

REACTOR LABORATORY MANUAL

Ford Nuclear Reactor
Phoenix Memorial Laboratory

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INTRODUCTION

The laboratory portion of the AEC-ASEE Summer Institute follows quite closely the course, Nuclear Engineering 298, Reactor Laboratory, offered as part of the Nuclear Engineering Program at the University of Michigan. Experiment No. 1 and Demonstration Experiment No. 2, however, are presented by the Chemistry Department as part of a regular course, Nuclear Chemistry Techniques, Chemistry 235.

The experiments in this course fall in the following three general categories:

I. Reactor Experiments - These experiments are concerned with the calibration and behavior of the Ford Nuclear Reactor. In this category are Exp. No. 2, The Critical Experiment; Exp. No. 4, Reactor Operation; Exp. No. 7, Reactor Power Measurements; Exp. No. 8, Control Rod Calibration; and Exp. No. 10, Shim Rod Calibration.

II. Reactor Utilization Experiments - These experiments use the reactor as a source of radiation. Exp. No. 1, Activation Analysis and Exp. No. 6, Neutron Diffraction, are included under this heading.

III. General Experiments - This category includes experiments which can be performed without a critical reactor but are related to reactor design and utilization. These experiments are Exp. No. 3, Scintillation Counting Techniques in Gamma Ray Spectroscopy; Exp. No. 5, The Subcritical Experiment; Exp. No. 9, Fermi Age and Mean Square Slowing Down Distance Measurements; Exp. No. 11, Calibration of the Composite Safety Amplifier; and Exp. No. 12, Electromagnet-Rod Performance.

Two demonstration experiments are performed by the Institute staff during the course. Demonstration Experiment No. 1, Health Physics, is designed to acquaint the student with the techniques and measurements important to personnel protection. Demonstration Experiment No. 2, Separation of Fission Products, is presented as an introduction to the techniques of radiochemistry.

The AEC-ASEE Summer Institute Laboratory Course is presented by the combined staffs of the Nuclear Engineering Department, the Phoenix Memorial Laboratory, and the Chemistry Department.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 1

ACTIVATION ANALYSIS

OBJECT:

The purpose of this experiment is to illustrate the determination of trace impurities by neutron activation.

DISCUSSION:

Activation analysis is an analytical technique for the detection of impurities in materials by formation of their radioactive isotopes. There are various techniques such as colorimetric, spectrographic, and mass spectrographic techniques for measuring trace impurities but the limit of detection is about 10⁻⁶% impurity. Activation analysis, when applicable, can measure trace impurities to about 10⁻⁸%. It is usually free from interferences by other elements by virtue of the unique radiations emitted. Table 1 lists the elements which can be detected in activation analysis with their corresponding sensitivities.⁶

Table 1 - ELEMENTS DETERMINED IN TRACE QUANTITIES BY NEUTRON RADIOACTIVATION ANALYSIS⁶

Elements	Sensitivity of Detection -g.*
Bismuth, calcium, iron, sulfur, silicon	10 ⁻⁶
Cerium, chromium, mercury, molybdenum, neodymium, platinum, ruthenium, silver, strontium, tellurium, thallium, tin, zirconium	10 ⁻⁷
Barium, cadmium, cesium, chlorine, cobalt erbium, gadolinium, germanium, hafnium, nickel, osmium, phosphorous, potassium, rubidium, selenium, yttrium, zinc	10 ⁻⁸
Aluminum, antimony, arsenic, bromine, copper, gallium, gold, iodine, lanthanum	10 ⁻⁹

* The amount of an element that would produce sufficient activity to be measured after the element has been exposed to a neutron flux of 10¹² neutrons per sq.cm.per sec. for a given period of irradiation.

Table 1 - ELEMENTS DETERMINED IN TRACE QUANTITIES BY NEUTRON RADIOACTIVATION ANALYSIS⁶ (continued)

Elements	Sensitivity of Detection -g.
palladium, scandium, sodium, praeeseodymium, tantalum, terbium, thulium, tungsten, vanadium, ytterbium	10 ⁻⁹
Holmium, indium, iridium, lutetium, manganese, rhenium, samarium	10 ⁻¹⁰
Europium, dysprosium	10 ⁻¹¹

Activation analysis can be applied to the analysis of the elements in Table 1 which may be present in the following substances:

- Biological material
- Drugs, pharmaceuticals, and related materials
- Fertilizers and feeding stuffs
- Fine chemicals
- Foods and food additives
- Fuels
- Glass and ceramic materials
- Insecticides, disinfectants, etc.
- Lubricants
- Metals and alloys
- Minerals and ores
- Paints, pigments, and related materials
- Petroleum products
- Plastics and resinous materials
- Soils, dusts, and waters
- Toxicants

It is possible to activate stable isotopes using charged particles from an accelerator such as the cyclotron; but because of the complication of competing nuclear reactions, activation is usually done by neutron irradiation, offering more accuracy and facility. There are various available sources which can be used, depending on the neutron flux desired. They vary in cost from \$600 for a 25-mg radium-beryllium source to several million for a suitable nuclear reactor. Table 2 lists a number of possible neutron sources with the usable flux of neutrons available.⁷

Table 2 - NEUTRON SOURCES AND USABLE FLUX OF NEUTRONS AVAILABLE FROM EACH

Neutron Source	Usable Flux (n/Sq. Cm./Sec.)
Nuclear Reactor	$10^{10} - 10^{12}$
Cyclotron	$10^8 - 10^9$
Low voltage DD Neutron Generator	$10^5 - 10^6$
Ra-Be, 1 gram	$10^4 - 10^5$
Sb-Be, 1 curie	$10^3 - 10^4$
Ra-Be, 25 mg.	$\sim 10^2$ (thermal neutrons only)

Good reviews of activation analysis and descriptions of applications of the technique to problems of analysis are contained in the literature.¹⁻¹²

