at the low sub-critical levels. Unfortunately, people would like to operate at even lower subcritical levels (Δk=0.05, or k=0.95) which would exacerbate the situation since there would be less fission neutrons available.

We also investigated the technique of calculating the effective absorption cross sections using the reactivity data. We looked at both one-group diffusion and multi-group transport perturbation methods. We concluded that the fabrication of controlled samples (geometry and compositions) is extremely important, but the methodology is correct given better samples and multi-dimensional transport codes capable of calculating forward and adjoint fluxes.

8. Future work

Although our initial conclusions would indicate that measurements at low subcritical states would not yield adequate uncertainties, it would be desirable to definitively be able to make that case. Therefore future experiments should focus on mainly two things.

Due to the small neutron population in both the AGN-reactor in the subcritical regime and the SCA, more sensitive detectors should be used. Previous oscillator experiments at ISU have been done with the reactor critical and at higher than 10 mW power, and they have accomplished good results with low uncertainties. We should be able to see at least some reduction in uncertainties with better detectors and stronger sources.

The second important thing is, as already mentioned, the availability of regular shape, solid absorber samples of known compositions. Best choices would be gold and indium. Cadmium can be used but analysis will require multidimensional multi-group transport codes.

Finally it must be stressed that applying these results to a fast subcritical system may not be possible because of the much lower cross-sections.

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Appendix A – Matlab code for inverse kinetics Created by B. Baker, adapted for this work by

D. Coll Segarra

```
%%% Inverse Kinetics Code
%Performs inverse kinetics on two vectors
clc; clear all; close all;
format('shorte'); %Changes the number of significant digits matlab uses
% User input for while material file to use
% d = dir;
% str = {d.name};
% str=str(3:end);
% [s,~] = listdlg('PromptString','Select a file:',...
% 'SelectionMode','single',...
% 'ListString',str);
% Data Import
%filetitle=str{s};
% Selection of which assemblies.
%prompts the user to set the name of the file it should look for.
%To add the changes for calculating the reactivity modify the file past
% second line that looks like the one below.
clf %clears the figure
%sr1=csvread(filetitle,0.0); %Reads in the data from the file
sr1=csvread('C:\Users\Lab User\Desktop\Project\Experiment
15/Exp15_Gold05.csv',0.0);
%Pertchoice2 = questdlg('Would you like to convert the LVM data?', ...
%'LVM convert','Yes','No','No');
Pertchoice2='No';
switch Pertchoice2
      case 'Yes'
         cps=[sr1(:,1) (1/10)*(1./(10.^(2.*sr1(:,2))))];
         x=cps(:,1);
         y=cps(:,2);
         Ylab='linear power / counts';
      case 'No'
         x=sr1(:,1); %Creates a vector from just the 3rd column of data.
    %(timestamp)
    y=sr1(:,2)*10^10; %Create another vector from the 2nd column of data
    %(Rawdata)
    y=sr1(:,2);
    Ylab='(Current from detector)*10^10';
end
%filetitle='lab2finerod.lvm'; %Testing purposes
%The reason the y data is multiplied by 10^10 is to just make the numbers a
%bit easier for matlab to process, it does not change your answer since it
%is only based upon the relative change in data points
filetitle = 'Power';
RawF=figure;
RawAx=axes(RawF);
plot(RawAx,x,y) %Displays the first plot, this shows the raw data gathered
from the reactor.
title('RAW Data of Power')
xlabel('Time in Seconds')
ylabel(Ylab)
```

```
n=1; %Sets a starting counter for the while loop
yf=zeros(length(y)+2,1); %yf is the filtered data, this creates a new vector
with 2 additional spots
%The reason for the two additional spots is because inorder to filter the
%data it needs the two previous points which the first element in y does
%not have.
%Copies the y vector to yf.
while(n<=length(y))
yf(n+2,1)=y(n,1);
n=n+1;
end
%Duplicates the first element twice and places them before the array
yf(1,1)=yf(3,1);
yf(2,1)=yf(3,1);
%Replaces y with yf.
y=yf;
%The following code performs the same actions on the x vector as the y
%vector. The new variables will be xf yf.
n=1;
xf=zeros(length(x)+2,1);
while(n<=length(x))
xf(n+2,1)=x(n,1);
n=n+1;
end
xf(1,1)=xf(3,1);
xf(2,1)=xf(3,1);
%The following code performs the filtering as laid out in the lab manual.
%The equation is the same as the one shown on pg. (insert page reference)
%Since the filtering equation needs to refer to previous points, we start
%the counter at 3 and look back by 2.
%The filtering equation takes in both filtered and unfiltered data, hence
%why everything is written to yf but reads from both yf and y.
n=3;
%The filtering equation
while(n<=length(yf))
yf(n,1)=1.779*yf(n-1,1)-0.8*yf(n-2,1)+0.00554*y(n,1)+0.01108*y(n-
1,1)+0.00554*y(n-2,1);
n=n+1;
end
n=1;
%Recreates x and y vectors to eb the same length as yf and xf. The old x
%and y will not be needed anymore.
x=zeros(length(xf)-2,1);
y=zeros(length(yf)-2,1);
%removes the first two extra values
while(n<=length(yf)-2)
x(n,1)=xf(n+2,1);
y(n,1)=yf(n+2,1);
n=n+1;
end
xf=x;
yf=y;
n=2;
i=1;
%Sets the beta i's and the lamdba i's for the AGN reactor.
B=[0.038; 0.213; 0.188; 0.407; 0.128; 0.026]*0.00745;
L=[1/55.72; 1/22.72; 1/6.22; 1/2.3; 1/0.610; 1/0.23]*log(2);
```

```
b=0;
yp=zeros(length(yf),1);
in=zeros(1,6);
% the following 2 while loops are peforming the invese kinetics.
while(n<=length(yf))
dt=(xf(n,1)-xf(n-1,1));
a=((yf(n,1)-yf(n-1,1))/dt)*(62.2E-6/yf(n,1))+0.00745;
while(i<=6)
in(i)=(in(i)*exp(-L(i,1)*dt))+(yf(n,1)+yf(n-1,1)*exp(-L(i,1)*dt))*dt/2;
b=b+B(i,1)*( yf(1,1)*exp(-L(i,1)*xf(n,1)) + L(i,1)*in(i));
i=i+1;
end
yp(n-1,1)=(a-(b/yf(n-1,1)))*(100/0.00745);
n=n+1;
i=1;
b=0;
end
% Refilter the same way as before the inverse kinetics.
n=4;
yfp=zeros(length(yp)+2,1);
yfp(1,1)=yp(1,1);
yfp(2,1)=yp(1,1);
yfp(3,1)=yp(1,1);
while(n<=length(yfp))
yfp(n,1)=yp(n-2,1);
n=n+1;
end
%removes infinities the come up because of the step change in the data
%point values. This is alright to do because we just replace inf with a
%copy of the previous data point.
for n=1:length(yfp)
if(yfp(n,1)==inf || yfp(n,1)==-inf)
yfp(n,1)=yfp(n-1,1);
end
end
for n=1:length(yp)
if(yp(n,1)==inf || yp(n,1)==-inf)
    yp(n,1)=yp(n-1,1);
end
end
%Refilter
for i=1:10
for n=3:length(yp)
yfp(n,1)=1.779*yfp(n-1,1)-0.8*yfp(n-2,1)+0.00554*yp(n,1)+0.01108*yp(n-
1,1)+0.00554*yp(n-2,1);
end
end
n=1;
xff=zeros(length(xf)+2,1);
xff(1,1)=xf(1,1);
xff(2,1)=xf(1,1);
xff(3,1)=xf(1,1);
while(n<=length(xf))
xff(n+2,1)=xf(n,1);
n=n+1;
end
IKFig=figure('units','normalized','outerposition',[0 0 1 1]);
```

```
%This creates all of the subplots the user sees.
subplot(1,2,1,'Parent',IKFig), plot(x,y)
title(['Power Plot for ',filetitle])
xlabel('Time in Seconds')
ylabel(Ylab)
subplot(1,2,2,'Parent',IKFig), plot(xff,yfp)
title(['Inverse Kinetics of ', filetitle])
xlabel('Time in Seconds')
ylabel('Reactivity in cents')
figure(1)
[pks,locs] = findpeaks(yfp,'MinPeakDistance',800)
[pkm,locm] = findpeaks(-yfp,'MinPeakDistance',800)
%plot(xff,yfp,xff([locs,locm]),[pks,-pkm],'or')
plot(xff,yfp,xff(locs),pks,'or')
plot(xff,yfp,xff([locm]),-pkm,'or')
meanpeakT = mean(pks)
meanpeakB = mean (-pkm)
STDT= std(pks)/sqrt(length(pks))
STDB= std(-pkm)/sqrt(length(pkm))
FullPk= (meanpeakT-meanpeakB)
FullSD=sqrt((STDT^2)+(STDB^2))
title(['Inverse Kinetics of ', filetitle])
xlabel('Time in Seconds')
ylabel('Reactivity in cents')
IK=[xff,yfp];
%IKS=smoothdata(IK,'movmedian')
csvwrite('IKinetics.csv',IK) %Writes the IK data to a csv file
%plot(IK,IKS)
%The filtered inverse kinetics data is the yfp vector and the timestamp
% is xfp.
% The original data is x for time and y for measured data
```

Appendix B - MCNP code

AGN reactor with no sample in core

AGN201 Simplified Model This version has k 1.02792 change

c Changed U Fuel Density by .989 across for m100

c Trevor Boaz

c 1.02792 with .989 U reactor materials*

c Adjusting density of graphite from 1.75 to 1.70 k=1.01629

c 8.5191371429E-02

c Adjusting graphite to 1.7 to 1.65 k-1.2011

c Adj to 1.6 k=1.0156

c adit to 1.55 k=1.00560

c adj to 1.54 k-1.00454!!!!!

c Cell Cards

c Air in glory hole

10 300 -.001205 -10 12 -13 imp:n=1 $

c Aluminum around Glory Hole

20 200 -2.6989 10 -11 12 -13 imp:n=1 $

c Fuse

25 500 1.12828199E-01 70 -71 -72 imp:n=1 $

c Air around fuse

26 300 -.001205 50 -71 -80 #25 imp:n=1 $ #25

c Reactor Core

30 100 1.199628696E-01 11 50 -51 -52 imp:n=1 $

c Graphite around core

40 400 7.717336E-02 11 60 -61 -62 #30 imp:n=1 $

c BOUNDING

400 0 -500 #10 #20 #30 #40 imp:n=1 $ -60:61:62 #20

401 0 500 imp:n=0 $

c Surface Cells

10 cx 1.1 $Inner glory hole dimensions diameter is 2.2cm

11 cx 1.43 $Outer glory hole dimension, thickness is .33cm

12 px -32.85 $ Place holder of back edge of tube

13 px 32.85 $ Place holder of front edge of tube

c Reactor Dimensions

50 pz -12 $Bottom of fuel plates

51 pz 11.7 $Top of fuel plates (NO RAD included 11.7+12=23.7)

52 cz 12.8 $ Fuel radius

c Graphite Dimensions

60 pz -34.5 $Bottom of graphite

61 pz 34.2 $Top of graphite

62 cz 32.8 $Radius of graphite

c Fuse Dimensions

70 pz -2.38 $just below glory hole 1.43+.95

71 pz -1.43

72 cz 1.1 $diameter is 2.2

c Air around fuse

80 cz 1.36

c BOUNDING

500 so 100

c Data Cards

kcode   1000000 1.0   25   125

ksrc   0 0 4 $ (x y z, chose above glory hole for ease)

c

c U02 in C2H4 rho=1.199628696 (Adjusted 235 by .9895813

m100 92235.70c 1.42205251457751E-04

*   92238.70c 5.69573100E-04*

92234.70c 8.5492372154227E-07

1001.70c 7.8545932730626E-02

6000.70c 3.92771498281218E-02

8016.70c 1.427693223911E-03

c

c Aluminum rho= 2.6989 g/cc

m200 13027.70c -1.0

c

c Air rho=.001205

m300 6000.70c .000151 $ C

7014.70c .784437 $ N

8016.70c .210750 $ O

18000 .004671

c Graphite

m400 6000.70c 7.717336E-02

c Fuse 1.12828199E-01

m500 92235.70c 2.63E-04

92234.70c 1.58E-06

92238.70c 1.05E-03

92236.70c 2.76E-06

8016.70c 2.64E-03

8017.70c 1.00E-06

6000.70c 3.63E-02

1001.70c 7.26E-02

1002.70c 8.35E-06

c S-Alpha/Beta Treatments

mt100 poly.10t o2/u.10t

mt400 grph.10t

AGN reactor with cadmium sample in core

AGN201 Simplified Model This version has k 1.02792 change

c Changed U Fuel Density by .989 across for m100

c Trevor Boaz

c 1.02792 with .989 U reactor materials*

c Adjusting density of graphite from 1.75 to 1.70 k=1.01629

c 8.5191371429E-02

c Adjusting graphite to 1.7 to 1.65 k-1.2011

c Adj to 1.6 k=1.0156

c adit to 1.55 k=1.00560

c adj to 1.54 k-1.00454!!!!!

c David Coll added cadmium sample in center glory hole

c Cell Cards

c Air in glory hole

10 300 -.001205 -10 12 -13 -14 16 -17 imp:n=1 $

c Aluminum around Glory Hole

20 200 -2.6989 10 -11 12 -13 15 -16 17 imp:n=1 $

c Fuse

25 500 1.12828199E-01 70 -71 -72 imp:n=1 $

c Air around fuse

26 300 -.001205 50 -71 -80 #25 imp:n=1 $ #25

c Reactor Core

30 100 1.199628696E-01 11 50 -51 -52 imp:n=1 $

c Graphite around core

40 400 7.717336E-02 11 60 -61 -62 #30 imp:n=1 $

c Cadmium sample

45 600 -8.65 14 -15 16 -17 imp:n=1 $

c BOUNDING

400 0 -500 #10 #20 #30 #40 imp:n=1 $ -60:61:62 #20

401 0 500   imp:n=0 $

c Surface Cells

10 cx 1.1 $Inner glory hole dimensions diameter is 2.2cm

11 cx 1.43 $Outer glory hole dimension, thickness is .33cm

12 px -32.85 $ Place holder of back edge of tube

13 px 32.85 $ Place holder of front edge of tube

14 cx 0.27 $ inner diameter sample

15 cx 0.30 $ outer diameter sample

16 px -0.88 $ one end of sample

17 px 0.88 $ other end sample

c Reactor Dimensions

50 pz -12 $Bottom of fuel plates

51 pz 11.7 $Top of fuel plates (NO RAD included 11.7+12=23.7)

52 cz 12.8 $ Fuel radius

c Graphite Dimensions

60 pz -34.5 $Bottom of graphite

61 pz 34.2 $Top of graphite

62 cz 32.8 $Radius of graphite

c Fuse Dimensions

70 pz -2.38 $just below glory hole 1.43+.95

71 pz -1.43

72 cz 1.1 $diameter is 2.2

c Air around fuse

80 cz 1.36

c BOUNDING

500 so 100

c Data Cards

kcode   1000000 1.0   25   125

ksrc 0 0 4 $ (x y z, chose above glory hole for ease)

c

c U02 in C2H4 rho=1.199628696 (Adjusted 235 by .9895813

m100 92235.70c 1.42205251457751E-04

92238.70c 5.69573100E-04

92234.70c 8.5492372154227E-07

1001.70c 7.8545932730626E-02

6000.70c 3.92771498281218E-02

8016.70c 1.427693223911E-03

c

c Aluminum rho= 2.6989 g/cc

m200 13027.70c -1.0

c

c Air rho=.001205

m300 6000.70c .000151 $ C

7014.70c .784437 $ N

8016.70c .210750 $ O

18000 .004671

c Graphite

m400 6000.70c 7.717336E-02

c Fuse 1.12828199E-01

m500 92235.70c 2.63E-04

92234.70c 1.58E-06

92238.70c 1.05E-03

92236.70c 2.76E-06

8016.70c 2.64E-03

8017.70c 1.00E-06

6000.70c 3.63E-02

1001.70c 7.26E-02

1002.70c 8.35E-06

c Cd sample

m600   48106.70c -0.0125

48108.70c -0.0089

48110.70c -0.1249

48111.70c -0.1280

48112.70c -0.2413

48113.70c -0.1222

48114.70c -0.2873

48116.70c -0.0749

c S-Alpha/Beta Treatments

mt100   poly.10t o2/u.10t

mt400   grph.10t

Appendix C ***<u>One-group perturbation theory Mathematica code</u>***

Stainless one group perturbation theory calculations in Mathematica

```
In[ ]:= Clear["`*"]

In[ ]:= H = 25.8;
        R = 12.8;
```

Take half sample to put it at +/- center of core in z direction

```
In[ ]:= sample = 4.0 / 2
Out[ ]= 2.
```

Center of core since using sine function for flux, zero position is bottom

```
In[ ]:= mid = H / 2
Out[ ]= 12.9
```

Bessel integrations

```
In[ ]:= B1 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0.38, 0.48}]
Out[ ]= 0.0428579

In[ ]:= B2 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0, R}]
Out[ ]= 22.0754
```