THEORY:

"In principle activation is accomplished by placing the sample to be analyzed in an intense flux of slow neutrons for an appropriately chosen length of time to produce a measurable amount of a radioisotope of the element to be determined. The activity, or the measurable amount of the radioisotope, A, present at a time t after the start of the bombardment is given by the expression

$$A = N \cdot f \cdot \sigma_{ac} \cdot S \quad \text{Eq. (1)}$$

where A is the activity in disintegrations per second, N is the number of nuclei of the element present in the sample, f is the slow neutron flux in neutrons per square centimeter per second, σ_{ac} is the atomic cross section in square centimeters for the (n, γ) reaction leading to the formation of the radioisotope of the element, and S is the saturation factor. The latter is the ratio of the amount of activity produced in time t to the amount of activity produced in infinite time and is given by $S = 1 - e^{-\lambda t}$, where λ is the decay constant for the radioisotope of interest and is equal to $0.693/\text{half-life}$. If it is assumed that the rate of radioisotope production, given by $Nf\sigma_{ac}$, is constant during bombardment, the weight W of the radioisotope produced is, from the preceding equation,

$$W = \frac{A \cdot M}{6.02 \times 10^{23} \cdot f \cdot \sigma_{ac} \cdot S} \quad \text{Eq. (2)}$$

where M = the chemical atomic weight of the element sought.⁹

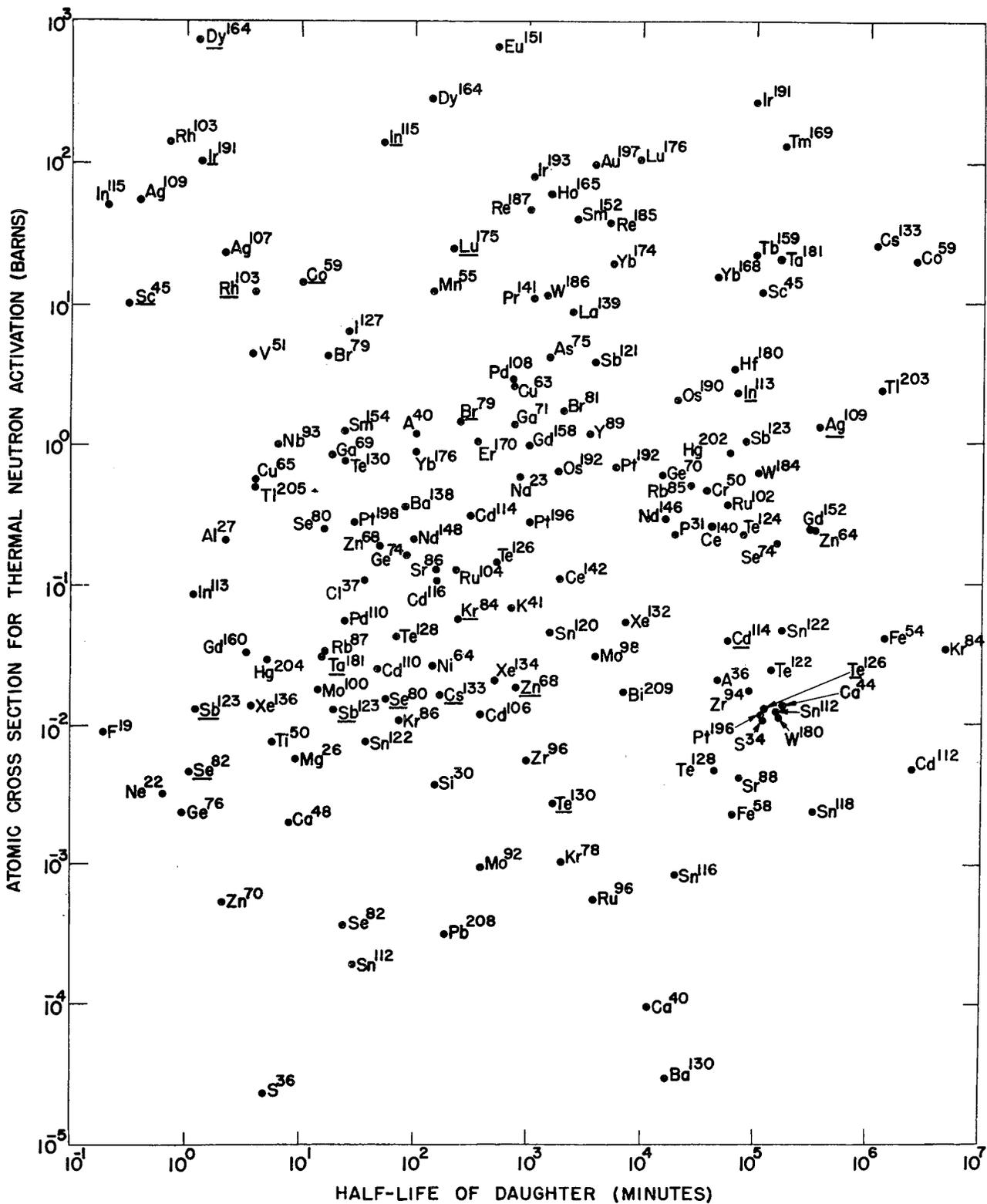


Figure 1. Atomic Cross Section for Thermal Neutron Activation against Half-Life of the Daughter Radioisotope Produced
 Underlined isotopes are activated to a metastable daughter activity

A plot of the thermal neutron activation cross section of the isotopes against the half-life of the daughter is seen in figure 1.7. A newer compilation can also be consulted.⁸

In practice it is very difficult to measure the concentration of an isotope using the absolute method (employing equation 2) because of the uncertainties in the values of the cross sections and number of corrections which must be made to the counting rate to obtain the disintegration rate of the isotope. The usual method compares the activity of the unknown with that of a sample of known composition. Using this technique an overall accuracy better than 10% may be achieved.

"The radioactivity of the samples and of the standards can be determined by one of two methods. The simplest determination is a direct measurement of the radioactivity of the irradiated material shortly after the irradiation has been completed. This method is one in which the irradiated material is suitably mounted on either a watch glass or a metal plate, or an aliquot placed in a small culture tube. The mount is then placed in some type of counter and its radioactivity measured by recording the number of counts per unit time. The analysis is completed by a resolution of the data obtained. This method of analysis is applicable to those samples where the contaminant can be appreciably activated in the presence of the major sample constituent which gives either practically no radioactivity or only a very short-lived radioactive isotope when irradiated by a source of nuclear particles.

However it cannot always be assumed that the major constituent of the sample will not become activated during irradiation, so a chemical separation of the desired element and its induced radioactivity is generally made. After the irradiation, a known amount of the inactive element as an 'isotope carrier' is added to the solutions of both the specimen and standard samples. This 'carrier' is then chemically processed to isolate it and the desired radioactivity from other elements and contaminating radioactivities. Since the procedures used in these chemical separations usually give less than quantitative yield, a correction for 'chemical yield' must be made. After the separation the carrier and the isolated radioactivity are placed into some type of counter and the radioactivity measured. The purity of the separated radioactivity may be checked by absorption techniques and a measurement of its half-life."³

This procedure may be outlined as follows:⁹

1. Irradiate sample and standard.
2. Dissolve sample and standard and add appropriate stable carrier to assist in chemical separations.
3. Ensure exchange between trace and carrier.
4. Chemically process until radioactively pure.
5. Determine the chemical yield by conventional methods.

REACTOR LABORATORY
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EXPERIMENT NO. 2

CRITICAL EXPERIMENT

OBJECT:

The purpose of this experiment is to determine the critical mass of an unknown configuration of fuel and reflector elements by performing a critical experiment on the Ford Nuclear Reactor.

DISCUSSION:

The critical experiment involves a number of unknown quantities, the most important of which is the critical mass of fuel required for the configuration. Therefore, a slow, careful procedure has been adopted for adding fuel. Another unknown quantity is the worth of the rods. Estimates of these values are made during the experiment. Since the entire experiment is done at very low power, the only reactor instrument able to measure the neutron flux is the fission chamber and the associated log count rate channel. As a check on this channel, two additional fission chambers connected to individual counting channels are lowered into the pool for use during the experiment.

As criticality is approached, an estimate of the critical mass is made from inverse multiplication plots. A more accurate estimate of the critical mass can be made after the rods have been calibrated for the configuration. This method is discussed in the Ford Nuclear Reactor calibration report referred to below.

PROCEDURE:

The procedure for a critical experiment is given in the Ford Nuclear Reactor Manual. The present experiment will be run on a modification of a known lattice. The class will be divided into three groups, each group monitoring one information channel (2 auxiliary, 1 reactor count rate channel). Each group will plot inverse multiplication as data become available and will estimate rod worths and critical mass for each data point.

Results of critical experiments similar to the Ford Nuclear Reactor can be found in references 1, 2, and 3. Most of the configurations already known on the Ford Nuclear Reactor are shown in the paper describing the initial calibration of the Ford Nuclear Reactor.⁴

QUESTIONS:

1. What are the safety precautions employed during the experiment?
2. Why does the slope of the inverse multiplication plot change as fuel is added?
3. a) What is the purpose of the neutron source?
b) If enough fuel is accidentally added to the reactor to make it supercritical, what effect does removal of the source have?

REFERENCES:

1. Bebbs, E. H. and Vogt, R. H., "Reactivity Measurements on a Graphite and Water Reflected Core", NRL 4729, May 24, 1956.
2. Nance, J. C., "Calibration of the ASTR", NARF-57-48T, November 1, 1957.
3. Noaks, J. W. and Johnson, W. R., "The Army Package Power Reactor, Zero Power Experiments", (ZPE-1), APAE-8, February 8, 1957.
4. Shapiro, J. L., et al, "Initial Calibration of the Ford Nuclear Reactor", MMPP 110-1, April 1958.

REACTOR LABORATORY
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EXPERIMENT No. 3

SCINTILLATION COUNTING TECHNIQUES
IN
GAMMA RAY SPECTROSCOPY

OBJECT:

To study the operation, calibration, and uses of scintillation counters in gamma ray spectroscopy.

DISCUSSION:

- I. Single Channel Analysers are used in this experiment for γ -ray counting and γ -ray Spectroscopy.
 - A. Crystal used for Detector
 1. NaI with Tl activator is usually used because of its high absorption and its comparatively high efficiency in converting the energy of the gamma rays into radiation in the visible region, or scintillations. In addition it provides a linear relationship between the energy absorbed as gamma rays and the number of photons produced over a significant range of gamma ray energies.
 2. The following are the three most important processes by which the crystal absorbs gamma radiation.
 - a. Photo electric absorption
 - b. Compton Scattering
 - c. Pair production
 3. A gamma ray absorbed in the crystal by any combination of the processes listed above produces scintillations. The mechanism of the scintillation process is discussed in references (1), (2) and (4) given below. In the NaI crystal the number of photons produced is directly proportional to the gamma energy absorbed by the crystals for the gamma energies which we will use.

4. The shapes of the experimentally determined curves of count rate vs. energy obtained depend upon the mechanism of energy absorption of the crystal. An understanding of these mechanisms is necessary to an understanding of the shapes and to an interpretation of important regions in the pulse height (or gamma ray) curve. The shapes of these spectra strongly depend on the energy of the gamma rays, and on the counter geometry. A discussion of this dependence will be found in reference (2).