Sine integrations

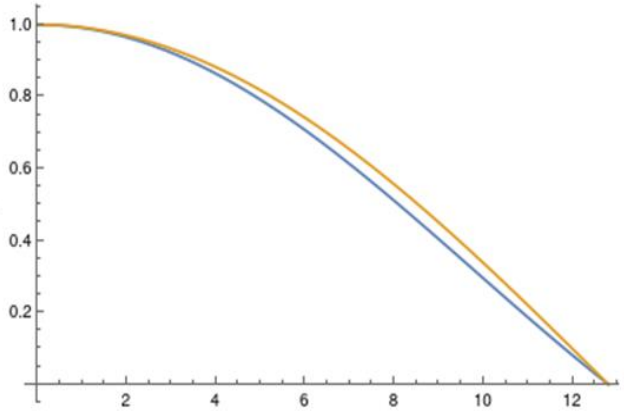
```
In[ ]:= S1 = Integrate [Sin[Pi * z / H] ^2, {z, mid - sample, mid + sample}]
Out[ ]= 3.92185

In[ ]:= S2 = Integrate [Sin[Pi * z / H] ^2, {z, 0, H}]
Out[ ]= 12.9

In[ ]:= FluxSample = 2 * Pi * B1 * S1
Out[ ]= 1.05609

In[ ]:= FluxReactor = 2 * Pi * B2 * S2
Out[ ]= 1789.28

In[ ]:= ν = 2.42;

In[ ]:= Σf = 0.0762;

In[ ]:= ρ = 0.0878 * 0.0074
Out[ ]= 0.00064972
```

```
In[•]:= Σap = ρ * ν * Σf * FluxReactor / FluxSample
Out[•]= 0.208075

In[•]:= ρCd = 8.00;

In[•]:= Ncd = (ρCd * 0.6022 / 55)
Out[•]= 0.0875927

In[•]:= σCd = Σap / Ncd
Out[•]= 2.37548
```

Not too far off given one group perturbation theory with a lot of assumptions

```
In[•]:= Plot[{BesselJ[0, 2.405 * x / R], Cos[π * x / 2 / R]}, {x, 0, R}]
```

Out[•]=



Note that we have effectively flipped the sine and Bessel behaviors by assuming the sample's geometry aligned z axis along glory hole and reactor's is vertical. This shows that the variational difference (flux squared is simply a weighting function) does not matter much over the 1.76 cm length of the sample

Cadmium one group perturbation theory calculations in Mathematica

```
In[ ]:= Clear["`*"]

In[ ]:= H = 25.8;
        R = 12.8;
```

Take half sample to put it at +/- center of core in z direction

```
In[ ]:= sample = 1.76 / 2
Out[ ]= 0.88
```

Center of core since using sine function for flux, zero position is bottom

```
In[ ]:= mid = H / 2
Out[ ]= 12.9
```

Bessel integrations

```
In[ ]:= B1 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0.28, 0.3}]
Out[ ]= 0.00579138

In[ ]:= B2 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0, R}]
Out[ ]= 22.0754
```

Sine integrations

```
In[ ]:= S1 = Integrate [Sin[Pi * z / H] ^2, {z, mid - sample, mid + sample}]
Out[ ]= 1.75328

In[ ]:= S2 = Integrate [Sin[Pi * z / H] ^2, {z, 0, H}]
Out[ ]= 12.9

In[ ]:= FluxSample = 2 * Pi * B1 * S1
Out[ ]= 0.0637989

In[ ]:= FluxReactor = 2 * Pi * B2 * S2
Out[ ]= 1789.28

In[ ]:= ν = 2.42;

In[ ]:= Σf = 0.0762;

In[ ]:= ρ = 0.1791 * 0.0074
Out[ ]= 0.00132534

In[ ]:= Σap = ρ * ν * Σf * FluxReactor / FluxSample
Out[ ]= 6.85429

In[ ]:= ρCd = 8.65;

In[ ]:= Ncd = (ρCd * 0.6022 / 112)
Out[ ]= 0.0465092

In[ ]:= σCd = Σap / Ncd
Out[ ]= 147.375
```

Indium one group perturbation theory calculations in Mathematica

```
In[ ]:= Clear["`*"]

In[ ]:= H = 25.8;
        R = 12.8;
```

Take half sample to put it at +/- center of core in z direction

```
In[ ]:= sample = 1.3 / 2
Out[ ]= 0.65
```

Center of core since using sine function for flux, zero position is bottom

```
In[ ]:= mid = H / 2
Out[ ]= 12.9
```

Bessel integrations

```
In[ ]:= B1 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0, 0.18}]
Out[ ]= 0.0161954

In[ ]:= B2 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0, R}]
Out[ ]= 22.0754
```

Sine integrations

```
In[ ]:= S1 = Integrate [Sin[Pi * z / H] ^2, {z, mid - sample, mid + sample}]
Out[ ]= 1.29729

In[ ]:= S2 = Integrate [Sin[Pi * z / H] ^2, {z, 0, H}]
Out[ ]= 12.9

In[ ]:= FluxSample = 2 * Pi * B1 * S1
Out[ ]= 0.13201

In[ ]:= FluxReactor = 2 * Pi * B2 * S2
Out[ ]= 1789.28

In[ ]:= ν = 2.42;

In[ ]:= Σf = 0.0762;

In[ ]:= ρ = 0.1151 * 0.0074
Out[ ]= 0.00085174

In[ ]:= Σap = ρ * ν * Σf * FluxReactor / FluxSample
Out[ ]= 2.12886

In[ ]:= ρIn = 7.31;

In[ ]:= Nin = (ρIn * 0.6022 / 114.8)
Out[ ]= 0.0383457

In[ ]:= σIn = Σap / Nin
Out[ ]= 55.5177
```

Gold one group perturbation theory calculations in Mathematica

```
In[ ]:= Clear["`*"]

In[ ]:= H = 25.8;
        R = 12.8;
```

Take half sample to put it at +/- center of core in z direction

```
In[ ]:= sample = 0.05 / 2
Out[ ]= 0.025
```

Center of core since using sine function for flux, zero position is bottom

```
In[ ]:= mid = H / 2
Out[ ]= 12.9
```

Bessel integrations

```
In[ ]:= B1 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0, 1.15}]
Out[ ]= 0.653577

In[ ]:= B2 = Integrate [x * (BesselJ[0, 2.405 * x / R]) ^2, {x, 0, R}]
Out[ ]= 22.0754
```

Sine integrations

```
In[ ]:= S1 = Integrate [Sin[Pi * z / H] ^2, {z, mid - sample, mid + sample}]
Out[ ]= 0.0499998

In[ ]:= S2 = Integrate [Sin[Pi * z / H] ^2, {z, 0, H}]
Out[ ]= 12.9

In[ ]:= FluxSample = (2 * Pi * B1 * S1) / 2
Out[ ]= 0.102663

In[ ]:= FluxReactor = 2 * Pi * B2 * S2
Out[ ]= 1789.28

In[ ]:= ν = 2.42;

In[ ]:= Σf = 0.0762;

In[ ]:= ρ = 0.0684 * 0.0074
Out[ ]= 0.00050616

In[ ]:= Σap = ρ * ν * Σf * FluxReactor / FluxSample
Out[ ]= 1.62675

In[ ]:= ρAu = 19.282;

In[ ]:= Nau = (ρAu * 0.6022 / 197)
Out[ ]= 0.0589422

In[ ]:= σAu = Σap / Nau
Out[ ]= 27.5991
```

Multigroup cadmium sample

```
In[ ]:= Clear["`*"]

In[ ]:= SetDirectory["dropbox/anisnworking"]

        SetDirectory: Cannot set current directory to dropbox/anisnworking.

Out[ ]= $Failed
```

.pun files are forward and adjoint flux files. 67 groups over 97 intervals. 47 groups are neutrons

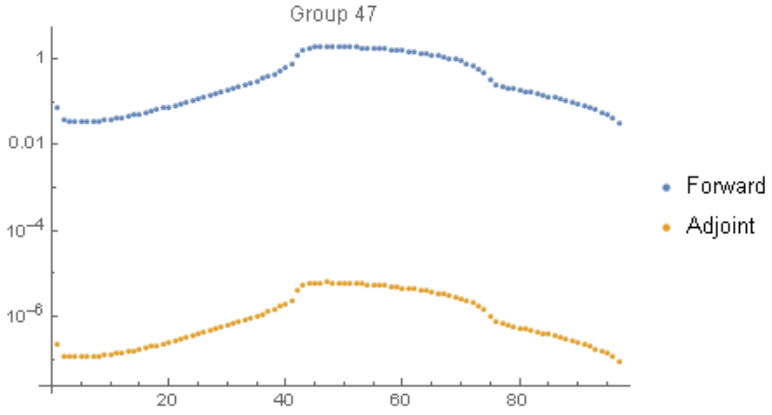
```
In[ ]:= forward = Flatten[Import["forwardcrit.pun", "Table"]];
```

Now pick out the lowest three groups assuming they will give the majority of the response

Group 47 (0-0.1 eV)

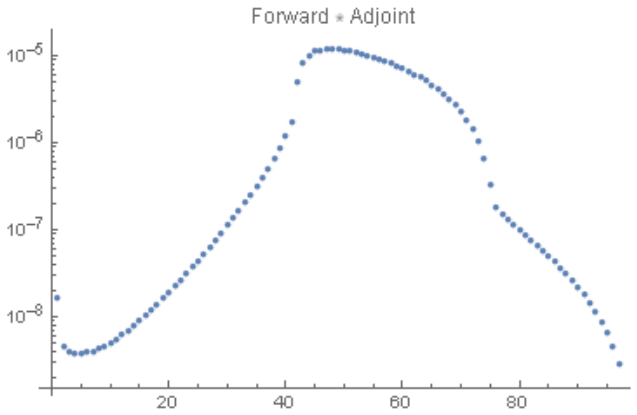
```
In[ ]:= ϕ47 = forward[[4463 ;; 4559]];

In[ ]:= adjoint = Flatten[Import["adjointcrit.pun", "Table"]];

In[ ]:= ϕad47 = adjoint[[4463 ;; 4559]];

In[ ]:= ListLogPlot[{ϕ47, ϕad47}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 47"]
```

Out[ ]=




```
In[ ]:= ListLogPlot[{ϕ47 * ϕad47}, PlotLabel → "Forward * Adjoint"]
```

Out[ ]=

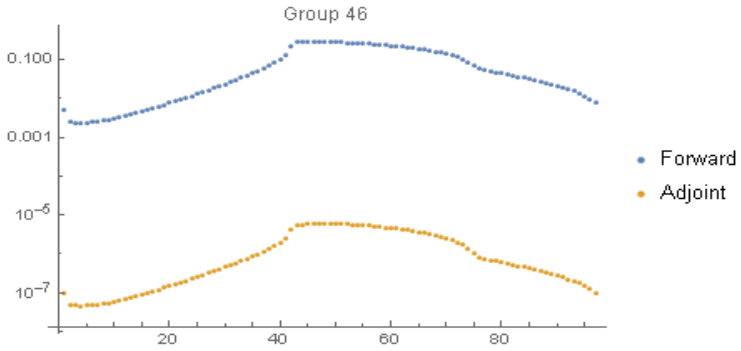



```
In[ ]:= Max[ϕ47 * ϕad47]

Out[ ]= 0.0000118886
```

Group 46 (0.1-0.414 eV)

```
In[ ]:= ϕ46 = forward[[4366 ;; 4462]];
In[ ]:= ϕad46 = adjoint[[4366 ;; 4462]];
In[ ]:= ListLogPlot[{ϕ46, ϕad46}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 46"]
```

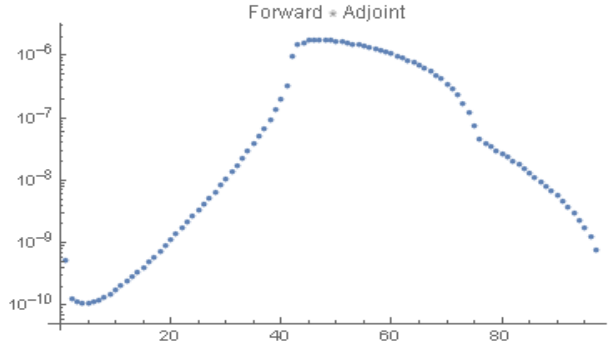
Out[ ]=



Group 46 almost a decade lower than group 47

```
In[ ]:= ListLogPlot[{ϕ46 * ϕad46}, PlotLabel → "Forward * Adjoint"]
```

Out[ ]=

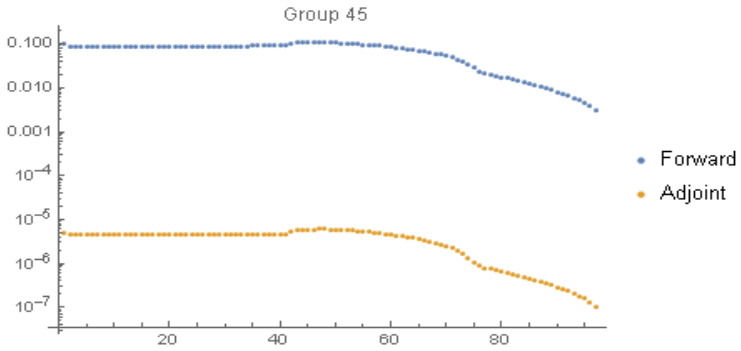



```
In[ ]:= Max[ϕ46 * ϕad46]
Out[ ]= 1.77331 × 10^-6
```

Group 45 (0.4-0.87)

```
In[ ]:= ϕ45 = forward[[4269 ;; 4365]];
In[ ]:= ϕad45 = adjoint[[4269 ;; 4365]];
In[ ]:= ListLogPlot[{ϕ45, ϕad45}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 45"]
```

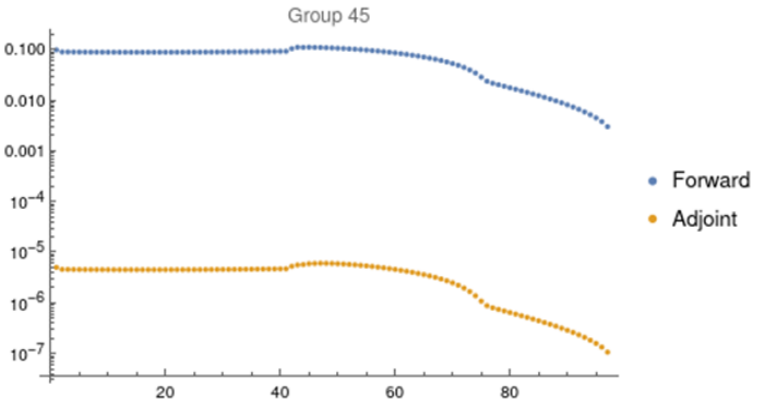
Out[ ]=



Note how the cadmium no longer self shields since we are above the cadmium cutoff

```
In[•]:= ListLogPlot[{ϕ45, ϕad45}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 45"]
```

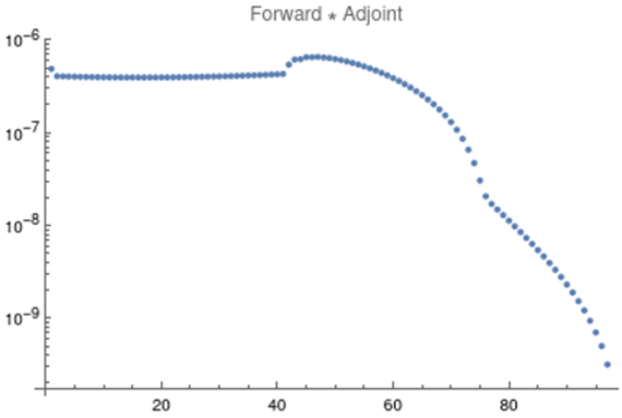
Out[•]=



Note how the cadmium no longer self shields since we are above the cadmium cutoff

```
In[•]:= ListLogPlot[{ϕ45 * ϕad45}, PlotLabel → "Forward * Adjoint"]
```

Out[•]=

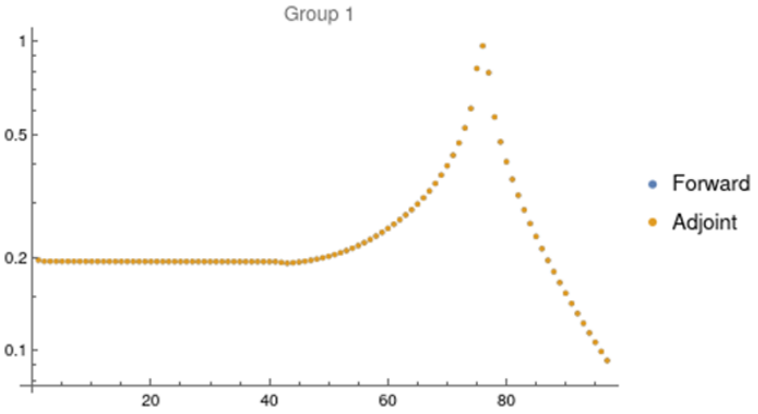



```
In[•]:= Max[ϕ45 * ϕad45]
```

Out[•]= 6.55591×10^{-7}

```
In[•]:= ϕ1 = forward[[1 ;; 97]];

In[•]:= ϕad1 = adjoint[[1 ;; 97]];

In[•]:= ListLogPlot[{ϕ1, ϕad1}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 1"]
```

Out[•]=



```
corevol = 4 / 3 * π * ((corerad + Δr) ^ 3 - corerad^3)
corevol = corevol[[1 ;; J - 1]]
```

Now core adjoint and forward fluxes (43 through 75 represent the intervals of the core)

```
adjointcoreflux = ϕad47[[43 ;; 75]] + ϕad46[[43 ;; 75]] + ϕad45[[43 ;; 75]]
forwardcoreflux = ϕ47[[43 ;; 75]]
```

Now the integrand of the core integration in perturbation theory which becomes the denominator

```
integrandcore = forwardfissiondensity * adjointcoreflux * corevol
denom = Total[integrandcore]
```

```
0.0153236
```