B. Multiplier Phototube (M.P.) and Associated High Voltage Supply

1. The M.P. is used to measure the number and intensity of light pulses or flashes by converting these flashes into voltage pulses whose heights are proportional to the size of the light pulses.
2. The gain of the multiplier phototube depends on the applied voltage which determines potential differences between the dynodes.

C. Preamplifier (P.A.) and Linear Amplifier (L.A.)

1. The preamplifier is used for impedance matching and the linear amplifier provides for amplification and shaping of the voltage pulses.
2. A delay line is used for pulse shaping on most linear amplifiers used for scintillation counting.
3. The voltage pulse out of the linear amplifier can either be used directly to trigger the scaler (Pulse Height Output) or used with a pulse height analyser (Amplifier Output).
4. Pulse height discrimination is possible using the pulse height discriminator on L.A. The "Pulse Height Output" produces a constant voltage pulse independent of the input to the amplifier. A pulse appears at this output only if its height corresponds to an energy above the energy level set on the pulse height discriminator.

III. Method for determining $I(\gamma)$ Value for the Sample Counted. (Reference 3)

A. $P = I(\gamma) \epsilon \Omega$

where P is the total count rate in the photo peak

$I(\gamma)$ is the intensity of gamma rays of a given energy emitted from the source in gamma/sec.

Ω is the fraction of the solid angle subtended by the source and surface of the crystal.

ϵ is the intrinsic peak efficiency. (i.e. fraction of gamma rays of a given energy in Ω that are completely absorbed by the crystal.) Values of ϵ are given in reference (1) and (2) for various geometrics and crystal sizes.

B. P is obtained by integrating the area in the photo peak.

If we assume the shape of the photo peak to be Gaussian, the area will be given by

$$P = \sqrt{\pi} A_{\max} \sigma$$

where

A_{\max} is the ratio of the maximum count rate at the photo peak to the energy increment, E.

σ is the half width at $\frac{A_{\max}}{e}$

PROCEDURE:

- I. Using a precision test pulse generator check the linearity of the single channel analyser. Also check the linearity of the "E" dial, and find the percent of the maximum "E" dial setting corresponding to various " ΔE " dial settings. Check Laboratory Copy of Differential Analyser Instruction Manual for testing procedure.
- II. Obtain differential curves of Cs^{137} at two different amplifier gains for a given multiplier phototube voltage, using the single channel analyser.

- A. Find the area under each photo peak and compare.
- B. Find the $I(\gamma)$ value for the Cs^{137} source. Compute source strength in microcuries.
- C. Determine the resolution of the analyser for Cs^{137} .
- III. Obtain integral spectra and from these obtain differential spectra.
- A. Use the AID L.A. without the pulse height analyser.
- B. Use the Well counter and plot counts/second versus voltage.
- C. Knowing that the energy of Cs^{137} is 0.661 Mev, and those for Co^{60} are 1.13 Mev and 1.3 Mev, determine the γ energies for unknown samples.

QUESTIONS:

1. In part I above, why should the point at one half the maximum counting rate be used as the reference point during linearity checks?
2. Why is it important to know the window widths in "E" dial units for the $I(\gamma)$ value calculation?
3. Is there such a thing as a plateau in an integral type scintillation counter? Discuss.
4. Show that the resolution R is given by

$$R = \frac{K_1}{\sqrt{E}}$$

where K_1 is a constant and E is the gamma ray energy. Assume that the intensity distribution as a function of energy E is given by

$$y = A_{\max} e^{-\frac{(E - E_0)^2}{\alpha^2 E_0}}$$

where

α is a constant

E_0 is the γ energy

REFERENCES:

1. Price, William J., Nuclear Radiation Detection, Chap. 7, McGraw-Hill Book Company, New York (1958).
2. Siegbaum, Kai, Gamma and Beta Spectroscopy, Chap. 5, Interscience Publishers, New York (1955).
3. Lazar, Bell and Davis, Intrinsic Peak Efficiencies for NaI (Tl) Crystal, Nucleonics, Vol. 14, 4, April 1956.
4. Goldstein, Herbert, The Attenuation of Gamma Rays and Neutrons in Reactor Shields, Prepared for U.S. A.E.C., Contract AT(30-1)-862. Available from U.S. Government Printing Office, Washington 25, D.C. (1957).

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 4

REACTOR OPERATION

OBJECT:

The purpose of this experiment is to impart an understanding and an appreciation of the problems of reactor startup, operation at power level, and shutdown.

DISCUSSION:

The Ford Nuclear Reactor its control and safety system are described in references 1, 2, and 3.

Operating procedures for the reactor are included in the Ford Nuclear Reactor Manual. These procedures will be followed by all operators. Each student must be familiar with and have an understanding of the Ford Nuclear Reactor and its operational procedures prior to operation. One student will be designated as the reactor operator and one student will serve as assistant. All other students will observe the operation of the reactor from the east side of the control room. The licensed reactor operator, a member of the Ford Nuclear Reactor staff, will be in charge of the group.

PROCEDURE:

Each student operator will start the reactor and operate at a power level of 1 KW on manual control for approximately five (5) minutes. The reactor power will then be changed to 10 KW which will be held for another five (5) minutes.

From 10 KW the reactor power level will be changed to 1 KW. These power level changes will give the student an opportunity to observe the behavior of the reactor. To observe the effect of the negative temperature coefficient of reactivity, the reactor power will be raised from 1 KW to 100 KW; and the reactor will be operated on automatic control. The reactor will be shut down by "slow scrambling" the reactor. The decay of the neutron population will be observed on the Log N channel. From this observation the compensation of the ionization chamber can be evaluated.

QUESTIONS:

1. Why is a neutron source used during the reactor startup?

2. After operating the Ford Nuclear Reactor at the power level of 100 KW for several hours, the reactor is shut down by dropping all rods into the reactor.

a. Assuming the ionization chamber is perfectly compensated, what curve shape is expected on the Log N recorder?

b. Assuming the ionization chamber is over-compensated, what curve shape is expected on the Log N recorder?

c. Assuming the ionization chamber is under-compensated, what curve shape is expected on the Log N recorder?

3. What is the most important instrumentation channel(s) on the Ford Nuclear Reactor. Explain its operation.

REFERENCES:

1. Ricker, C. W. and Gomberg, H. J., "Control System of the Ford Nuclear Reactor", ISA Journal, 4: 496-501, November 1957.
2. Cole, T. E., St. John, E. E., and Hanauer, S. H., "The MTR Safety System and its Components", ORNL-1139, April 4, 1952.
3. "Ford Nuclear Reactor Manual, Description and Operation", Michigan Memorial-Phoenix Project, University of Michigan, 1957.
4. Green, F. P., ed. "Reactor Safety System Response", ORNL-2318, February 14, 1958.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 5

THE SUBCRITICAL EXPERIMENT

OBJECT:

To obtain an estimate of the material buckling of a subcritical light water moderated natural uranium lattice by measuring the relaxation length of the neutron flux within the lattice.

DISCUSSION:

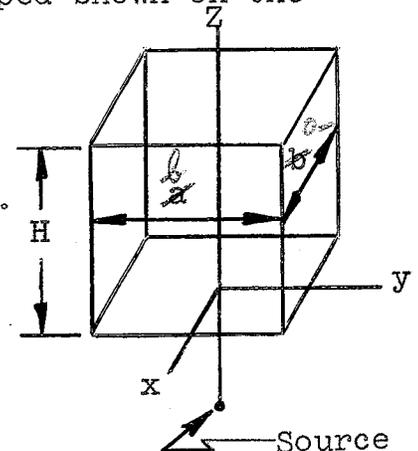
In a subcritical nuclear reactor assembly--or exponential pile--, as its name implies, a self-sustaining chain reaction is not possible. In the presence of a neutron source however, a steady state flux can be attained. The flux distribution in such an assembly is not the same as in a critical reactor, nevertheless if the assembly is relatively large, as in the case of a natural uranium system, the thermal flux distribution at a large enough distance from the source and the boundaries can be represented by the wave equation

$$\nabla^2 \phi + B_m^2 \phi = 0$$

where B_m is the material buckling of the system. A sufficient distance from the source is attained when substantially all the local neutrons have resulted from fissions. A sufficient distance from the boundaries is more than one migration length. This equation, strictly speaking, applies only to a homogeneous system, but it will give the macroscopic flux distribution of a heterogeneous system.

The solution of the above equation for an assembly in the shape of a rectangular parallelepiped shown on the right is:*

$$\phi = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \sinh \gamma_{mn}(H-Z).$$



*For detailed solution see reference 1.

$$1 = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} A_{mn} J_m(\alpha_m r) \cos(\beta_n z) \sinh(\gamma(H-z)) \quad (21)$$

At a distance far enough from the source the fundamental mode, that is $m = 1$ and $n = 1$, is predominant, so that

$$\phi \approx A_{11} \cos \frac{\pi x}{a} \cos \frac{\pi y}{b} \sinh \gamma(H-z)$$

and

$$B_m^2 = \left(\frac{\pi}{a} \right)^2 + \left(\frac{\pi}{b} \right)^2 - \gamma^2$$

In the case of a cylindrical assembly the general solution of the wave equation is

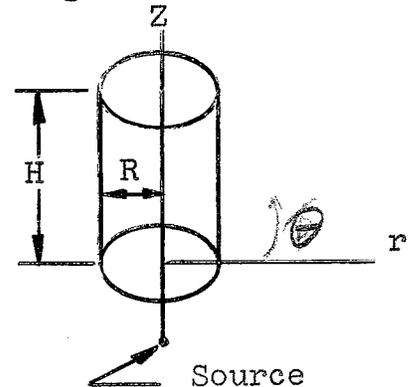
$$\phi = \sum_{n=1}^{\infty} A_n J_0(\alpha_n r) \sinh \gamma_n(H-z)$$

and far enough from the source:

$$\phi \approx A J_0 \left(\frac{2.405}{R} r \right) \sinh \gamma(H-z)$$

and

$$B_m^2 = \left(\frac{2.405}{R} \right)^2 - \gamma^2$$



In all the above equations the dimensions are effective ones, that is, they include extrapolation distances and reflector savings if any. For both of the above cases, using the fundamental term only, the flux variation parallel to the z axis can be represented as

$$\phi(z) = A' \sinh \gamma(H-z) = C e^{-\gamma z} [1 - e^{-2\gamma(H-z)}]$$

At points far enough from the upper boundary such that

$$2\gamma(H-z) > 4.6$$

the effect of the term within the brackets, the "end effect", is less than 1%, so that

$$\phi(z) = C e^{-\gamma z}$$

Thus in this region the neutron flux falls off exponentially with relaxation length $1/\gamma$. By measuring this relaxation length in an assembly of known effective dimensions, a good approximation of B_m can be obtained. Since for criticality $B_g^2 = B_m^2$, one can then compute the critical dimensions of the lattice under consideration.

A subcritical assembly does not necessarily exhibit the simple exponential flux attenuation described by the last equation above. It is quite possible that the end effect becomes appreciable before the harmonics are damped out. As can be seen from the above equations, the distance over which

the end effect has an appreciable effect is determined by the size and shape of the assembly. A convenient method of damping out some of the harmonics is to place the neutron source in a nonmultiplying medium which is a good moderator. In this way most of the source neutrons are slowed down before reaching the multiplying medium and the flux is thereby made to approximate that obtained from a plane source more closely.

When this method is used, there is a loss of neutrons by absorption in the moderator. The harmonics introduced by the possible geometrical mismatch and the change in nuclear properties occurring at the interface between the nonmultiplying medium and the subcritical assembly proper are virtually damped out within two diffusion lengths in the multiplying medium.