Now repeat in the cadmium region, including Group 45 even though its contribution is small

```
adjointcadflux47 = ϕad47[[2 ;; 41]];
adjointcadflux46 = ϕad46[[2 ;; 41]];
adjointcadflux45 = ϕad45[[2 ;; 41]];
forwardcadflux47 = ϕ47[[2 ;; 41]];
forwardcadflux46 = ϕ46[[2 ;; 41]];
forwardcadflux45 = ϕ45[[2 ;; 41]];
J = Length[forwardcadflux46]
```

```
40
```

```
Δrcad = 0.0005;
cadrad = Table[0.48 + Δrcad * n, {n, 0, J}]
cadvol = 4 / 3 * π * ((cadrad + Δrcad) ^ 3 - cadrad^3)
cadvol = cadvol[[1 ;; J]]
Total[cadvol]
```

```
0.0603521
```

```
integrandcad = ((forwardcadflux47 * adjointcadflux47 + forwardcadflux46 * adjointcadflux46
    + forwardcadflux45 * adjointcadflux45) * cadvol
num = Total[integrandcad]
```

$$3.71225 \times 10^{-8}$$

```
Σ = 0.18 * 0.0065 * denom / num
```

```
482.958
```

Divide by mass ratio and correct for 2200 m/s

```
Σa = Σ / 3.1
```

```
155.793
```

Multigroup cadmium zeroed out

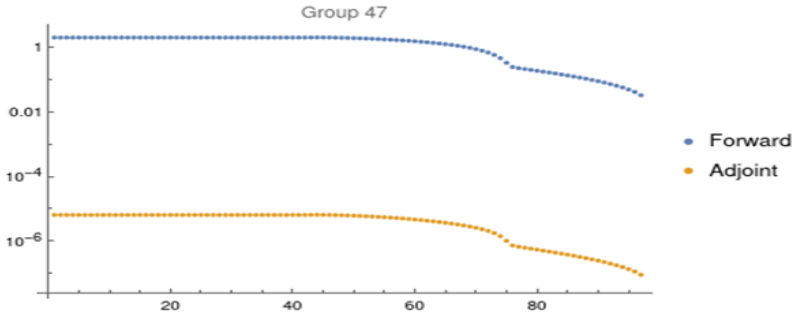
We do the same procedure as the case in which we modeled the cadmium as a shell, except now the cadmium density is zeroed out, and it would just be a volume of the perturbation.

```
In[•]:= Clear["`*"]
In[•]:= SetDirectory["dropbox/anisnworking"]
In[•]:= forward = Flatten[Import["forwardnocd.pun", "Table"]];
```

Group 47 "thermal" flux (0-0.1 eV)

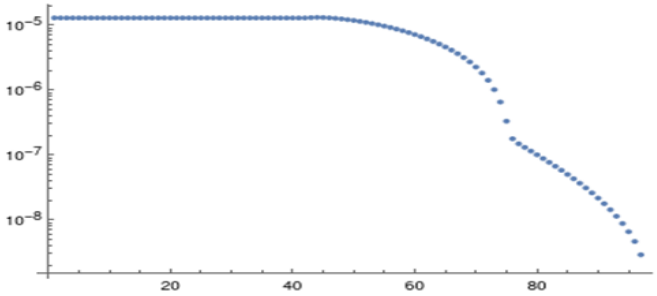
```
In[•]:= ϕ47 = forward[[4463 ;; 4559]];
In[•]:= adjoint = Flatten[Import["adjointnocd.pun", "Table"]];
In[•]:= ϕad47 = adjoint[[4463 ;; 4559]];
In[•]:= ListLogPlot[{ϕ47, ϕad47}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 47"]
```

Out[•]=




```
In[•]:= ListLogPlot[{ϕ47 * ϕad47}]
```

Out[•]=

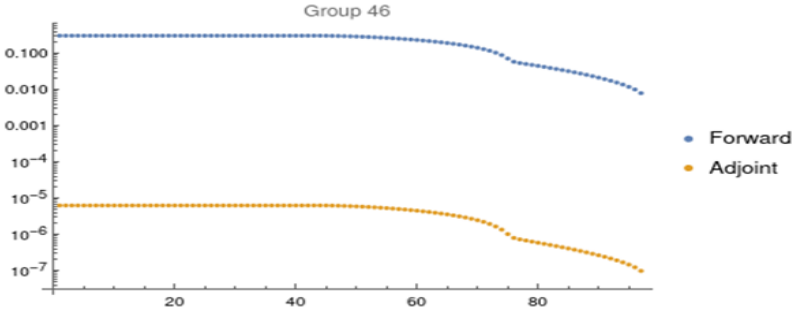



```
In[•]:= Max[ϕ47 * ϕad47]
Out[•]= 0.0000130689
```

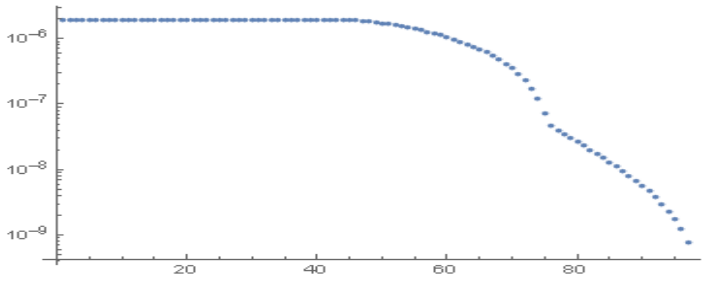
Group 46 (0.1-0.414 eV)

```
In[•]:= ϕ46 = forward[[4366 ;; 4462]];
In[•]:= ϕad46 = adjoint[[4366 ;; 4462]];
In[•]:= ListLogPlot[{ϕ46, ϕad46}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 46"]
```

Out[•]=



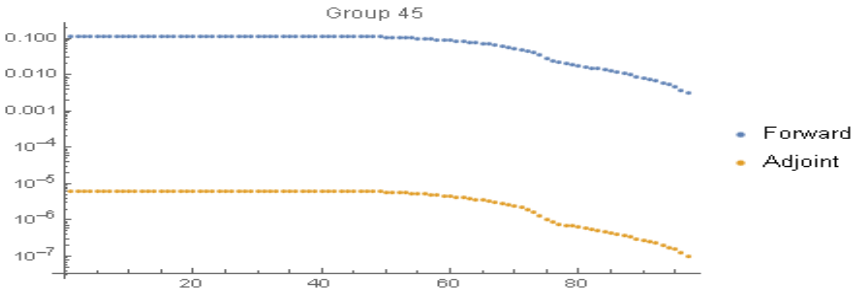
```
In[•]:= ListLogPlot[{ϕ46 * ϕad46}]
```



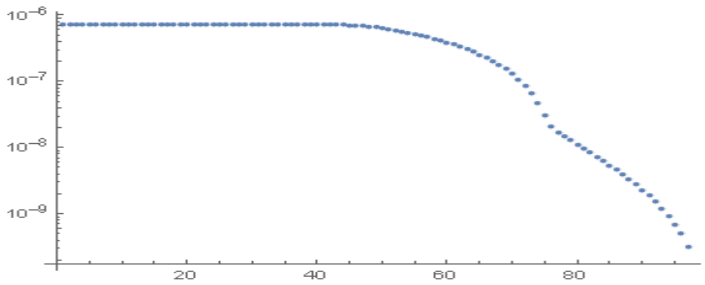

```
In[•]:= Max[ϕ46 * ϕad46]
Out[•]= 1.92871 × 10^-6
```

Group 45 (0.4-0.87 eV)

```
In[•]:= ϕ45 = forward[[4269 ;; 4365]];
In[•]:= ϕad45 = adjoint[[4269 ;; 4365]];
In[•]:= ListLogPlot[{ϕ45, ϕad45}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 45"]
```



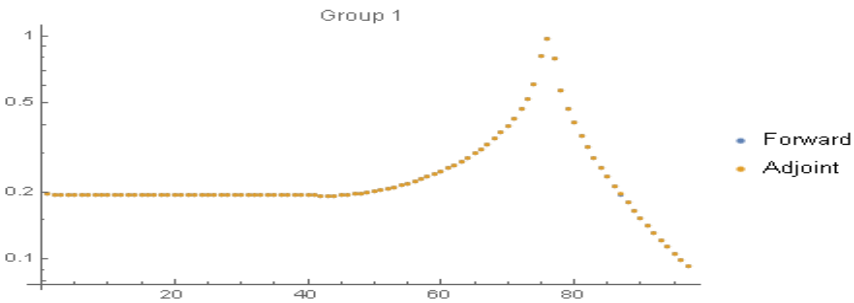

```
In[•]:= ListLogPlot[{ϕ45 * ϕad45}]
```



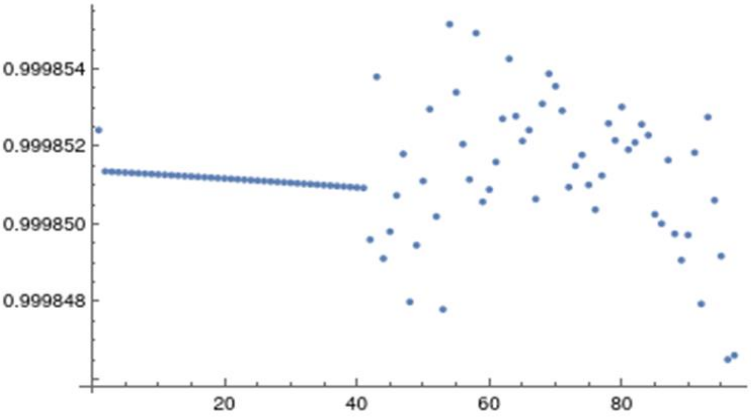

```
In[•]:= Max[ϕ45 * ϕad45]
Out[•]= 7.15488 × 10^-7
```

Group 1 (14.1-17 MeV)

```
In[•]:= ϕ1 = forward[[1 ;; 97]];
In[•]:= ϕad1 = adjoint[[1 ;; 97]];
In[•]:= ListLogPlot[{ϕ1, ϕad1}, PlotLegends → {"Forward", "Adjoint"}, PlotLabel → "Group 1"]
```



```
In[•]:= ListLogPlot[{ϕ1 / ϕad1}]
```



Out[•]=

```
In[•]:= forwardfission = Import["forwardcritfission.txt", "Table"];

In[•]:= J = Length[forwardfission]

Out[•]= 33

In[•]:= Δr = 0.3485;

In[•]:= forwardfissiondensity = Table[forwardfission[[n, 2]], {n, 1, J}];

In[•]:= corerad = Table[1.0 + Δr * n, {n, 0, J}]

In[•]:= J = Length[corerad]

Out[•]= 34

In[•]:= corevol = 4 / 3 * π * ((corerad + Δr) ^ 3 - corerad ^ 3)

In[•]:= corevol = corevol[[1 ;; J - 1]]

In[•]:= adjointcoreflux = ϕad47[[43 ;; 75]] + ϕad46[[43 ;; 75]] + ϕad45[[43 ;; 75]]

In[•]:= forwardcoreflux = ϕ47[[43 ;; 75]]

In[•]:= integrandcore = forwardfissiondensity * adjointcoreflux * corevol

In[•]:= denom = Total[integrandcore]

Out[•]= 0.0150981
```

```
In[•]:= adjointcadflux47 = ϕad47[[2 ;; 41]];

In[•]:= adjointcadflux46 = ϕad46[[2 ;; 41]];

In[•]:= adjointcadflux45 = ϕad45[[2 ;; 41]];

In[•]:= forwardcadflux47 = ϕ47[[2 ;; 41]];

In[•]:= forwardcadflux46 = ϕ46[[2 ;; 41]];

In[•]:= forwardcadflux45 = ϕ45[[2 ;; 41]];

In[•]:= J = Length[forwardcadflux47]
Out[•]= 40

In[•]:= Δrcad = 0.0005;

In[•]:= cadrad = Table[0.48 + Δrcad * n, {n, 0, J}]

In[•]:= cadvol = 4 / 3 * π * ((cadrad + Δrcad) ^ 3 - cadrad^3)

In[•]:= cadvol = cadvol[[1 ;; J]]

In[•]:= Total[cadvol]
Out[•]= 0.0603521

        integrandcad = (forwardcadflux47 * adjointcadflux47 + forwardcadflux46 * adjointcadflux46
            + forwardcadflux45 * adjointcadflux45) * cadvol

In[•]:= num = Total[integrandcad]
Out[•]= 9.3211 × 10^-7

In[•]:= Σ = 0.18 * 0.0065 * denom / num
Out[•]= 18.9514

In[•]:= Σ / 3.1
Out[•]= 6.11337
```

Appendix D ANISN code

Forward flux with no absorber

```
*********************************************************
               *                                                       *
               *                                                       *
               *  AAAAAAAA  NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
               * AAAAAAAAAA NNN     NN IIIIIIIIII SSSSSSSSSS NNN     NN  *
               * AA      AA NNNN    NN     II     SS         NNNN    NN  *
               * AA      AA NNNNN   NN     II     SS         NNNNN   NN  *
               * AAAAAAAAAA NN NNN  NN     II     SSSSSSSSS  NN NNN  NN  *
               * AAAAAAAAAA NN  NNN NN     II      SSSSSSSSS NN  NNN NN  *
               * AA      AA NN   NNNNN     II              SS NN   NNNNN  *
               * AA      AA NN    NNNN     II              SS NN    NNNN  *
               * AA      AA NN     NNN IIIIIIIIII SSSSSSSSSS NN     NNN  *
               * AA      AA NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
               *                                                       *
               *        INEL Apollo 10000 VERSION 3.2 (AUG 1988)       *
               *        Revised 4-16-93 for ANL SPARC                  *
               *            G. R. IMEL----ANL                          *
               *                  D. KENT PARSONS                      *
               *                  EG&G IDAHO, INC                      *
               *                   P.O. BOX 1625                       *
               *               IDAHO FALLS, ID 83415                   *
               *                                                       *
               *********************************************************


0 agn reactor
0   15$ ARRAY     36 ENTRIES READ
0   16* ARRAY     14 ENTRIES READ
0    0T
0 ID    PROBLEM ID NO.               1    ITH   0/1 = REG./ADJ.
0
  ISCT  ORDER OF SCATTERING          3    ISN   QUADRATURE ORDER
16
  IGE   1/2/3 = PLA/CYL/SPH          3    IBL   0/1/2/3 =
VAC/REFL/PER/ALBDO   1
  IBR   RT BC SAME AS LEFT BC,IBL    0    IZM   NO. OF ZONES
5
  IM    NO. OF INTERVALS            97    IEVT
0/1/2/3/4/5/6=Q/K/A/C/Z/R/H    0
  IGM   NO. OF GROUPS               67    IHT   POS. OF SIGMA T
3
  IHS   POS. OF SIGMA GG             4    IHM   TABLE LENGTH
70
  MS    MIXING TABLE LENGTH         28    MCR   NO. MATLS. FROM CARDS
0
  MTP   NO. MATLS. FROM LIB TAPE    24    MT    NO. OF MATLS.
40
```

```
  IDFM  0/1=NONE/DEN FACTORS(21*)     1    IPVT  0/1/2=NONE/K/ALPHA
0
  IQM   0/1=NONE/DIST. SOURCE         1    IPM
0/1/IM=NO/S(MM,IPP)/S(MM,IM)    0
  IPP   INT OF SHELL SOURCE           0    IIM   INNER ITER. MAX.
100
  ID1   0/1/2/3=NO/PRNT/PNCH/BOTH     2    ID2   -N/-1/0/1/2=ITX/IGX/-
/ITX/PRV  3
  ID3   0/N=NO/ACTIV. BY ZONE         2    ID4   0/1=NO/ACTIV. BY INT
1
  ICM   OUTER ITER. MAX.            100    IDAT1 0/1/2=NO/MIN/MAX TAPE
0
  IDAT2 0/1=NO/DIFF/INFN(24$)         0    IFG   0/1/2/3/4 NO/FG/R/W/RW
0
  IFLU  -1/0/1/2/3/4=DSA/LS/L/S/W/LW 3    IFN   -1/0/1/2=CCCC/2*/3*/PREV.
1
  IPRT  0/1 = PRINT XS/DO NOT         1    IXTR  0/1/2/3=FLUX SAVE-
NO/R/W/R&W   0
0 EV    EIGENVALUE GUESS     0.000E+00    EVM   EV MODIFIER, SEARCH
0.000E+00
  EPS   PRECISION DESIRED    1.000E-04    BF    BUCKLING FACTOR
1.421E+00
  DY    CYL OR PLA HEIGHT    0.000E+00    DZ    PLANE DEPTH
0.000E+00
  DFM1  HT. FOR VOID CORR.   0.000E+00    XNF   NORMALIZATION
0.000E+00
  PV    IPVT=1/2 - K/ALPHA   0.000E+00    RYF   SCAT, UPSCAT RELAX
5.000E-01
  XLAL  PT CONV EPS IF NE 0  1.000E-04    XLAH  1-LAMBDA MAX.,SEARCH
5.000E-02
  EQL   EV DEL EPS.,SEARCH   1.000E-03    XNPM  UNDERRELAXATION,SEARCH
7.500E-01
0450002 LOCATIONS ARE AVAILABLE FOR THIS PROBLEM
0234883 LOCATIONS WILL BE REQUIRED FOR FLUX CALCULATION
0230117 LOCATIONS WILL BE REQUIRED FOR COMPLETE SUMMARY TABLES
0227286 LOCATIONS WILL BE REQUIRED FOR COMPLETE ACTIVITY TABLES
0  6664 BYTES WILL BE REQUIRED FOR THE PROFORT RUN-TIME BUFFER
0   13$ ARRAY     24 ENTRIES READ
0    0T
0 ELEMENTS READ FROM LIBRARY TAPE
0 MAT. NO.    ID
         1    13       p0  al27    v91.94 standard wgt e601325b93vb630
         2    14       p1  al27
         3    15       p2  al27
         4    16       p3  al27
        17    95       p0  c       v91.94 standard wgt e620600b93vb630
        18    96       p1  c
        19    97       p2  c
        20    98       p3  c
         5   119       p0  cd(nat) v91.94 standard wgt e604800b93vb630
         6   120       p1  cd(nat)
         7   121       p2  cd(nat)
         8   122       p3  cd(nat)
        21   313       p0  h1(h2o) v91.94 standard wgt e620125b93vb630
```

```
        22   315       p2  h1(h2o)
        23   318       p5  h1(h2o)
        24   320       p7  h1(h2o)
         9   737       p0  u235    v91.94 standard wgt e639228b93vb630
        10   738       p1  u235
        11   739       p2  u235
        12   740       p3  u235
        13   755       p0  u238    v91.94 standard wgt e639237b93vb630
        14   756       p1  u238
        15   757       p2  u238
        16   758       p3  u238
0   17* ARRAY   6499 ENTRIES READ
0    0T
0    3* ARRAY   6499 ENTRIES READ
0    0T
0    1* ARRAY     67 ENTRIES READ
0    4* ARRAY     98 ENTRIES READ
0    5* ARRAY     67 ENTRIES READ
0    6* ARRAY     17 ENTRIES READ
0    7* ARRAY     17 ENTRIES READ
0    8$ ARRAY     97 ENTRIES READ
0    9$ ARRAY      5 ENTRIES READ
0   10$ ARRAY     28 ENTRIES READ
0   11$ ARRAY     28 ENTRIES READ
0   12* ARRAY     28 ENTRIES READ
0   19$ ARRAY      5 ENTRIES READ
0   21* ARRAY     97 ENTRIES READ
0   22$ ARRAY      2 ENTRIES READ
0   23$ ARRAY      2 ENTRIES READ
0    0T
0******  TOTAL FIXED SOURCE BEFORE NORMALIZATION  1.02154E+03


0 agn reactor
0 GEOMETRY EDIT
0 INT   ZONE       RADIUS     AREA     VOLUME  FISS DENS DEN FACTS
    1     1      0.000E+00 0.000E+00 4.632E-01 0.000E+00 0.000E+00
    2     2      4.800E-01 2.895E+00 1.449E-03 0.000E+00 0.000E+00
    3     2      4.805E-01 2.901E+00 1.452E-03 0.000E+00 0.000E+00
    4     2      4.810E-01 2.907E+00 1.455E-03 0.000E+00 0.000E+00
    5     2      4.815E-01 2.913E+00 1.458E-03 0.000E+00 0.000E+00
    6     2      4.820E-01 2.919E+00 1.461E-03 0.000E+00 0.000E+00
    7     2      4.825E-01 2.926E+00 1.464E-03 0.000E+00 0.000E+00
    8     2      4.830E-01 2.932E+00 1.467E-03 0.000E+00 0.000E+00
    9     2      4.835E-01 2.938E+00 1.470E-03 0.000E+00 0.000E+00
   10     2      4.840E-01 2.944E+00 1.473E-03 0.000E+00 0.000E+00
   11     2      4.845E-01 2.950E+00 1.476E-03 0.000E+00 0.000E+00
   12     2      4.850E-01 2.956E+00 1.479E-03 0.000E+00 0.000E+00
   13     2      4.855E-01 2.962E+00 1.483E-03 0.000E+00 0.000E+00
   14     2      4.860E-01 2.968E+00 1.486E-03 0.000E+00 0.000E+00
   15     2      4.865E-01 2.974E+00 1.489E-03 0.000E+00 0.000E+00
   16     2      4.870E-01 2.980E+00 1.492E-03 0.000E+00 0.000E+00
   17     2      4.875E-01 2.986E+00 1.495E-03 0.000E+00 0.000E+00
   18     2      4.880E-01 2.993E+00 1.498E-03 0.000E+00 0.000E+00
```