PROCEDURE:

Measure the axial and radial neutron flux distributions in the multiplying medium. From the data calculate the material buckling, the infinite and effective multiplication factors, and the source multiplication of the assembly.

QUESTIONS:

1. What is the significance of a negative material buckling?
2. How might the effective radius of a reflected subcritical assembly be calculated or measured? Discuss at least two methods of measurement.

REFERENCES:

1. Glasstone and Edlund, "The Elements of Nuclear Reactor Theory", Van Nostrand, New York, N. Y., (1952).
2. Holmes and Meghreblian, "Notes on Reactor Analysis, Part II -- Theory", CF-54-7-88 (1955).
3. Arnette, et al, "Exponential Experiments with Water-Metal Rod Lattices", CP-2048 (1944).
4. Kouts, et al, "Exponential Experiments with Slightly Enriched Uranium Rods in Ordinary Water", Geneva Conference Paper No. 600, August 1955.
5. Davenport, D. E., "Exponential Experiments in Graphite Systems", Geneva Conference Paper No. 599, August 1955.
6. Gyorey, G. L., "The Design of the University of Michigan Subcritical Nuclear Reactor Assembly", University of Michigan Master's Thesis, January 1957.

REACTOR LABORATORY
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EXPERIMENT No. 6
NEUTRON DIFFRACTION

OBJECT:

This experiment illustrates neutron diffraction and the measurement of nuclear cross sections with a neutron crystal spectrometer.

DISCUSSION:

The theory of neutron scattering and the theoretical analysis of a crystal spectrometer will be given in the class lecture. The measurements to be made will illustrate the theory and use of a crystal spectrometer.

The neutron crystal spectrometer makes use of the Bragg relation:

$$n\lambda = 2d \sin \theta$$

where n = order of reflection, $n = 1, 2, 3...$

λ = neutron wavelength

d = crystal lattice spacing

θ = Bragg angle between incident beam and scattering plane

The instrument consists of:

1. A collimator inserted into a reactor beam plug.
2. A monochromatizing crystal such as NaCl
3. Crystal table coupled to a four foot arm via a mechanical 2:1 divider to maintain the Bragg relation at all arm angle positions.
4. A specimen holder on the arm for cross section measurements.
5. A BF_3 neutron counter at the end of the arm.

In addition, paraffin, masonite and lead are used as shielding around the crystal to keep the background below biological and experimental tolerance.

1. Direct Beam Spectrum

The direct beam spectrum from the reactor in the spectrometer energy range is a Maxwell Boltzmann distribution at some effective neutron temperature with a $1/E$ tail at energies above 0.2 ev.

The direct beam intensity is modified by the crystal reflectivity and detector sensitivity which are both energy dependent functions. At low energies (around .01 ev) higher order contamination (i.e., neutrons of higher energy are scattered since the Bragg relation holds for neutrons of energy $E_2 = 4 E_1$ for $n = 2$ where E_1 is the first order energy) contributes additional counts that have to be taken into account.

2. Crystal Rocking Curve

The rocking curve is a measure of the mosaic spread of a crystal. A crystal is composed of mosaic blocks each individually perfect with the characteristic lattice spacing. The angular distribution of the normals from these blocks to the Miller planes is assumed Gaussian, and gives a measure of the deviation from a 'perfect' crystal. The mosaic spread can be measured with a two crystal arrangement by using the first crystal as an ideal monochromatizer (such as calcite) and measuring the scattered neutron intensity from the second crystal as a function of the angle of rotation about the Bragg angle with the detector fixed at the Bragg position. The full width at half maximum is taken as the value of mosaic spread. When (i) a single crystal, two symmetric collimator system is used and (ii) a single crystal single collimator is used, the crystal rocking curve is a measure of the combined resolution effect of collimator divergence (channel width divided by length) and mosaic spread. The analytical functions are different in these two cases.

3. Nuclear Cross Sections

The total cross section for the interaction of neutrons with nuclei as a function of energy in the range of 01 ev to 10 ev can be measured with

a crystal spectrometer. Heavy nuclei exhibit large resonances of the order of millivolts wide and spaced fractions of a volt apart.

These parameters can be correlated with various nuclear models which describe nuclear structure. The values of resonance cross sections are also extremely important in multigroup reactor calculations.

PROCEDURE:

1. Direct Beam Spectrum

Measure the direct beam intensity from .01 ev to 5 ev using an appropriate plane in a 1/4 in. thick NaCl crystal.

2. Crystal Rocking Curve

Measure the neutron intensity from a single crystal, single collimator arrangement with the arm set at 0.05 ev and the NaCl crystal rotated in steps through a rocking curve. Repeat at 0.5 ev.

3. Nuclear Cross Sections

Measure the first resonance in Au and In by adjusting the foil thicknesses to maintain transmission values no less than .05. The transmission is

$$T = e^{-N\sigma x}$$

where N = number of nuclei/volume

σ = total cross section

x = foil thickness

Also

$$T = \frac{I_{sB} - I_{s1}}{I_{oB} - I_{o1}}$$

where I is intensity and

s refers to sample

o refers to no sample

B refers to Bragg angle position

1 refers to 1° off Bragg angle position.

QUESTIONS:

1. Calculate the beam spectrum by correcting the data for crystal reflectivity and counter sensitivity and compare it to the Maxwell Boltzmann and $1/E$ distributions.
2. Calculate the mosaic spread for the NaCl crystal by using the theoretical angular divergence of the collimator ($s = 0.256$ in., $l = 32$ in.). Explain the difference between the data at the two energies.
3. Discuss very briefly the difference between shape and area analysis of nuclear resonances and what method would apply to your data.