19	2	4.885E-01	2.999E+00	1.501E-03	0.000E+00	0.000E+00
20	2	4.890E-01	3.005E+00	1.504E-03	0.000E+00	0.000E+00
21	2	4.895E-01	3.011E+00	1.507E-03	0.000E+00	0.000E+00
22	2	4.900E-01	3.017E+00	1.510E-03	0.000E+00	0.000E+00
23	2	4.905E-01	3.023E+00	1.513E-03	0.000E+00	0.000E+00
24	2	4.910E-01	3.030E+00	1.516E-03	0.000E+00	0.000E+00
25	2	4.915E-01	3.036E+00	1.519E-03	0.000E+00	0.000E+00
26	2	4.920E-01	3.042E+00	1.522E-03	0.000E+00	0.000E+00
27	2	4.925E-01	3.048E+00	1.526E-03	0.000E+00	0.000E+00
28	2	4.930E-01	3.054E+00	1.529E-03	0.000E+00	0.000E+00
29	2	4.935E-01	3.060E+00	1.532E-03	0.000E+00	0.000E+00
30	2	4.940E-01	3.067E+00	1.535E-03	0.000E+00	0.000E+00
31	2	4.945E-01	3.073E+00	1.538E-03	0.000E+00	0.000E+00
32	2	4.950E-01	3.079E+00	1.541E-03	0.000E+00	0.000E+00
33	2	4.955E-01	3.085E+00	1.544E-03	0.000E+00	0.000E+00
34	2	4.960E-01	3.092E+00	1.547E-03	0.000E+00	0.000E+00
35	2	4.965E-01	3.098E+00	1.550E-03	0.000E+00	0.000E+00
36	2	4.970E-01	3.104E+00	1.554E-03	0.000E+00	0.000E+00
37	2	4.975E-01	3.110E+00	1.557E-03	0.000E+00	0.000E+00
38	2	4.980E-01	3.117E+00	1.560E-03	0.000E+00	0.000E+00
39	2	4.985E-01	3.123E+00	1.563E-03	0.000E+00	0.000E+00
40	2	4.990E-01	3.129E+00	1.566E-03	0.000E+00	0.000E+00
41	2	4.995E-01	3.135E+00	1.569E-03	0.000E+00	0.000E+00
42	3	5.000E-01	3.142E+00	3.665E+00	0.000E+00	1.000E+00
43	4	1.000E+00	1.257E+01	6.083E+00	0.000E+00	1.000E+00
44	4	1.348E+00	2.285E+01	1.020E+01	0.000E+00	1.000E+00
45	4	1.697E+00	3.619E+01	1.538E+01	0.000E+00	1.000E+00
46	4	2.045E+00	5.258E+01	2.162E+01	0.000E+00	1.000E+00
47	4	2.394E+00	7.202E+01	2.893E+01	0.000E+00	1.000E+00
48	4	2.742E+00	9.451E+01	3.730E+01	0.000E+00	1.000E+00
49	4	3.091E+00	1.201E+02	4.673E+01	0.000E+00	1.000E+00
50	4	3.439E+00	1.487E+02	5.723E+01	0.000E+00	1.000E+00
51	4	3.788E+00	1.803E+02	6.879E+01	0.000E+00	1.000E+00
52	4	4.136E+00	2.150E+02	8.142E+01	0.000E+00	1.000E+00
53	4	4.485E+00	2.528E+02	9.510E+01	0.000E+00	1.000E+00
54	4	4.833E+00	2.936E+02	1.099E+02	0.000E+00	1.000E+00
55	4	5.182E+00	3.374E+02	1.257E+02	0.000E+00	1.000E+00
56	4	5.530E+00	3.843E+02	1.426E+02	0.000E+00	1.000E+00
57	4	5.879E+00	4.343E+02	1.605E+02	0.000E+00	1.000E+00
58	4	6.227E+00	4.873E+02	1.795E+02	0.000E+00	1.000E+00
59	4	6.576E+00	5.434E+02	1.996E+02	0.000E+00	1.000E+00
60	4	6.924E+00	6.025E+02	2.207E+02	0.000E+00	1.000E+00
61	4	7.273E+00	6.647E+02	2.429E+02	0.000E+00	1.000E+00
62	4	7.621E+00	7.299E+02	2.662E+02	0.000E+00	1.000E+00
63	4	7.970E+00	7.982E+02	2.905E+02	0.000E+00	1.000E+00
64	4	8.318E+00	8.695E+02	3.159E+02	0.000E+00	1.000E+00
65	4	8.667E+00	9.439E+02	3.423E+02	0.000E+00	1.000E+00
66	4	9.015E+00	1.021E+03	3.698E+02	0.000E+00	1.000E+00
67	4	9.364E+00	1.102E+03	3.984E+02	0.000E+00	1.000E+00
68	4	9.712E+00	1.185E+03	4.281E+02	0.000E+00	1.000E+00
69	4	1.006E+01	1.272E+03	4.588E+02	0.000E+00	1.000E+00
70	4	1.041E+01	1.362E+03	4.905E+02	0.000E+00	1.000E+00
71	4	1.076E+01	1.454E+03	5.234E+02	0.000E+00	1.000E+00
72	4	1.111E+01	1.550E+03	5.573E+02	0.000E+00	1.000E+00

```
   73     4      1.145E+01 1.649E+03 5.922E+02 0.000E+00 1.000E+00
   74     4      1.180E+01 1.751E+03 6.283E+02 0.000E+00 1.000E+00
   75     4      1.215E+01 1.856E+03 6.654E+02 0.000E+00 1.000E+00
   76     5      1.250E+01 1.963E+03 1.022E+03 0.000E+00 1.000E+00
   77     5      1.300E+01 2.124E+03 7.262E+02 0.000E+00 1.000E+00
   78     5      1.333E+01 2.234E+03 7.634E+02 0.000E+00 1.000E+00
   79     5      1.367E+01 2.347E+03 8.016E+02 0.000E+00 1.000E+00
   80     5      1.400E+01 2.463E+03 8.407E+02 0.000E+00 1.000E+00
   81     5      1.433E+01 2.582E+03 8.807E+02 0.000E+00 1.000E+00
   82     5      1.467E+01 2.703E+03 9.217E+02 0.000E+00 1.000E+00
   83     5      1.500E+01 2.827E+03 9.636E+02 0.000E+00 1.000E+00
   84     5      1.533E+01 2.954E+03 1.006E+03 0.000E+00 1.000E+00
   85     5      1.567E+01 3.084E+03 1.050E+03 0.000E+00 1.000E+00
   86     5      1.600E+01 3.217E+03 1.095E+03 0.000E+00 1.000E+00
   87     5      1.633E+01 3.352E+03 1.140E+03 0.000E+00 1.000E+00
   88     5      1.667E+01 3.491E+03 1.187E+03 0.000E+00 1.000E+00
   89     5      1.700E+01 3.632E+03 1.234E+03 0.000E+00 1.000E+00
   90     5      1.733E+01 3.775E+03 1.283E+03 0.000E+00 1.000E+00
   91     5      1.767E+01 3.922E+03 1.332E+03 0.000E+00 1.000E+00
   92     5      1.800E+01 4.072E+03 1.382E+03 0.000E+00 1.000E+00
   93     5      1.833E+01 4.224E+03 1.434E+03 0.000E+00 1.000E+00
   94     5      1.867E+01 4.379E+03 1.486E+03 0.000E+00 1.000E+00
   95     5      1.900E+01 4.536E+03 1.539E+03 0.000E+00 1.000E+00
   96     5      1.933E+01 4.697E+03 1.593E+03 0.000E+00 1.000E+00
   97     5      1.967E+01 4.860E+03 1.648E+03 0.000E+00 1.000E+00
   98            2.000E+01 5.027E+03


0 agn reactor
0 GROUP DEPENDENT PARAMETERS EDIT
0 GRP  FISS SPEC  VELOCITY
    1  0.000E+00 4.670E+03
    2  0.000E+00 5.100E+03
    3  0.000E+00 6.100E+03
    4  0.000E+00 6.800E+03
    5  0.000E+00 6.800E+03
    6  1.430E-02 6.740E+03
    7  3.200E-02 6.510E+03
    8  7.000E-02 6.710E+03
    9  8.000E-02 7.290E+03
   10  4.500E-02 7.650E+03
   11  3.500E-02 7.900E+03
   12  1.900E-02 7.990E+03
   13  2.000E-02 7.970E+03
   14  2.100E-02 7.960E+03
   15  7.000E-02 7.920E+03
   16  5.250E-02 7.850E+03
   17  8.800E-02 7.770E+03
   18  1.320E-01 7.670E+03
   19  6.350E-02 7.970E+03
   20  2.900E-02 8.610E+04
   21  5.000E-02 9.280E+03
   22  4.000E-02 1.030E+04
   23  4.000E-02 1.230E+04
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   24  4.800E-02 1.560E+04
   25  8.000E-03 2.090E+04
   26  1.900E-02 3.250E+04
   27  7.300E-03 5.030E+04
   28  6.500E-03 7.450E+04
   29  0.000E+00 1.020E+05
   30  0.000E+00 1.220E+05
   31  0.000E+00 1.360E+05
   32  0.000E+00 1.450E+05
   33  0.000E+00 1.730E+05
   34  0.000E+00 2.410E+05
   35  0.000E+00 2.800E+05
   36  0.000E+00 2.750E+05
   37  0.000E+00 2.660E+05
   38  0.000E+00 2.530E+05
   39  0.000E+00 2.440E+05
   40  0.000E+00 2.350E+05
   41  0.000E+00 2.250E+05
   42  0.000E+00 2.200E+05
   43  0.000E+00 2.190E+05
   44  0.000E+00 2.220E+05
   45  0.000E+00 2.300E+05
   46  0.000E+00 2.470E+05
   47  0.000E+00 2.720E+05
   48  0.000E+00 9.070E+04
   49  0.000E+00 1.140E+05
   50  0.000E+00 1.310E+05
   51  0.000E+00 1.440E+05
   52  0.000E+00 1.620E+05
   53  0.000E+00 1.850E+05
   54  0.000E+00 2.160E+05
   55  0.000E+00 2.690E+05
   56  0.000E+00 3.420E+05
   57  0.000E+00 4.320E+05
   58  0.000E+00 5.460E+05
   59  0.000E+00 6.240E+05
   60  0.000E+00 6.940E+05
   61  0.000E+00 8.530E+05
   62  0.000E+00 1.330E+06
   63  0.000E+00 2.610E+06
   64  0.000E+00 3.780E+06
   65  0.000E+00 2.870E+06
   66  0.000E+00 1.210E+06
   67  0.000E+00 4.660E+05


0 agn reactor
0 ZONE DEPENDENT PARAMETERS EDIT
0 ZONE MATL/ZONE L OF P(L)
    1    29         3
    2    29         3
    3    25         3
    4    33         3
    5    37         3
```

ZONE	WIDTH	OUTER RADIUS	NO. OF INT.
1	4.80000E-01	4.80000E-01	1
2	2.00000E-02	5.00000E-01	40
3	5.00000E-01	1.00000E+00	1
4	1.15000E+01	1.25000E+01	33
5	7.50000E+00	2.00000E+01	22

0 agn reactor
0CROSS SECTION MIXING TABLE

	MATL	COMP.	NO. DENSITY
1	25	1	6.000E-02
2	26	2	6.000E-02
3	27	3	6.000E-02
4	28	4	6.000E-02
5	29	5	4.640E-02
6	30	6	4.640E-02
7	31	7	4.640E-02
8	32	8	4.640E-02
9	33	17	3.950E-02
10	34	18	3.950E-02
11	35	19	3.950E-02
12	36	20	3.950E-02
13	33	21	7.900E-02
14	34	22	7.900E-02
15	35	23	7.900E-02
16	36	24	7.900E-02
17	33	9	1.280E-04
18	34	10	1.280E-04
19	35	11	1.280E-04
20	36	12	1.280E-04
21	33	13	5.120E-04
22	34	14	5.120E-04
23	35	15	5.120E-04
24	36	16	5.120E-04
25	37	17	8.000E-02
26	38	18	8.000E-02
27	39	19	8.000E-02
28	40	20	8.000E-02

0 agn reactor
0ANGULAR QUADRATURE CONSTANTS

ANGLE	COSINE(MU)	WEIGHT	REFL DIR.	WT * COS
1	-9.903E-01	0.000E+00	17	-0.000E+00
2	-9.805E-01	2.449E-02	17	-2.402E-02
3	-9.093E-01	4.133E-02	16	-3.758E-02
4	-8.320E-01	3.926E-02	15	-3.266E-02
5	-7.468E-01	4.008E-02	14	-2.993E-02
6	-6.504E-01	6.438E-02	13	-4.187E-02

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    7 -5.377E-01 4.421E-02   12     -2.377E-02
    8 -3.923E-01 1.091E-01   11     -4.279E-02
    9 -1.390E-01 1.372E-01   10     -1.906E-02
   10  1.390E-01 1.372E-01    9      1.906E-02
   11  3.923E-01 1.091E-01    8      4.279E-02
   12  5.377E-01 4.421E-02    7      2.377E-02
   13  6.504E-01 6.438E-02    6      4.187E-02
   14  7.468E-01 4.008E-02    5      2.993E-02
   15  8.320E-01 3.926E-02    4      3.266E-02
   16  9.093E-01 4.133E-02    3      3.758E-02
   17  9.805E-01 2.449E-02    2      2.402E-02
0 CONSTANTS FOR P( 3) SCATTERING
0 ANGL   SET   1     SET   2     SET   3
    1 -9.90299E-01 9.71037E-01-9.42495E-01
    2 -9.80501E-01 9.42073E-01-8.85839E-01
    3 -9.09286E-01 7.40201E-01-5.15566E-01
    4 -8.31997E-01 5.38328E-01-1.91814E-01
    5 -7.46751E-01 3.36455E-01 7.90872E-02
    6 -6.50427E-01 1.34582E-01 2.87725E-01
    7 -5.37710E-01-6.63022E-02 4.17892E-01
    8 -3.92289E-01-2.69164E-01 4.37510E-01
    9 -1.38957E-01-4.71036E-01 2.01727E-01
   10  1.38957E-01-4.71036E-01-2.01727E-01
   11  3.92289E-01-2.69164E-01-4.37510E-01
   12  5.37710E-01-6.63022E-02-4.17892E-01
   13  6.50427E-01 1.34582E-01-2.87725E-01
   14  7.46751E-01 3.36455E-01-7.90872E-02
   15  8.31997E-01 5.38328E-01 1.91814E-01
   16  9.09286E-01 7.40201E-01 5.15566E-01
   17  9.80501E-01 9.42073E-01 8.85839E-01
```

Forward flux with absorber

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*************************************************************
*                                                           *
*                                                           *
*  AAAAAAAA  NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
* AAAAAAAAAA NNN     NN IIIIIIIIII SSSSSSSSSS NNN     NN  *
* AA      AA NNNN    NN     II     SS         NNNN    NN  *
* AA      AA NNNNN   NN     II     SS         NNNNN   NN  *
* AAAAAAAAAA NN NNN  NN     II     SSSSSSSSS  NN NNN  NN  *
* AAAAAAAAAA NN  NNN NN     II      SSSSSSSSS NN  NNN NN  *
* AA      AA NN   NNNNN     II             SS NN   NNNNN  *
* AA      AA NN    NNNN     II             SS NN    NNNN  *
* AA      AA NN     NNN IIIIIIIIII SSSSSSSSS NN     NNN  *
* AA      AA NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
*                                                           *
*        INEL Apollo 10000 VERSION 3.2 (AUG 1988)           *
*        Revised 4-16-93 for ANL SPARC                      *
*            G. R. IMEL----ANL                              *
*                  D. KENT PARSONS                          *
*                  EG&G IDAHO, INC                          *
*                   P.O. BOX 1625                           *
*               IDAHO FALLS, ID 83415                       *
*                                                           *
*************************************************************


0 agn reactor
0   15$ ARRAY     36 ENTRIES READ
0   16* ARRAY     14 ENTRIES READ
0    0T
0 ID    PROBLEM ID NO.               1    ITH   0/1 = REG./ADJ.
0
  ISCT  ORDER OF SCATTERING          3    ISN   QUADRATURE ORDER
16
  IGE   1/2/3 = PLA/CYL/SPH          3    IBL   0/1/2/3 =
VAC/REFL/PER/ALBDO   1
  IBR   RT BC SAME AS LEFT BC,IBL    0    IZM   NO. OF ZONES
5
  IM    NO. OF INTERVALS            97    IEVT
0/1/2/3/4/5/6=Q/K/A/C/Z/R/H    0
  IGM   NO. OF GROUPS               67    IHT   POS. OF SIGMA T
3
  IHS   POS. OF SIGMA GG             4    IHM   TABLE LENGTH
70
  MS    MIXING TABLE LENGTH         28    MCR   NO. MATLS. FROM CARDS
0
  MTP   NO. MATLS. FROM LIB TAPE    24    MT    NO. OF MATLS.
40
  IDFM  0/1=NONE/DEN FACTORS(21*)    1    IPVT  0/1/2=NONE/K/ALPHA
0
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  IQM   0/1=NONE/DIST. SOURCE        1    IPM
0/1/IM=NO/S(MM,IPP)/S(MM,IM)   0
  IPP   INT OF SHELL SOURCE          0    IIM   INNER ITER. MAX.
100
  ID1   0/1/2/3=NO/PRNT/PNCH/BOTH    2    ID2   -N/-1/0/1/2=ITX/IGX/-
/ITX/PRV  3
  ID3   0/N=NO/ACTIV. BY ZONE        2    ID4   0/1=NO/ACTIV. BY INT
1
  ICM   OUTER ITER. MAX.           100    IDAT1 0/1/2=NO/MIN/MAX TAPE
0
  IDAT2 0/1=NO/DIFF/INFN(24$)        0    IFG   0/1/2/3/4 NO/FG/R/W/RW
0
  IFLU  -1/0/1/2/3/4=DSA/LS/L/S/W/LW 3    IFN   -1/0/1/2=CCCC/2*/3*/PREV.
1
  IPRT  0/1 = PRINT XS/DO NOT        1    IXTR  0/1/2/3=FLUX SAVE-
NO/R/W/R&W   0
0 EV    EIGENVALUE GUESS     0.000E+00    EVM   EV MODIFIER, SEARCH
0.000E+00
  EPS   PRECISION DESIRED    1.000E-04    BF    BUCKLING FACTOR
1.421E+00
  DY    CYL OR PLA HEIGHT    0.000E+00    DZ    PLANE DEPTH
0.000E+00
  DFM1  HT. FOR VOID CORR.   0.000E+00    XNF   NORMALIZATION
0.000E+00
  PV    IPVT=1/2 - K/ALPHA   0.000E+00    RYF   SCAT, UPSCAT RELAX
5.000E-01
  XLAL  PT CONV EPS IF NE 0  1.000E-04    XLAH  1-LAMBDA MAX.,SEARCH
5.000E-02
  EQL   EV DEL EPS.,SEARCH   1.000E-03    XNPM  UNDERRELAXATION,SEARCH
7.500E-01
0450002 LOCATIONS ARE AVAILABLE FOR THIS PROBLEM
0234883 LOCATIONS WILL BE REQUIRED FOR FLUX CALCULATION
0230117 LOCATIONS WILL BE REQUIRED FOR COMPLETE SUMMARY TABLES
0227286 LOCATIONS WILL BE REQUIRED FOR COMPLETE ACTIVITY TABLES
0  6664 BYTES WILL BE REQUIRED FOR THE PROFORT RUN-TIME BUFFER
0   13$ ARRAY     24 ENTRIES READ
0    0T
0 ELEMENTS READ FROM LIBRARY TAPE
0 MAT. NO.    ID
         1    13       p0  al27    v91.94 standard wgt e601325b93vb630
         2    14       p1  al27
         3    15       p2  al27
         4    16       p3  al27
        17    95       p0  c       v91.94 standard wgt e620600b93vb630
        18    96       p1  c
        19    97       p2  c
        20    98       p3  c
         5   119       p0  cd(nat) v91.94 standard wgt e604800b93vb630
         6   120       p1  cd(nat)
         7   121       p2  cd(nat)
         8   122       p3  cd(nat)
        21   313       p0  h1(h2o) v91.94 standard wgt e620125b93vb630
        22   315       p2  h1(h2o)
        23   318       p5  h1(h2o)
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        24   320       p7  h1(h2o)
         9   737       p0  u235    v91.94 standard wgt e639228b93vb630
        10   738       p1  u235
        11   739       p2  u235
        12   740       p3  u235
        13   755       p0  u238    v91.94 standard wgt e639237b93vb630
        14   756       p1  u238
        15   757       p2  u238
        16   758       p3  u238
0   17* ARRAY   6499 ENTRIES READ
0    0T
0    3* ARRAY   6499 ENTRIES READ
0    0T
0    1* ARRAY     67 ENTRIES READ
0    4* ARRAY     98 ENTRIES READ
0    5* ARRAY     67 ENTRIES READ
0    6* ARRAY     17 ENTRIES READ
0    7* ARRAY     17 ENTRIES READ
0    8$ ARRAY     97 ENTRIES READ
0    9$ ARRAY      5 ENTRIES READ
0   10$ ARRAY     28 ENTRIES READ
0   11$ ARRAY     28 ENTRIES READ
0   12* ARRAY     28 ENTRIES READ
0   19$ ARRAY      5 ENTRIES READ
0   21* ARRAY     97 ENTRIES READ
0   22$ ARRAY      2 ENTRIES READ
0   23$ ARRAY      2 ENTRIES READ
0    0T
0******  TOTAL FIXED SOURCE BEFORE NORMALIZATION  1.02154E+03


0 agn reactor
0 GEOMETRY EDIT
0 INT   ZONE       RADIUS     AREA     VOLUME  FISS DENS DEN FACTS
    1     1      0.000E+00 0.000E+00 4.632E-01 0.000E+00 0.000E+00
    2     2      4.800E-01 2.895E+00 1.449E-03 0.000E+00 1.000E+00
    3     2      4.805E-01 2.901E+00 1.452E-03 0.000E+00 1.000E+00
    4     2      4.810E-01 2.907E+00 1.455E-03 0.000E+00 1.000E+00
    5     2      4.815E-01 2.913E+00 1.458E-03 0.000E+00 1.000E+00
    6     2      4.820E-01 2.919E+00 1.461E-03 0.000E+00 1.000E+00
    7     2      4.825E-01 2.926E+00 1.464E-03 0.000E+00 1.000E+00
    8     2      4.830E-01 2.932E+00 1.467E-03 0.000E+00 1.000E+00
    9     2      4.835E-01 2.938E+00 1.470E-03 0.000E+00 1.000E+00
   10     2      4.840E-01 2.944E+00 1.473E-03 0.000E+00 1.000E+00
   11     2      4.845E-01 2.950E+00 1.476E-03 0.000E+00 1.000E+00
   12     2      4.850E-01 2.956E+00 1.479E-03 0.000E+00 1.000E+00
   13     2      4.855E-01 2.962E+00 1.483E-03 0.000E+00 1.000E+00
   14     2      4.860E-01 2.968E+00 1.486E-03 0.000E+00 1.000E+00
   15     2      4.865E-01 2.974E+00 1.489E-03 0.000E+00 1.000E+00
   16     2      4.870E-01 2.980E+00 1.492E-03 0.000E+00 1.000E+00
   17     2      4.875E-01 2.986E+00 1.495E-03 0.000E+00 1.000E+00
   18     2      4.880E-01 2.993E+00 1.498E-03 0.000E+00 1.000E+00
   19     2      4.885E-01 2.999E+00 1.501E-03 0.000E+00 1.000E+00
   20     2      4.890E-01 3.005E+00 1.504E-03 0.000E+00 1.000E+00
```

21	2	4.895E-01	3.011E+00	1.507E-03	0.000E+00	1.000E+00
22	2	4.900E-01	3.017E+00	1.510E-03	0.000E+00	1.000E+00
23	2	4.905E-01	3.023E+00	1.513E-03	0.000E+00	1.000E+00
24	2	4.910E-01	3.030E+00	1.516E-03	0.000E+00	1.000E+00
25	2	4.915E-01	3.036E+00	1.519E-03	0.000E+00	1.000E+00
26	2	4.920E-01	3.042E+00	1.522E-03	0.000E+00	1.000E+00
27	2	4.925E-01	3.048E+00	1.526E-03	0.000E+00	1.000E+00
28	2	4.930E-01	3.054E+00	1.529E-03	0.000E+00	1.000E+00
29	2	4.935E-01	3.060E+00	1.532E-03	0.000E+00	1.000E+00
30	2	4.940E-01	3.067E+00	1.535E-03	0.000E+00	1.000E+00
31	2	4.945E-01	3.073E+00	1.538E-03	0.000E+00	1.000E+00
32	2	4.950E-01	3.079E+00	1.541E-03	0.000E+00	1.000E+00
33	2	4.955E-01	3.085E+00	1.544E-03	0.000E+00	1.000E+00
34	2	4.960E-01	3.092E+00	1.547E-03	0.000E+00	1.000E+00
35	2	4.965E-01	3.098E+00	1.550E-03	0.000E+00	1.000E+00
36	2	4.970E-01	3.104E+00	1.554E-03	0.000E+00	1.000E+00
37	2	4.975E-01	3.110E+00	1.557E-03	0.000E+00	1.000E+00
38	2	4.980E-01	3.117E+00	1.560E-03	0.000E+00	1.000E+00
39	2	4.985E-01	3.123E+00	1.563E-03	0.000E+00	1.000E+00
40	2	4.990E-01	3.129E+00	1.566E-03	0.000E+00	1.000E+00
41	2	4.995E-01	3.135E+00	1.569E-03	0.000E+00	1.000E+00
42	3	5.000E-01	3.142E+00	3.665E+00	0.000E+00	1.000E+00
43	4	1.000E+00	1.257E+01	6.083E+00	0.000E+00	1.000E+00
44	4	1.348E+00	2.285E+01	1.020E+01	0.000E+00	1.000E+00
45	4	1.697E+00	3.619E+01	1.538E+01	0.000E+00	1.000E+00
46	4	2.045E+00	5.258E+01	2.162E+01	0.000E+00	1.000E+00
47	4	2.394E+00	7.202E+01	2.893E+01	0.000E+00	1.000E+00
48	4	2.742E+00	9.451E+01	3.730E+01	0.000E+00	1.000E+00
49	4	3.091E+00	1.201E+02	4.673E+01	0.000E+00	1.000E+00
50	4	3.439E+00	1.487E+02	5.723E+01	0.000E+00	1.000E+00
51	4	3.788E+00	1.803E+02	6.879E+01	0.000E+00	1.000E+00
52	4	4.136E+00	2.150E+02	8.142E+01	0.000E+00	1.000E+00
53	4	4.485E+00	2.528E+02	9.510E+01	0.000E+00	1.000E+00
54	4	4.833E+00	2.936E+02	1.099E+02	0.000E+00	1.000E+00
55	4	5.182E+00	3.374E+02	1.257E+02	0.000E+00	1.000E+00
56	4	5.530E+00	3.843E+02	1.426E+02	0.000E+00	1.000E+00
57	4	5.879E+00	4.343E+02	1.605E+02	0.000E+00	1.000E+00
58	4	6.227E+00	4.873E+02	1.795E+02	0.000E+00	1.000E+00
59	4	6.576E+00	5.434E+02	1.996E+02	0.000E+00	1.000E+00
60	4	6.924E+00	6.025E+02	2.207E+02	0.000E+00	1.000E+00
61	4	7.273E+00	6.647E+02	2.429E+02	0.000E+00	1.000E+00
62	4	7.621E+00	7.299E+02	2.662E+02	0.000E+00	1.000E+00
63	4	7.970E+00	7.982E+02	2.905E+02	0.000E+00	1.000E+00
64	4	8.318E+00	8.695E+02	3.159E+02	0.000E+00	1.000E+00
65	4	8.667E+00	9.439E+02	3.423E+02	0.000E+00	1.000E+00
66	4	9.015E+00	1.021E+03	3.698E+02	0.000E+00	1.000E+00
67	4	9.364E+00	1.102E+03	3.984E+02	0.000E+00	1.000E+00
68	4	9.712E+00	1.185E+03	4.281E+02	0.000E+00	1.000E+00
69	4	1.006E+01	1.272E+03	4.588E+02	0.000E+00	1.000E+00
70	4	1.041E+01	1.362E+03	4.905E+02	0.000E+00	1.000E+00
71	4	1.076E+01	1.454E+03	5.234E+02	0.000E+00	1.000E+00
72	4	1.111E+01	1.550E+03	5.573E+02	0.000E+00	1.000E+00
73	4	1.145E+01	1.649E+03	5.922E+02	0.000E+00	1.000E+00
74	4	1.180E+01	1.751E+03	6.283E+02	0.000E+00	1.000E+00

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   75     4      1.215E+01 1.856E+03 6.654E+02 0.000E+00 1.000E+00
   76     5      1.250E+01 1.963E+03 1.022E+03 0.000E+00 1.000E+00
   77     5      1.300E+01 2.124E+03 7.262E+02 0.000E+00 1.000E+00
   78     5      1.333E+01 2.234E+03 7.634E+02 0.000E+00 1.000E+00
   79     5      1.367E+01 2.347E+03 8.016E+02 0.000E+00 1.000E+00
   80     5      1.400E+01 2.463E+03 8.407E+02 0.000E+00 1.000E+00
   81     5      1.433E+01 2.582E+03 8.807E+02 0.000E+00 1.000E+00
   82     5      1.467E+01 2.703E+03 9.217E+02 0.000E+00 1.000E+00
   83     5      1.500E+01 2.827E+03 9.636E+02 0.000E+00 1.000E+00
   84     5      1.533E+01 2.954E+03 1.006E+03 0.000E+00 1.000E+00
   85     5      1.567E+01 3.084E+03 1.050E+03 0.000E+00 1.000E+00
   86     5      1.600E+01 3.217E+03 1.095E+03 0.000E+00 1.000E+00
   87     5      1.633E+01 3.352E+03 1.140E+03 0.000E+00 1.000E+00
   88     5      1.667E+01 3.491E+03 1.187E+03 0.000E+00 1.000E+00
   89     5      1.700E+01 3.632E+03 1.234E+03 0.000E+00 1.000E+00
   90     5      1.733E+01 3.775E+03 1.283E+03 0.000E+00 1.000E+00
   91     5      1.767E+01 3.922E+03 1.332E+03 0.000E+00 1.000E+00
   92     5      1.800E+01 4.072E+03 1.382E+03 0.000E+00 1.000E+00
   93     5      1.833E+01 4.224E+03 1.434E+03 0.000E+00 1.000E+00
   94     5      1.867E+01 4.379E+03 1.486E+03 0.000E+00 1.000E+00
   95     5      1.900E+01 4.536E+03 1.539E+03 0.000E+00 1.000E+00
   96     5      1.933E+01 4.697E+03 1.593E+03 0.000E+00 1.000E+00
   97     5      1.967E+01 4.860E+03 1.648E+03 0.000E+00 1.000E+00
   98            2.000E+01 5.027E+03