REFERENCES:

1. Borst, L. B. and Sailor, V. L., "Neutron Measurements with the Brookhaven Crystal Spectrometer", Rev. of Sci. Inst. Vol. 24, No. 2, February 1953.
2. Sailor, Foote, London, Weed, "High Resolution Crystal Spectrometer for Neutrons", Rev. of Sci. Inst., Vol. 27, No. 1, January 1956.
3. Pattenden, N. J. and Baston, A. H., "The Construction and Operation of a Single Crystal Neutron Spectrometer", NP/R 2251, May 1957.
4. Hughes, D. J., "Neutron Optics", Interscience Tracts on Physics and Astronomy, 1954.
5. Hughes, D. J., "Pile Neutron Research", Addison-Wesley Publishing Co., 1953.
6. Bacon, G. E., "Neutron Diffraction", Oxford, Clarendon Press, 1955.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 7

REACTOR POWER MEASUREMENT

OBJECT:

To measure the thermal neutron flux throughout one coolant channel in the core of the Ford Nuclear Reactor and from this measurement estimate the power level of the reactor.

DISCUSSION:

Reactor power may be determined from:

- A) Measurement of the temperature rise and the flow of the coolant through the core;
- B) The mapping of the neutron flux throughout the core.

Method A is, of course, the most direct one. It gives good results for power reactors at high power. This method could be applied successfully to a reactor like the FNR at a power of one megawatt.

At low powers it is necessary to use method B. Further discussion here will be restricted to this method. Determination of neutron flux by activation techniques may make use of a comparative or an absolute method. For the former, a bare and a cadmium covered foil are exposed in a known neutron flux, their activities are measured, and their saturated activities computed. Other foils, after exposure in the flux to be measured, are counted using the same counter. From a comparison of their saturated activities with those of the standard foils, the magnitude of the thermal flux is computed.

In the absolute method the thermal flux is determined by counting the foils with a known counting efficiency as described in Appendix A. Both the comparative and the absolute method have been used to measure power of the FNR with good agreement between the two results. In both methods the reactor core is divided into a number of volume elements and the average thermal flux for each element is obtained. From this information, the fission rate, and finally the energy release can be computed.

One of the problems of the method is that flux measurements are made in the moderator (possibly on the surface of the fuel plates), while the thermal fission rate depends on the thermal flux within the fuel. The thermal flux level, however, is not constant within the fuel, but drops off toward the center. The flux also varies in the moderator.

During the power calibration of the Bulk Shielding Reactor, which uses the same type fuel elements as the FNR, the ratio of the fission rate to the thermal flux measured on the side of the element was determined experimentally¹. The result was as follows:

$$\text{fissions/sec/gram of U-235} = 1.38 \phi_{\text{th}}$$

Using the fast fission factor $\epsilon = 1.035$ as assumed in the aforementioned reference, we get

$$\text{fissions/sec/gram of U-235} = 1.34 \phi_{\text{th}} \epsilon$$

If this ratio is calculated from the thermal fission cross section of U-235 ($\sigma_f = 570$ barns, corrected for Maxwell-Boltzmann distribution with $E_T = .03$ ev) and if it is assumed that the measured flux is uniform throughout the fuel, then

$$\text{fissions/sec/gram of U-235} = 1.46 \phi_{\text{th}} \epsilon$$

PROCEDURE:

A complete flux mapping in the reactor core takes a prohibitive amount of time. In this experiment only an estimate will be made of the reactor power level. The neutron flux distribution will be determined in one coolant channel in a region of nearly average flux. From this measurement an estimate of the reactor power will be made. The absolute method will be used for neutron flux measurement.

QUESTIONS:

1. If the same experiment is done using a well scintillation counter with an efficiency of 40%, how long and at what power level would you irradiate 100 mg Au foils? Why?
2. Plot the Cd ratios versus foil position in the core. Why is the plot not symmetrical about the horizontal midplane of the core?
3. What is the effect of a control rod channel on the thermal flux and the Cd ratio in its vicinity with
 - a) the rod 100% withdrawn, and
 - b) the rod 100% inserted?

REFERENCES:

1. J. L. Meem et al, "Determination of the Power of the Bulk Shielding Reactor," Part III, ORNL-1537 (1954).
2. J. L. Shapiro et al, "Initial Calibration of the Ford Nuclear Reactor," MMPP 110-1, April 1958.
3. W. S. Chmielewski, "A Method for Power Calibration of the Ford Nuclear Reactor," University of Michigan Master's Thesis, August 1957.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 8

CONTROL ROD CALIBRATION

OBJECT:

The purpose of this experiment is the calibration of the Ford Nuclear Reactor control rod over its entire length.

DISCUSSION:

In order to determine the excess reactivity available in the reactor, it is necessary to calibrate the control rod. The calibrated rod can then be used to measure the magnitude of the reactivity effect of other parameters on the reactor. The calibration is achieved by observing the effects of a movement of the rod on the power level of the reactor. This is done at low powers, so that there is little, if any, effect on the reactivity due to temperature variation. Since the behavior of the reactor is more simply described when an external neutron source is not present the source is removed during the calibration.

The accuracies of the rod position indicators on the control console are insufficient for calibration purposes, therefore scales are attached directly to the rod actuators. The control rod scale can be read to 1/32 inch. The linear level recorder, fed by a compensated ionization chamber is used to indicate whether or not the reactor is critical.

PROCEDURE:

Two methods will be used. The first is the "Pile Period" method which is outlined in detail in references 3 and 4 and was used in reference 5. Briefly, the method consists of putting the reactor on a positive period by withdrawing the rod a measured distance. The reactivity is then calculated from the "Inhour" equation. This gives a rod worth per inch which can be graphically integrated to give the total worth.

The second method consists of oscillating the control rod. As shown in reference 6, the amplitude of the power level oscillations is directly proportional to the reactivity worth of the oscillated length of rod (for small rod oscillations). An electronic oscillator is attached to the control system. It is designed to periodically actuate the control rod "raise" and "lower" relays. Thus, for small rod oscillations, the reactivity oscillation will have a triangular wave form.