0 agn reactor
0 GROUP DEPENDENT PARAMETERS EDIT
0 GRP  FISS SPEC  VELOCITY
    1  0.000E+00 4.670E+03
    2  0.000E+00 5.100E+03
    3  0.000E+00 6.100E+03
    4  0.000E+00 6.800E+03
    5  0.000E+00 6.800E+03
    6  1.430E-02 6.740E+03
    7  3.200E-02 6.510E+03
    8  7.000E-02 6.710E+03
    9  8.000E-02 7.290E+03
   10  4.500E-02 7.650E+03
   11  3.500E-02 7.900E+03
   12  1.900E-02 7.990E+03
   13  2.000E-02 7.970E+03
   14  2.100E-02 7.960E+03
   15  7.000E-02 7.920E+03
   16  5.250E-02 7.850E+03
   17  8.800E-02 7.770E+03
   18  1.320E-01 7.670E+03
   19  6.350E-02 7.970E+03
   20  2.900E-02 8.610E+04
   21  5.000E-02 9.280E+03
   22  4.000E-02 1.030E+04
   23  4.000E-02 1.230E+04
   24  4.800E-02 1.560E+04
   25  8.000E-03 2.090E+04
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   26  1.900E-02 3.250E+04
   27  7.300E-03 5.030E+04
   28  6.500E-03 7.450E+04
   29  0.000E+00 1.020E+05
   30  0.000E+00 1.220E+05
   31  0.000E+00 1.360E+05
   32  0.000E+00 1.450E+05
   33  0.000E+00 1.730E+05
   34  0.000E+00 2.410E+05
   35  0.000E+00 2.800E+05
   36  0.000E+00 2.750E+05
   37  0.000E+00 2.660E+05
   38  0.000E+00 2.530E+05
   39  0.000E+00 2.440E+05
   40  0.000E+00 2.350E+05
   41  0.000E+00 2.250E+05
   42  0.000E+00 2.200E+05
   43  0.000E+00 2.190E+05
   44  0.000E+00 2.220E+05
   45  0.000E+00 2.300E+05
   46  0.000E+00 2.470E+05
   47  0.000E+00 2.720E+05
   48  0.000E+00 9.070E+04
   49  0.000E+00 1.140E+05
   50  0.000E+00 1.310E+05
   51  0.000E+00 1.440E+05
   52  0.000E+00 1.620E+05
   53  0.000E+00 1.850E+05
   54  0.000E+00 2.160E+05
   55  0.000E+00 2.690E+05
   56  0.000E+00 3.420E+05
   57  0.000E+00 4.320E+05
   58  0.000E+00 5.460E+05
   59  0.000E+00 6.240E+05
   60  0.000E+00 6.940E+05
   61  0.000E+00 8.530E+05
   62  0.000E+00 1.330E+06
   63  0.000E+00 2.610E+06
   64  0.000E+00 3.780E+06
   65  0.000E+00 2.870E+06
   66  0.000E+00 1.210E+06
   67  0.000E+00 4.660E+05


0 agn reactor
0 ZONE DEPENDENT PARAMETERS EDIT
0 ZONE MATL/ZONE L OF P(L)
    1    29         3
    2    29         3
    3    25         3
    4    33         3
    5    37         3
```

ZONE	WIDTH	OUTER RADIUS	NO. OF INT.
1	4.80000E-01	4.80000E-01	1
2	2.00000E-02	5.00000E-01	40
3	5.00000E-01	1.00000E+00	1
4	1.15000E+01	1.25000E+01	33
5	7.50000E+00	2.00000E+01	22

0 agn reactor
0CROSS SECTION MIXING TABLE

	MATL	COMP.	NO. DENSITY
1	25	1	6.000E-02
2	26	2	6.000E-02
3	27	3	6.000E-02
4	28	4	6.000E-02
5	29	5	4.640E-02
6	30	6	4.640E-02
7	31	7	4.640E-02
8	32	8	4.640E-02
9	33	17	3.950E-02
10	34	18	3.950E-02
11	35	19	3.950E-02
12	36	20	3.950E-02
13	33	21	7.900E-02
14	34	22	7.900E-02
15	35	23	7.900E-02
16	36	24	7.900E-02
17	33	9	1.280E-04
18	34	10	1.280E-04
19	35	11	1.280E-04
20	36	12	1.280E-04
21	33	13	5.120E-04
22	34	14	5.120E-04
23	35	15	5.120E-04
24	36	16	5.120E-04
25	37	17	8.000E-02
26	38	18	8.000E-02
27	39	19	8.000E-02
28	40	20	8.000E-02

0 agn reactor
0ANGULAR QUADRATURE CONSTANTS

ANGLE	COSINE(MU)	WEIGHT	REFL DIR.	WT * COS
1	-9.903E-01	0.000E+00	17	-0.000E+00
2	-9.805E-01	2.449E-02	17	-2.402E-02
3	-9.093E-01	4.133E-02	16	-3.758E-02
4	-8.320E-01	3.926E-02	15	-3.266E-02
5	-7.468E-01	4.008E-02	14	-2.993E-02
6	-6.504E-01	6.438E-02	13	-4.187E-02
7	-5.377E-01	4.421E-02	12	-2.377E-02
8	-3.923E-01	1.091E-01	11	-4.279E-02

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    9 -1.390E-01 1.372E-01   10     -1.906E-02
   10  1.390E-01 1.372E-01    9      1.906E-02
   11  3.923E-01 1.091E-01    8      4.279E-02
   12  5.377E-01 4.421E-02    7      2.377E-02
   13  6.504E-01 6.438E-02    6      4.187E-02
   14  7.468E-01 4.008E-02    5      2.993E-02
   15  8.320E-01 3.926E-02    4      3.266E-02
   16  9.093E-01 4.133E-02    3      3.758E-02
   17  9.805E-01 2.449E-02    2      2.402E-02
0 CONSTANTS FOR P( 3) SCATTERING
0 ANGL   SET   1     SET   2     SET   3
    1 -9.90299E-01 9.71037E-01-9.42495E-01
    2 -9.80501E-01 9.42073E-01-8.85839E-01
    3 -9.09286E-01 7.40201E-01-5.15566E-01
    4 -8.31997E-01 5.38328E-01-1.91814E-01
    5 -7.46751E-01 3.36455E-01 7.90872E-02
    6 -6.50427E-01 1.34582E-01 2.87725E-01
    7 -5.37710E-01-6.63022E-02 4.17892E-01
    8 -3.92289E-01-2.69164E-01 4.37510E-01
    9 -1.38957E-01-4.71036E-01 2.01727E-01
   10  1.38957E-01-4.71036E-01-2.01727E-01
   11  3.92289E-01-2.69164E-01-4.37510E-01
   12  5.37710E-01-6.63022E-02-4.17892E-01
   13  6.50427E-01 1.34582E-01-2.87725E-01
   14  7.46751E-01 3.36455E-01-7.90872E-02
   15  8.31997E-01 5.38328E-01 1.91814E-01
   16  9.09286E-01 7.40201E-01 5.15566E-01
   17  9.80501E-01 9.42073E-01 8.85839E-01
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Adjoint flux with no absorber

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*********************************************************
               *                                                *
               *                                                *
               *  AAAAAAAA  NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
               * AAAAAAAAAA NNN     NN IIIIIIIIII SSSSSSSSSS NNN     NN  *
               * AA      AA NNNN    NN     II     SS         NNNN    NN  *
               * AA      AA NNNNN   NN     II     SS         NNNNN   NN  *
               * AAAAAAAAAA NN NNN  NN     II     SSSSSSSSS  NN NNN  NN  *
               * AAAAAAAAAA NN  NNN NN     II      SSSSSSSSS NN  NNN NN  *
               * AA      AA NN   NNNNN     II             SS NN   NNNNN  *
               * AA      AA NN    NNNN     II             SS NN    NNNN  *
               * AA      AA NN     NNN IIIIIIIIII SSSSSSSSS NN     NNN  *
               * AA      AA NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
               *                                                *
               *        INEL Apollo 10000 VERSION 3.2 (AUG 1988)        *
               *        Revised 4-16-93 for ANL SPARC                   *
               *            G. R. IMEL----ANL                           *
               *                  D. KENT PARSONS                       *
               *                  EG&G IDAHO, INC                       *
               *                   P.O. BOX 1625                        *
               *               IDAHO FALLS, ID 83415                    *
               *                                                        *
               **********************************************************


0 agn reactor
0   15$ ARRAY     36 ENTRIES READ
0   16* ARRAY     14 ENTRIES READ
0    0T
0 ID    PROBLEM ID NO.               1    ITH   0/1 = REG./ADJ.
1
  ISCT  ORDER OF SCATTERING          3    ISN   QUADRATURE ORDER
16
  IGE   1/2/3 = PLA/CYL/SPH          3    IBL   0/1/2/3 =
VAC/REFL/PER/ALBDO   1
  IBR   RT BC SAME AS LEFT BC,IBL    0    IZM   NO. OF ZONES
5
  IM    NO. OF INTERVALS            97    IEVT
0/1/2/3/4/5/6=Q/K/A/C/Z/R/H    0
  IGM   NO. OF GROUPS               67    IHT   POS. OF SIGMA T
3
  IHS   POS. OF SIGMA GG             4    IHM   TABLE LENGTH
70
  MS    MIXING TABLE LENGTH         28    MCR   NO. MATLS. FROM CARDS
0
  MTP   NO. MATLS. FROM LIB TAPE    24    MT    NO. OF MATLS.
40
  IDFM  0/1=NONE/DEN FACTORS(21*)    1    IPVT  0/1/2=NONE/K/ALPHA
0
```

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  IQM   0/1=NONE/DIST. SOURCE        1    IPM
0/1/IM=NO/S(MM,IPP)/S(MM,IM)   0
  IPP   INT OF SHELL SOURCE          0    IIM   INNER ITER. MAX.
100
  ID1   0/1/2/3=NO/PRNT/PNCH/BOTH    2    ID2   -N/-1/0/1/2=ITX/IGX/-
/ITX/PRV  3
  ID3   0/N=NO/ACTIV. BY ZONE        2    ID4   0/1=NO/ACTIV. BY INT
1
  ICM   OUTER ITER. MAX.           100    IDAT1 0/1/2=NO/MIN/MAX TAPE
0
  IDAT2 0/1=NO/DIFF/INFN(24$)        0    IFG   0/1/2/3/4 NO/FG/R/W/RW
0
  IFLU  -1/0/1/2/3/4=DSA/LS/L/S/W/LW 3    IFN   -1/0/1/2=CCCC/2*/3*/PREV.
1
  IPRT  0/1 = PRINT XS/DO NOT        1    IXTR  0/1/2/3=FLUX SAVE-
NO/R/W/R&W   0
0 EV    EIGENVALUE GUESS     0.000E+00    EVM   EV MODIFIER, SEARCH
0.000E+00
  EPS   PRECISION DESIRED    1.000E-04    BF    BUCKLING FACTOR
1.421E+00
  DY    CYL OR PLA HEIGHT    0.000E+00    DZ    PLANE DEPTH
0.000E+00
  DFM1  HT. FOR VOID CORR.   0.000E+00    XNF   NORMALIZATION
0.000E+00
  PV    IPVT=1/2 - K/ALPHA   0.000E+00    RYF   SCAT, UPSCAT RELAX
5.000E-01
  XLAL  PT CONV EPS IF NE 0  1.000E-04    XLAH  1-LAMBDA MAX.,SEARCH
5.000E-02
  EQL   EV DEL EPS.,SEARCH   1.000E-03    XNPM  UNDERRELAXATION,SEARCH
7.500E-01
0450002 LOCATIONS ARE AVAILABLE FOR THIS PROBLEM
0234883 LOCATIONS WILL BE REQUIRED FOR FLUX CALCULATION
0230117 LOCATIONS WILL BE REQUIRED FOR COMPLETE SUMMARY TABLES
0227286 LOCATIONS WILL BE REQUIRED FOR COMPLETE ACTIVITY TABLES
0  6664 BYTES WILL BE REQUIRED FOR THE PROFORT RUN-TIME BUFFER
0   13$ ARRAY     24 ENTRIES READ
0    0T
0 ELEMENTS READ FROM LIBRARY TAPE
0 MAT. NO.    ID
         1    13       p0  al27    v91.94 standard wgt e601325b93vb630
         2    14       p1  al27
         3    15       p2  al27
         4    16       p3  al27
        17    95       p0  c       v91.94 standard wgt e620600b93vb630
        18    96       p1  c
        19    97       p2  c
        20    98       p3  c
         5   119       p0  cd(nat) v91.94 standard wgt e604800b93vb630
         6   120       p1  cd(nat)
         7   121       p2  cd(nat)
         8   122       p3  cd(nat)
        21   313       p0  h1(h2o) v91.94 standard wgt e620125b93vb630
        22   315       p2  h1(h2o)
        23   318       p5  h1(h2o)
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        24   320       p7  h1(h2o)
         9   737       p0  u235    v91.94 standard wgt e639228b93vb630
        10   738       p1  u235
        11   739       p2  u235
        12   740       p3  u235
        13   755       p0  u238    v91.94 standard wgt e639237b93vb630
        14   756       p1  u238
        15   757       p2  u238
        16   758       p3  u238
0   17* ARRAY   6499 ENTRIES READ
0    0T
0    3* ARRAY   6499 ENTRIES READ
0    0T
0    1* ARRAY     67 ENTRIES READ
0    4* ARRAY     98 ENTRIES READ
0    5* ARRAY     67 ENTRIES READ
0    6* ARRAY     17 ENTRIES READ
0    7* ARRAY     17 ENTRIES READ
0    8$ ARRAY     97 ENTRIES READ
0    9$ ARRAY      5 ENTRIES READ
0   10$ ARRAY     28 ENTRIES READ
0   11$ ARRAY     28 ENTRIES READ
0   12* ARRAY     28 ENTRIES READ
0   19$ ARRAY      5 ENTRIES READ
0   21* ARRAY     97 ENTRIES READ
0   22$ ARRAY      2 ENTRIES READ
0   23$ ARRAY      2 ENTRIES READ
0    0T
0******  TOTAL FIXED SOURCE BEFORE NORMALIZATION  1.02154E+03


0 agn reactor
0 GEOMETRY EDIT
0 INT   ZONE       RADIUS     AREA     VOLUME  FISS DENS DEN FACTS
    1     1      0.000E+00 0.000E+00 4.632E-01 0.000E+00 0.000E+00
    2     2      4.800E-01 2.895E+00 1.449E-03 0.000E+00 0.000E+00
    3     2      4.805E-01 2.901E+00 1.452E-03 0.000E+00 0.000E+00
    4     2      4.810E-01 2.907E+00 1.455E-03 0.000E+00 0.000E+00
    5     2      4.815E-01 2.913E+00 1.458E-03 0.000E+00 0.000E+00
    6     2      4.820E-01 2.919E+00 1.461E-03 0.000E+00 0.000E+00
    7     2      4.825E-01 2.926E+00 1.464E-03 0.000E+00 0.000E+00
    8     2      4.830E-01 2.932E+00 1.467E-03 0.000E+00 0.000E+00
    9     2      4.835E-01 2.938E+00 1.470E-03 0.000E+00 0.000E+00
   10     2      4.840E-01 2.944E+00 1.473E-03 0.000E+00 0.000E+00
   11     2      4.845E-01 2.950E+00 1.476E-03 0.000E+00 0.000E+00
   12     2      4.850E-01 2.956E+00 1.479E-03 0.000E+00 0.000E+00
   13     2      4.855E-01 2.962E+00 1.483E-03 0.000E+00 0.000E+00
   14     2      4.860E-01 2.968E+00 1.486E-03 0.000E+00 0.000E+00
   15     2      4.865E-01 2.974E+00 1.489E-03 0.000E+00 0.000E+00
   16     2      4.870E-01 2.980E+00 1.492E-03 0.000E+00 0.000E+00
   17     2      4.875E-01 2.986E+00 1.495E-03 0.000E+00 0.000E+00
   18     2      4.880E-01 2.993E+00 1.498E-03 0.000E+00 0.000E+00
   19     2      4.885E-01 2.999E+00 1.501E-03 0.000E+00 0.000E+00
   20     2      4.890E-01 3.005E+00 1.504E-03 0.000E+00 0.000E+00
```

21	2	4.895E-01	3.011E+00	1.507E-03	0.000E+00	0.000E+00
22	2	4.900E-01	3.017E+00	1.510E-03	0.000E+00	0.000E+00
23	2	4.905E-01	3.023E+00	1.513E-03	0.000E+00	0.000E+00
24	2	4.910E-01	3.030E+00	1.516E-03	0.000E+00	0.000E+00
25	2	4.915E-01	3.036E+00	1.519E-03	0.000E+00	0.000E+00
26	2	4.920E-01	3.042E+00	1.522E-03	0.000E+00	0.000E+00
27	2	4.925E-01	3.048E+00	1.526E-03	0.000E+00	0.000E+00
28	2	4.930E-01	3.054E+00	1.529E-03	0.000E+00	0.000E+00
29	2	4.935E-01	3.060E+00	1.532E-03	0.000E+00	0.000E+00
30	2	4.940E-01	3.067E+00	1.535E-03	0.000E+00	0.000E+00
31	2	4.945E-01	3.073E+00	1.538E-03	0.000E+00	0.000E+00
32	2	4.950E-01	3.079E+00	1.541E-03	0.000E+00	0.000E+00
33	2	4.955E-01	3.085E+00	1.544E-03	0.000E+00	0.000E+00
34	2	4.960E-01	3.092E+00	1.547E-03	0.000E+00	0.000E+00
35	2	4.965E-01	3.098E+00	1.550E-03	0.000E+00	0.000E+00
36	2	4.970E-01	3.104E+00	1.554E-03	0.000E+00	0.000E+00
37	2	4.975E-01	3.110E+00	1.557E-03	0.000E+00	0.000E+00
38	2	4.980E-01	3.117E+00	1.560E-03	0.000E+00	0.000E+00
39	2	4.985E-01	3.123E+00	1.563E-03	0.000E+00	0.000E+00
40	2	4.990E-01	3.129E+00	1.566E-03	0.000E+00	0.000E+00
41	2	4.995E-01	3.135E+00	1.569E-03	0.000E+00	0.000E+00
42	3	5.000E-01	3.142E+00	3.665E+00	0.000E+00	1.000E+00
43	4	1.000E+00	1.257E+01	6.083E+00	0.000E+00	1.000E+00
44	4	1.348E+00	2.285E+01	1.020E+01	0.000E+00	1.000E+00
45	4	1.697E+00	3.619E+01	1.538E+01	0.000E+00	1.000E+00
46	4	2.045E+00	5.258E+01	2.162E+01	0.000E+00	1.000E+00
47	4	2.394E+00	7.202E+01	2.893E+01	0.000E+00	1.000E+00
48	4	2.742E+00	9.451E+01	3.730E+01	0.000E+00	1.000E+00
49	4	3.091E+00	1.201E+02	4.673E+01	0.000E+00	1.000E+00
50	4	3.439E+00	1.487E+02	5.723E+01	0.000E+00	1.000E+00
51	4	3.788E+00	1.803E+02	6.879E+01	0.000E+00	1.000E+00
52	4	4.136E+00	2.150E+02	8.142E+01	0.000E+00	1.000E+00
53	4	4.485E+00	2.528E+02	9.510E+01	0.000E+00	1.000E+00
54	4	4.833E+00	2.936E+02	1.099E+02	0.000E+00	1.000E+00
55	4	5.182E+00	3.374E+02	1.257E+02	0.000E+00	1.000E+00
56	4	5.530E+00	3.843E+02	1.426E+02	0.000E+00	1.000E+00
57	4	5.879E+00	4.343E+02	1.605E+02	0.000E+00	1.000E+00
58	4	6.227E+00	4.873E+02	1.795E+02	0.000E+00	1.000E+00
59	4	6.576E+00	5.434E+02	1.996E+02	0.000E+00	1.000E+00
60	4	6.924E+00	6.025E+02	2.207E+02	0.000E+00	1.000E+00
61	4	7.273E+00	6.647E+02	2.429E+02	0.000E+00	1.000E+00
62	4	7.621E+00	7.299E+02	2.662E+02	0.000E+00	1.000E+00
63	4	7.970E+00	7.982E+02	2.905E+02	0.000E+00	1.000E+00
64	4	8.318E+00	8.695E+02	3.159E+02	0.000E+00	1.000E+00
65	4	8.667E+00	9.439E+02	3.423E+02	0.000E+00	1.000E+00
66	4	9.015E+00	1.021E+03	3.698E+02	0.000E+00	1.000E+00
67	4	9.364E+00	1.102E+03	3.984E+02	0.000E+00	1.000E+00
68	4	9.712E+00	1.185E+03	4.281E+02	0.000E+00	1.000E+00
69	4	1.006E+01	1.272E+03	4.588E+02	0.000E+00	1.000E+00
70	4	1.041E+01	1.362E+03	4.905E+02	0.000E+00	1.000E+00
71	4	1.076E+01	1.454E+03	5.234E+02	0.000E+00	1.000E+00
72	4	1.111E+01	1.550E+03	5.573E+02	0.000E+00	1.000E+00
73	4	1.145E+01	1.649E+03	5.922E+02	0.000E+00	1.000E+00
74	4	1.180E+01	1.751E+03	6.283E+02	0.000E+00	1.000E+00

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   75     4      1.215E+01 1.856E+03 6.654E+02 0.000E+00 1.000E+00
   76     5      1.250E+01 1.963E+03 1.022E+03 0.000E+00 1.000E+00
   77     5      1.300E+01 2.124E+03 7.262E+02 0.000E+00 1.000E+00
   78     5      1.333E+01 2.234E+03 7.634E+02 0.000E+00 1.000E+00
   79     5      1.367E+01 2.347E+03 8.016E+02 0.000E+00 1.000E+00
   80     5      1.400E+01 2.463E+03 8.407E+02 0.000E+00 1.000E+00
   81     5      1.433E+01 2.582E+03 8.807E+02 0.000E+00 1.000E+00
   82     5      1.467E+01 2.703E+03 9.217E+02 0.000E+00 1.000E+00
   83     5      1.500E+01 2.827E+03 9.636E+02 0.000E+00 1.000E+00
   84     5      1.533E+01 2.954E+03 1.006E+03 0.000E+00 1.000E+00
   85     5      1.567E+01 3.084E+03 1.050E+03 0.000E+00 1.000E+00
   86     5      1.600E+01 3.217E+03 1.095E+03 0.000E+00 1.000E+00
   87     5      1.633E+01 3.352E+03 1.140E+03 0.000E+00 1.000E+00
   88     5      1.667E+01 3.491E+03 1.187E+03 0.000E+00 1.000E+00
   89     5      1.700E+01 3.632E+03 1.234E+03 0.000E+00 1.000E+00
   90     5      1.733E+01 3.775E+03 1.283E+03 0.000E+00 1.000E+00
   91     5      1.767E+01 3.922E+03 1.332E+03 0.000E+00 1.000E+00
   92     5      1.800E+01 4.072E+03 1.382E+03 0.000E+00 1.000E+00
   93     5      1.833E+01 4.224E+03 1.434E+03 0.000E+00 1.000E+00
   94     5      1.867E+01 4.379E+03 1.486E+03 0.000E+00 1.000E+00
   95     5      1.900E+01 4.536E+03 1.539E+03 0.000E+00 1.000E+00
   96     5      1.933E+01 4.697E+03 1.593E+03 0.000E+00 1.000E+00
   97     5      1.967E+01 4.860E+03 1.648E+03 0.000E+00 1.000E+00
   98            2.000E+01 5.027E+03


0 agn reactor

 ***************************************************
  (FOR ADJOINT PROBS., THE GROUPS ARE REVERSED HERE)
 ***************************************************

0 GROUP DEPENDENT PARAMETERS EDIT
0 GRP  FISS SPEC  VELOCITY
    1  0.000E+00 4.660E+05
    2  0.000E+00 1.210E+06
    3  0.000E+00 2.870E+06
    4  0.000E+00 3.780E+06
    5  0.000E+00 2.610E+06
    6  0.000E+00 1.330E+06
    7  0.000E+00 8.530E+05
    8  0.000E+00 6.940E+05
    9  0.000E+00 6.240E+05
   10  0.000E+00 5.460E+05
   11  0.000E+00 4.320E+05
   12  0.000E+00 3.420E+05
   13  0.000E+00 2.690E+05
   14  0.000E+00 2.160E+05
   15  0.000E+00 1.850E+05
   16  0.000E+00 1.620E+05
   17  0.000E+00 1.440E+05
   18  0.000E+00 1.310E+05
   19  0.000E+00 1.140E+05
   20  0.000E+00 9.070E+04
```

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   21  0.000E+00 2.720E+05
   22  0.000E+00 2.470E+05
   23  0.000E+00 2.300E+05
   24  0.000E+00 2.220E+05
   25  0.000E+00 2.190E+05
   26  0.000E+00 2.200E+05
   27  0.000E+00 2.250E+05
   28  0.000E+00 2.350E+05
   29  0.000E+00 2.440E+05
   30  0.000E+00 2.530E+05
   31  0.000E+00 2.660E+05
   32  0.000E+00 2.750E+05
   33  0.000E+00 2.800E+05
   34  0.000E+00 2.410E+05
   35  0.000E+00 1.730E+05
   36  0.000E+00 1.450E+05
   37  0.000E+00 1.360E+05
   38  0.000E+00 1.220E+05
   39  0.000E+00 1.020E+05
   40  6.500E-03 7.450E+04
   41  7.300E-03 5.030E+04
   42  1.900E-02 3.250E+04
   43  8.000E-03 2.090E+04
   44  4.800E-02 1.560E+04
   45  4.000E-02 1.230E+04
   46  4.000E-02 1.030E+04
   47  5.000E-02 9.280E+03
   48  2.900E-02 8.610E+04
   49  6.350E-02 7.970E+03
   50  1.320E-01 7.670E+03
   51  8.800E-02 7.770E+03
   52  5.250E-02 7.850E+03
   53  7.000E-02 7.920E+03
   54  2.100E-02 7.960E+03
   55  2.000E-02 7.970E+03
   56  1.900E-02 7.990E+03
   57  3.500E-02 7.900E+03
   58  4.500E-02 7.650E+03
   59  8.000E-02 7.290E+03
   60  7.000E-02 6.710E+03
   61  3.200E-02 6.510E+03
   62  1.430E-02 6.740E+03
   63  0.000E+00 6.800E+03
   64  0.000E+00 6.800E+03
   65  0.000E+00 6.100E+03
   66  0.000E+00 5.100E+03
   67  0.000E+00 4.670E+03


0 agn reactor
0 ZONE DEPENDENT PARAMETERS EDIT
0 ZONE MATL/ZONE L OF P(L)
    1    29         3
    2    29         3
```

3	25	3
4	33	3
5	37	3

ZONE	WIDTH	OUTER RADIUS	NO. OF INT.
1	4.80000E-01	4.80000E-01	1
2	2.00000E-02	5.00000E-01	40
3	5.00000E-01	1.00000E+00	1
4	1.15000E+01	1.25000E+01	33
5	7.50000E+00	2.00000E+01	22

0 agn reactor
0CROSS SECTION MIXING TABLE

	MATL	COMP.	NO. DENSITY
1	25	1	6.000E-02
2	26	2	6.000E-02
3	27	3	6.000E-02
4	28	4	6.000E-02
5	29	5	4.640E-02
6	30	6	4.640E-02
7	31	7	4.640E-02
8	32	8	4.640E-02
9	33	17	3.950E-02
10	34	18	3.950E-02
11	35	19	3.950E-02
12	36	20	3.950E-02
13	33	21	7.900E-02
14	34	22	7.900E-02
15	35	23	7.900E-02
16	36	24	7.900E-02
17	33	9	1.280E-04
18	34	10	1.280E-04
19	35	11	1.280E-04
20	36	12	1.280E-04
21	33	13	5.120E-04
22	34	14	5.120E-04
23	35	15	5.120E-04
24	36	16	5.120E-04
25	37	17	8.000E-02
26	38	18	8.000E-02
27	39	19	8.000E-02
28	40	20	8.000E-02

0 agn reactor
0ANGULAR QUADRATURE CONSTANTS

ANGLE	COSINE(MU)	WEIGHT	REFL DIR.	WT * COS
1	-9.903E-01	0.000E+00	17	-0.000E+00
2	-9.805E-01	2.449E-02	17	-2.402E-02
3	-9.093E-01	4.133E-02	16	-3.758E-02

```
    4 -8.320E-01 3.926E-02   15     -3.266E-02
    5 -7.468E-01 4.008E-02   14     -2.993E-02
    6 -6.504E-01 6.438E-02   13     -4.187E-02
    7 -5.377E-01 4.421E-02   12     -2.377E-02
    8 -3.923E-01 1.091E-01   11     -4.279E-02
    9 -1.390E-01 1.372E-01   10     -1.906E-02
   10  1.390E-01 1.372E-01    9      1.906E-02
   11  3.923E-01 1.091E-01    8      4.279E-02
   12  5.377E-01 4.421E-02    7      2.377E-02
   13  6.504E-01 6.438E-02    6      4.187E-02
   14  7.468E-01 4.008E-02    5      2.993E-02
   15  8.320E-01 3.926E-02    4      3.266E-02
   16  9.093E-01 4.133E-02    3      3.758E-02
   17  9.805E-01 2.449E-02    2      2.402E-02
0 CONSTANTS FOR P( 3) SCATTERING
0 ANGL   SET   1     SET   2     SET   3
    1 -9.90299E-01 9.71037E-01-9.42495E-01
    2 -9.80501E-01 9.42073E-01-8.85839E-01
    3 -9.09286E-01 7.40201E-01-5.15566E-01
    4 -8.31997E-01 5.38328E-01-1.91814E-01
    5 -7.46751E-01 3.36455E-01 7.90872E-02
    6 -6.50427E-01 1.34582E-01 2.87725E-01
    7 -5.37710E-01-6.63022E-02 4.17892E-01
    8 -3.92289E-01-2.69164E-01 4.37510E-01
    9 -1.38957E-01-4.71036E-01 2.01727E-01
   10  1.38957E-01-4.71036E-01-2.01727E-01
   11  3.92289E-01-2.69164E-01-4.37510E-01
   12  5.37710E-01-6.63022E-02-4.17892E-01
   13  6.50427E-01 1.34582E-01-2.87725E-01
   14  7.46751E-01 3.36455E-01-7.90872E-02
   15  8.31997E-01 5.38328E-01 1.91814E-01
   16  9.09286E-01 7.40201E-01 5.15566E-01
   17  9.80501E-01 9.42073E-01 8.85839E-01
```

Adjoint flux with absorber

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*********************************************************
               *                                                       *
               *                                                       *
               *  AAAAAAAA  NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
               * AAAAAAAAAA NNN     NN IIIIIIIIII SSSSSSSSSS NNN     NN  *
               * AA      AA NNNN    NN     II     SS         NNNN    NN  *
               * AA      AA NNNNN   NN     II     SS         NNNNN   NN  *
               * AAAAAAAAAA NN NNN  NN     II     SSSSSSSSS  NN NNN  NN  *
               * AAAAAAAAAA NN  NNN NN     II      SSSSSSSSS NN  NNN NN  *
               * AA      AA NN   NNNNN     II             SS NN   NNNNN  *
               * AA      AA NN    NNNN     II             SS NN    NNNN  *
               * AA      AA NN     NNN IIIIIIIIII SSSSSSSSS NN     NNN  *
               * AA      AA NN      NN IIIIIIIIII  SSSSSSSS  NN      NN  *
               *                                                       *
               *        INEL Apollo 10000 VERSION 3.2 (AUG 1988)       *
               *        Revised 4-16-93 for ANL SPARC                  *
               *            G. R. IMEL----ANL                          *
               *                 D. KENT PARSONS                       *
               *                 EG&G IDAHO, INC                       *
               *                  P.O. BOX 1625                        *
               *              IDAHO FALLS, ID 83415                    *
               *                                                       *
               *********************************************************


0 agn reactor
0   15$ ARRAY     36 ENTRIES READ
0   16* ARRAY     14 ENTRIES READ
0    0T
0 ID    PROBLEM ID NO.               1    ITH   0/1 = REG./ADJ.
1
  ISCT  ORDER OF SCATTERING          3    ISN   QUADRATURE ORDER
16
  IGE   1/2/3 = PLA/CYL/SPH          3    IBL   0/1/2/3 =
VAC/REFL/PER/ALBDO   1
  IBR   RT BC SAME AS LEFT BC,IBL    0    IZM   NO. OF ZONES
5
  IM    NO. OF INTERVALS            97    IEVT
0/1/2/3/4/5/6=Q/K/A/C/Z/R/H    0
  IGM   NO. OF GROUPS               67    IHT   POS. OF SIGMA T
3
  IHS   POS. OF SIGMA GG             4    IHM   TABLE LENGTH
70
  MS    MIXING TABLE LENGTH         28    MCR   NO. MATLS. FROM CARDS
0
  MTP   NO. MATLS. FROM LIB TAPE    24    MT    NO. OF MATLS.
40
  IDFM  0/1=NONE/DEN FACTORS(21*)    1    IPVT  0/1/2=NONE/K/ALPHA
0
```

```
  IQM   0/1=NONE/DIST. SOURCE        1    IPM
0/1/IM=NO/S(MM,IPP)/S(MM,IM)   0
  IPP   INT OF SHELL SOURCE          0    IIM   INNER ITER. MAX.
100
  ID1   0/1/2/3=NO/PRNT/PNCH/BOTH    2    ID2   -N/-1/0/1/2=ITX/IGX/-
/ITX/PRV  3
  ID3   0/N=NO/ACTIV. BY ZONE        2    ID4   0/1=NO/ACTIV. BY INT
1
  ICM   OUTER ITER. MAX.           100    IDAT1 0/1/2=NO/MIN/MAX TAPE
0
  IDAT2 0/1=NO/DIFF/INFN(24$)        0    IFG   0/1/2/3/4 NO/FG/R/W/RW
0
  IFLU  -1/0/1/2/3/4=DSA/LS/L/S/W/LW 3    IFN   -1/0/1/2=CCCC/2*/3*/PREV.
1
  IPRT  0/1 = PRINT XS/DO NOT        1    IXTR  0/1/2/3=FLUX SAVE-
NO/R/W/R&W   0
0 EV    EIGENVALUE GUESS     0.000E+00    EVM   EV MODIFIER, SEARCH
0.000E+00
  EPS   PRECISION DESIRED    1.000E-04    BF    BUCKLING FACTOR
1.421E+00
  DY    CYL OR PLA HEIGHT    0.000E+00    DZ    PLANE DEPTH
0.000E+00
  DFM1  HT. FOR VOID CORR.   0.000E+00    XNF   NORMALIZATION
0.000E+00
  PV    IPVT=1/2 - K/ALPHA   0.000E+00    RYF   SCAT, UPSCAT RELAX
5.000E-01
  XLAL  PT CONV EPS IF NE 0  1.000E-04    XLAH  1-LAMBDA MAX.,SEARCH
5.000E-02
  EQL   EV DEL EPS.,SEARCH   1.000E-03    XNPM  UNDERRELAXATION,SEARCH
7.500E-01
0450002 LOCATIONS ARE AVAILABLE FOR THIS PROBLEM
0234883 LOCATIONS WILL BE REQUIRED FOR FLUX CALCULATION
0230117 LOCATIONS WILL BE REQUIRED FOR COMPLETE SUMMARY TABLES
0227286 LOCATIONS WILL BE REQUIRED FOR COMPLETE ACTIVITY TABLES
0  6664 BYTES WILL BE REQUIRED FOR THE PROFORT RUN-TIME BUFFER
0   13$ ARRAY     24 ENTRIES READ
0    0T
0 ELEMENTS READ FROM LIBRARY TAPE
0 MAT. NO.    ID
         1    13       p0  al27    v91.94 standard wgt e601325b93vb630
         2    14       p1  al27
         3    15       p2  al27
         4    16       p3  al27
        17    95       p0  c       v91.94 standard wgt e620600b93vb630
        18    96       p1  c
        19    97       p2  c
        20    98       p3  c
         5   119       p0  cd(nat) v91.94 standard wgt e604800b93vb630
         6   120       p1  cd(nat)
         7   121       p2  cd(nat)
         8   122       p3  cd(nat)
        21   313       p0  h1(h2o) v91.94 standard wgt e620125b93vb630
        22   315       p2  h1(h2o)
        23   318       p5  h1(h2o)
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        24   320       p7  h1(h2o)
         9   737       p0  u235    v91.94 standard wgt e639228b93vb630
        10   738       p1  u235
        11   739       p2  u235
        12   740       p3  u235
        13   755       p0  u238    v91.94 standard wgt e639237b93vb630
        14   756       p1  u238
        15   757       p2  u238
        16   758       p3  u238
0   17* ARRAY   6499 ENTRIES READ
0    0T
0    3* ARRAY   6499 ENTRIES READ
0    0T
0    1* ARRAY     67 ENTRIES READ
0    4* ARRAY     98 ENTRIES READ
0    5* ARRAY     67 ENTRIES READ
0    6* ARRAY     17 ENTRIES READ
0    7* ARRAY     17 ENTRIES READ
0    8$ ARRAY     97 ENTRIES READ
0    9$ ARRAY      5 ENTRIES READ
0   10$ ARRAY     28 ENTRIES READ
0   11$ ARRAY     28 ENTRIES READ
0   12* ARRAY     28 ENTRIES READ
0   19$ ARRAY      5 ENTRIES READ
0   21* ARRAY     97 ENTRIES READ
0   22$ ARRAY      2 ENTRIES READ
0   23$ ARRAY      2 ENTRIES READ
0    0T
0******  TOTAL FIXED SOURCE BEFORE NORMALIZATION  1.02154E+03


0 agn reactor
0 GEOMETRY EDIT
0 INT   ZONE       RADIUS     AREA     VOLUME  FISS DENS DEN FACTS
    1     1      0.000E+00 0.000E+00 4.632E-01 0.000E+00 0.000E+00
    2     2      4.800E-01 2.895E+00 1.449E-03 0.000E+00 1.000E+00
    3     2      4.805E-01 2.901E+00 1.452E-03 0.000E+00 1.000E+00
    4     2      4.810E-01 2.907E+00 1.455E-03 0.000E+00 1.000E+00
    5     2      4.815E-01 2.913E+00 1.458E-03 0.000E+00 1.000E+00
    6     2      4.820E-01 2.919E+00 1.461E-03 0.000E+00 1.000E+00
    7     2      4.825E-01 2.926E+00 1.464E-03 0.000E+00 1.000E+00
    8     2      4.830E-01 2.932E+00 1.467E-03 0.000E+00 1.000E+00
    9     2      4.835E-01 2.938E+00 1.470E-03 0.000E+00 1.000E+00
   10     2      4.840E-01 2.944E+00 1.473E-03 0.000E+00 1.000E+00
   11     2      4.845E-01 2.950E+00 1.476E-03 0.000E+00 1.000E+00
   12     2      4.850E-01 2.956E+00 1.479E-03 0.000E+00 1.000E+00
   13     2      4.855E-01 2.962E+00 1.483E-03 0.000E+00 1.000E+00
   14     2      4.860E-01 2.968E+00 1.486E-03 0.000E+00 1.000E+00
   15     2      4.865E-01 2.974E+00 1.489E-03 0.000E+00 1.000E+00
   16     2      4.870E-01 2.980E+00 1.492E-03 0.000E+00 1.000E+00
   17     2      4.875E-01 2.986E+00 1.495E-03 0.000E+00 1.000E+00
   18     2      4.880E-01 2.993E+00 1.498E-03 0.000E+00 1.000E+00
   19     2      4.885E-01 2.999E+00 1.501E-03 0.000E+00 1.000E+00
   20     2      4.890E-01 3.005E+00 1.504E-03 0.000E+00 1.000E+00
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21	2	4.895E-01	3.011E+00	1.507E-03	0.000E+00	1.000E+00
22	2	4.900E-01	3.017E+00	1.510E-03	0.000E+00	1.000E+00
23	2	4.905E-01	3.023E+00	1.513E-03	0.000E+00	1.000E+00
24	2	4.910E-01	3.030E+00	1.516E-03	0.000E+00	1.000E+00
25	2	4.915E-01	3.036E+00	1.519E-03	0.000E+00	1.000E+00
26	2	4.920E-01	3.042E+00	1.522E-03	0.000E+00	1.000E+00
27	2	4.925E-01	3.048E+00	1.526E-03	0.000E+00	1.000E+00
28	2	4.930E-01	3.054E+00	1.529E-03	0.000E+00	1.000E+00
29	2	4.935E-01	3.060E+00	1.532E-03	0.000E+00	1.000E+00
30	2	4.940E-01	3.067E+00	1.535E-03	0.000E+00	1.000E+00
31	2	4.945E-01	3.073E+00	1.538E-03	0.000E+00	1.000E+00
32	2	4.950E-01	3.079E+00	1.541E-03	0.000E+00	1.000E+00
33	2	4.955E-01	3.085E+00	1.544E-03	0.000E+00	1.000E+00
34	2	4.960E-01	3.092E+00	1.547E-03	0.000E+00	1.000E+00
35	2	4.965E-01	3.098E+00	1.550E-03	0.000E+00	1.000E+00
36	2	4.970E-01	3.104E+00	1.554E-03	0.000E+00	1.000E+00
37	2	4.975E-01	3.110E+00	1.557E-03	0.000E+00	1.000E+00
38	2	4.980E-01	3.117E+00	1.560E-03	0.000E+00	1.000E+00
39	2	4.985E-01	3.123E+00	1.563E-03	0.000E+00	1.000E+00
40	2	4.990E-01	3.129E+00	1.566E-03	0.000E+00	1.000E+00
41	2	4.995E-01	3.135E+00	1.569E-03	0.000E+00	1.000E+00
42	3	5.000E-01	3.142E+00	3.665E+00	0.000E+00	1.000E+00
43	4	1.000E+00	1.257E+01	6.083E+00	0.000E+00	1.000E+00
44	4	1.348E+00	2.285E+01	1.020E+01	0.000E+00	1.000E+00
45	4	1.697E+00	3.619E+01	1.538E+01	0.000E+00	1.000E+00
46	4	2.045E+00	5.258E+01	2.162E+01	0.000E+00	1.000E+00
47	4	2.394E+00	7.202E+01	2.893E+01	0.000E+00	1.000E+00
48	4	2.742E+00	9.451E+01	3.730E+01	0.000E+00	1.000E+00
49	4	3.091E+00	1.201E+02	4.673E+01	0.000E+00	1.000E+00
50	4	3.439E+00	1.487E+02	5.723E+01	0.000E+00	1.000E+00
51	4	3.788E+00	1.803E+02	6.879E+01	0.000E+00	1.000E+00
52	4	4.136E+00	2.150E+02	8.142E+01	0.000E+00	1.000E+00
53	4	4.485E+00	2.528E+02	9.510E+01	0.000E+00	1.000E+00
54	4	4.833E+00	2.936E+02	1.099E+02	0.000E+00	1.000E+00
55	4	5.182E+00	3.374E+02	1.257E+02	0.000E+00	1.000E+00
56	4	5.530E+00	3.843E+02	1.426E+02	0.000E+00	1.000E+00
57	4	5.879E+00	4.343E+02	1.605E+02	0.000E+00	1.000E+00
58	4	6.227E+00	4.873E+02	1.795E+02	0.000E+00	1.000E+00
59	4	6.576E+00	5.434E+02	1.996E+02	0.000E+00	1.000E+00
60	4	6.924E+00	6.025E+02	2.207E+02	0.000E+00	1.000E+00
61	4	7.273E+00	6.647E+02	2.429E+02	0.000E+00	1.000E+00
62	4	7.621E+00	7.299E+02	2.662E+02	0.000E+00	1.000E+00
63	4	7.970E+00	7.982E+02	2.905E+02	0.000E+00	1.000E+00
64	4	8.318E+00	8.695E+02	3.159E+02	0.000E+00	1.000E+00
65	4	8.667E+00	9.439E+02	3.423E+02	0.000E+00	1.000E+00
66	4	9.015E+00	1.021E+03	3.698E+02	0.000E+00	1.000E+00
67	4	9.364E+00	1.102E+03	3.984E+02	0.000E+00	1.000E+00
68	4	9.712E+00	1.185E+03	4.281E+02	0.000E+00	1.000E+00
69	4	1.006E+01	1.272E+03	4.588E+02	0.000E+00	1.000E+00
70	4	1.041E+01	1.362E+03	4.905E+02	0.000E+00	1.000E+00
71	4	1.076E+01	1.454E+03	5.234E+02	0.000E+00	1.000E+00
72	4	1.111E+01	1.550E+03	5.573E+02	0.000E+00	1.000E+00
73	4	1.145E+01	1.649E+03	5.922E+02	0.000E+00	1.000E+00
74	4	1.180E+01	1.751E+03	6.283E+02	0.000E+00	1.000E+00

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   75     4      1.215E+01 1.856E+03 6.654E+02 0.000E+00 1.000E+00
   76     5      1.250E+01 1.963E+03 1.022E+03 0.000E+00 1.000E+00
   77     5      1.300E+01 2.124E+03 7.262E+02 0.000E+00 1.000E+00
   78     5      1.333E+01 2.234E+03 7.634E+02 0.000E+00 1.000E+00
   79     5      1.367E+01 2.347E+03 8.016E+02 0.000E+00 1.000E+00
   80     5      1.400E+01 2.463E+03 8.407E+02 0.000E+00 1.000E+00
   81     5      1.433E+01 2.582E+03 8.807E+02 0.000E+00 1.000E+00
   82     5      1.467E+01 2.703E+03 9.217E+02 0.000E+00 1.000E+00
   83     5      1.500E+01 2.827E+03 9.636E+02 0.000E+00 1.000E+00
   84     5      1.533E+01 2.954E+03 1.006E+03 0.000E+00 1.000E+00
   85     5      1.567E+01 3.084E+03 1.050E+03 0.000E+00 1.000E+00
   86     5      1.600E+01 3.217E+03 1.095E+03 0.000E+00 1.000E+00
   87     5      1.633E+01 3.352E+03 1.140E+03 0.000E+00 1.000E+00
   88     5      1.667E+01 3.491E+03 1.187E+03 0.000E+00 1.000E+00
   89     5      1.700E+01 3.632E+03 1.234E+03 0.000E+00 1.000E+00
   90     5      1.733E+01 3.775E+03 1.283E+03 0.000E+00 1.000E+00
   91     5      1.767E+01 3.922E+03 1.332E+03 0.000E+00 1.000E+00
   92     5      1.800E+01 4.072E+03 1.382E+03 0.000E+00 1.000E+00
   93     5      1.833E+01 4.224E+03 1.434E+03 0.000E+00 1.000E+00
   94     5      1.867E+01 4.379E+03 1.486E+03 0.000E+00 1.000E+00
   95     5      1.900E+01 4.536E+03 1.539E+03 0.000E+00 1.000E+00
   96     5      1.933E+01 4.697E+03 1.593E+03 0.000E+00 1.000E+00
   97     5      1.967E+01 4.860E+03 1.648E+03 0.000E+00 1.000E+00
   98            2.000E+01 5.027E+03


0 agn reactor

 ***************************************************
  (FOR ADJOINT PROBS., THE GROUPS ARE REVERSED HERE)
 ***************************************************

0 GROUP DEPENDENT PARAMETERS EDIT
0 GRP  FISS SPEC  VELOCITY
    1  0.000E+00 4.660E+05
    2  0.000E+00 1.210E+06
    3  0.000E+00 2.870E+06
    4  0.000E+00 3.780E+06
    5  0.000E+00 2.610E+06
    6  0.000E+00 1.330E+06
    7  0.000E+00 8.530E+05
    8  0.000E+00 6.940E+05
    9  0.000E+00 6.240E+05
   10  0.000E+00 5.460E+05
   11  0.000E+00 4.320E+05
   12  0.000E+00 3.420E+05
   13  0.000E+00 2.690E+05
   14  0.000E+00 2.160E+05
   15  0.000E+00 1.850E+05
   16  0.000E+00 1.620E+05
   17  0.000E+00 1.440E+05
   18  0.000E+00 1.310E+05
   19  0.000E+00 1.140E+05
   20  0.000E+00 9.070E+04
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   21  0.000E+00 2.720E+05
   22  0.000E+00 2.470E+05
   23  0.000E+00 2.300E+05
   24  0.000E+00 2.220E+05
   25  0.000E+00 2.190E+05
   26  0.000E+00 2.200E+05
   27  0.000E+00 2.250E+05
   28  0.000E+00 2.350E+05
   29  0.000E+00 2.440E+05
   30  0.000E+00 2.530E+05
   31  0.000E+00 2.660E+05
   32  0.000E+00 2.750E+05
   33  0.000E+00 2.800E+05
   34  0.000E+00 2.410E+05
   35  0.000E+00 1.730E+05
   36  0.000E+00 1.450E+05
   37  0.000E+00 1.360E+05
   38  0.000E+00 1.220E+05
   39  0.000E+00 1.020E+05
   40  6.500E-03 7.450E+04
   41  7.300E-03 5.030E+04
   42  1.900E-02 3.250E+04
   43  8.000E-03 2.090E+04
   44  4.800E-02 1.560E+04
   45  4.000E-02 1.230E+04
   46  4.000E-02 1.030E+04
   47  5.000E-02 9.280E+03
   48  2.900E-02 8.610E+04
   49  6.350E-02 7.970E+03
   50  1.320E-01 7.670E+03
   51  8.800E-02 7.770E+03
   52  5.250E-02 7.850E+03
   53  7.000E-02 7.920E+03
   54  2.100E-02 7.960E+03
   55  2.000E-02 7.970E+03
   56  1.900E-02 7.990E+03
   57  3.500E-02 7.900E+03
   58  4.500E-02 7.650E+03
   59  8.000E-02 7.290E+03
   60  7.000E-02 6.710E+03
   61  3.200E-02 6.510E+03
   62  1.430E-02 6.740E+03
   63  0.000E+00 6.800E+03
   64  0.000E+00 6.800E+03
   65  0.000E+00 6.100E+03
   66  0.000E+00 5.100E+03
   67  0.000E+00 4.670E+03


0 agn reactor
0 ZONE DEPENDENT PARAMETERS EDIT
0 ZONE MATL/ZONE L OF P(L)
    1    29         3
    2    29         3
```

3	25	3
4	33	3
5	37	3

ZONE	WIDTH	OUTER RADIUS	NO. OF INT.
1	4.80000E-01	4.80000E-01	1
2	2.00000E-02	5.00000E-01	40
3	5.00000E-01	1.00000E+00	1
4	1.15000E+01	1.25000E+01	33
5	7.50000E+00	2.00000E+01	22

0 agn reactor
0CROSS SECTION MIXING TABLE

	MATL	COMP.	NO. DENSITY
1	25	1	6.000E-02
2	26	2	6.000E-02
3	27	3	6.000E-02
4	28	4	6.000E-02
5	29	5	4.640E-02
6	30	6	4.640E-02
7	31	7	4.640E-02
8	32	8	4.640E-02
9	33	17	3.950E-02
10	34	18	3.950E-02
11	35	19	3.950E-02
12	36	20	3.950E-02
13	33	21	7.900E-02
14	34	22	7.900E-02
15	35	23	7.900E-02
16	36	24	7.900E-02
17	33	9	1.280E-04
18	34	10	1.280E-04
19	35	11	1.280E-04
20	36	12	1.280E-04
21	33	13	5.120E-04
22	34	14	5.120E-04
23	35	15	5.120E-04
24	36	16	5.120E-04
25	37	17	8.000E-02
26	38	18	8.000E-02
27	39	19	8.000E-02
28	40	20	8.000E-02

0 agn reactor
0ANGULAR QUADRATURE CONSTANTS

ANGLE	COSINE(MU)	WEIGHT	REFL DIR.	WT * COS
1	-9.903E-01	0.000E+00	17	-0.000E+00
2	-9.805E-01	2.449E-02	17	-2.402E-02
3	-9.093E-01	4.133E-02	16	-3.758E-02

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    4 -8.320E-01 3.926E-02   15     -3.266E-02
    5 -7.468E-01 4.008E-02   14     -2.993E-02
    6 -6.504E-01 6.438E-02   13     -4.187E-02
    7 -5.377E-01 4.421E-02   12     -2.377E-02
    8 -3.923E-01 1.091E-01   11     -4.279E-02
    9 -1.390E-01 1.372E-01   10     -1.906E-02
   10  1.390E-01 1.372E-01    9      1.906E-02
   11  3.923E-01 1.091E-01    8      4.279E-02
   12  5.377E-01 4.421E-02    7      2.377E-02
   13  6.504E-01 6.438E-02    6      4.187E-02
   14  7.468E-01 4.008E-02    5      2.993E-02
   15  8.320E-01 3.926E-02    4      3.266E-02
   16  9.093E-01 4.133E-02    3      3.758E-02
   17  9.805E-01 2.449E-02    2      2.402E-02
0 CONSTANTS FOR P( 3) SCATTERING
0 ANGL   SET   1     SET   2     SET   3
    1 -9.90299E-01 9.71037E-01-9.42495E-01
    2 -9.80501E-01 9.42073E-01-8.85839E-01
    3 -9.09286E-01 7.40201E-01-5.15566E-01
    4 -8.31997E-01 5.38328E-01-1.91814E-01
    5 -7.46751E-01 3.36455E-01 7.90872E-02
    6 -6.50427E-01 1.34582E-01 2.87725E-01
    7 -5.37710E-01-6.63022E-02 4.17892E-01
    8 -3.92289E-01-2.69164E-01 4.37510E-01
    9 -1.38957E-01-4.71036E-01 2.01727E-01
   10  1.38957E-01-4.71036E-01-2.01727E-01
   11  3.92289E-01-2.69164E-01-4.37510E-01
   12  5.37710E-01-6.63022E-02-4.17892E-01
   13  6.50427E-01 1.34582E-01-2.87725E-01
   14  7.46751E-01 3.36455E-01-7.90872E-02
   15  8.31997E-01 5.38328E-01 1.91814E-01
   16  9.09286E-01 7.40201E-01 5.15566E-01
   17  9.80501E-01 9.42073E-01 8.85839E-01
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