Because of the nature of the control rod drive mechanism, the rod drives faster when inserting than when withdrawing. The insertion rate is about 3.4 per cent more than

the withdrawal rate. This does not significantly affect the analysis of the data. It does allow the calibration to proceed almost automatically. The control rod is completely withdrawn and the power level is adjusted to be approximately constant. Simultaneously, the rod oscillator and the Sanborn recorder attached to the Log N amplifier are started. They run continuously throughout the experiment. As the control rod slowly drifts downward, the average power level is maintained approximately constant by shim rod adjustment whenever necessary. A mark is made on the recorder each time the shims are moved. This procedure continues until the control rod reaches the lower limit. The recorder trace is a continuous record (except for the points where shimming occurred) of the power level oscillation amplitudes. A plot of amplitude as a function of rod position is then made and a proportionality factor determined by comparison with the differential rod worth curve from method I. In future calibrations, provided the same oscillation period is used, the same proportionality factor is valid. This factor can also be calculated by the method shown in reference 6.

Reference 7 is an analytical treatment of reactor oscillations. References 1 and 2 include general treatments of reactor kinetics.

QUESTIONS:

How can method I of this experiment be used to determine the average lifetime of neutrons in the core? Why is this not done at the FNR?

2. What are two reasons for limiting the size of the rod oscillations of method II?

REFERENCES:

1. Glasstone and Edlund, "The Elements of Nuclear Reactor Theory", D. Van Nostrand Company, Inc., Princeton, New Jersey (1952).
2. Henry, A. F., "The Application of Reactor Kinetics To The Analysis of Experiments", Nuclear Science and Engineering, Vol. 3, No. 1, pp. 52-70, January 1958.
3. Cochran, R. G., et al, "Reactivity Measurements with the BSR", ORNL-1682, November 18, 1954.
4. Moore, R. A., et al, "GTR Rod Calibration", NARF-54-14T, January 1955.
5. Shapiro, J. L., et al, "Initial Calibration of the Ford Nuclear Reactor", MMPP 110-1, April 1958.

6. Jankowski, F. J., Klein, D. and Miller, T. M., "Calibration of Control Rods", Nuclear Science and Engineering, Vol. 2, No. 3, pp. 288-302, May 1957.
7. Akcasu, Z., "General Solution of the Reactor Kinetic Equations Without Feed Back", Nuclear Science and Engineering, Vol. 3, No. 4, pp. 456-467, April 1958.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT No. 9

FERMI AGE AND MEAN SQUARE SLOWING DOWN DISTANCE MEASUREMENTS

OBJECT:

To measure Fermi Age and the Mean-Square Slowing Down Distance in graphite and to correlate the experimental results with theoretical models.

DISCUSSION AND PROCEDURE:

The neutron flux corresponding to a given neutron energy or energy region is measured as a function of distance in graphite. Cadmium covered indium foils are used as detectors. The neutron source is a Sb-Be source and is placed at the center of a graphite column. The source is considered a point source for analytical purposes.

The Ford Nuclear Reactor graphite column is eight feet deep, six feet high, and six feet wide. At the center of the accessible surface of the column, two 4"x4"x4' graphite stringers can be removed from the column. The front stringer contains a series of channels cut parallel to the front face of the stringer. Aluminum foil holders are placed in these channels. There are three holes drilled in the back stringer. The source is placed in one of these holes, and the other holes are plugged with aluminum cans containing graphite. The stringer containing the source is placed in the column first, so that the source will be at the center of the column. The second stringer containing the foils is then placed into the thermal column. Exposures at various distances from the source are then made.

During this operation one member of the group must have a survey meter. The radiation level must be monitored during this procedure.

By using a well counter with a NaI(Tl) scintillation crystal, the activity of the indium foils are measured. The saturated activity is found from the measured activity, the exposure time, waiting time, and counting time.

Two methods are suggested for analyzing the data:

- A. Assume the flux distribution to be Gaussian, plot the \ln of A_{∞} versus r^2 (r is the distance from source) and find the Fermi Age from the slope of this curve.

The Fermi Age, τ , is defined by the following relation:

$$\tau = \int_{\mu_1}^{\mu_2} \frac{D(\mu)}{\xi \Sigma_t(\mu)} d\mu \quad \text{Eq. 1}$$

μ is the lethargy

ξ is average logarithmic lethargy decrement per collision

$D(\mu)$ is the diffusion coefficient as a function of lethargy

$\Sigma_t(\mu)$ is the total macroscopic cross section as a function of lethargy

B. Measure the mean square slowing down distance by the method of moments.

$$\langle r^2 \rangle_{SD} = \frac{\int_0^{\infty} A_{\infty} r^4 dr}{\int_0^{\infty} A_{\infty} r^2 dr} \quad \text{Eq. 2}$$

where

$\langle r^2 \rangle_{SD} \equiv$ the mean square distance for slowing down

$A_{\infty} \equiv$ the saturated activity

Part of the above integration is performed by numerical integration and then, in order to extend the integration to infinity, it is assumed that the distribution follows a $K e^{-\lambda r}/r^2$ relation at distances greater than 60 centimeters. From the data, the values of K and λ can be obtained. Thus $\langle r^2 \rangle_{SD}$ becomes

$$\langle r^2 \rangle_{SD} = \frac{\int_0^{r_1} A_{\infty} r^4 dr + \int_{r_1}^{\infty} K e^{-\lambda r} r^2 dr}{\int_0^{r_1} A_{\infty} r^2 dr + \int_{r_1}^{\infty} K e^{-\lambda r} dr} \quad \text{Eq. 3}$$

The following curves should be plotted:

1. $\ln A_{\infty}$ versus r^2
2. $A_{\infty} r^2$ versus r

3. $A_{\infty} r^4$ versus r

4. $\ln(A_{\infty} r^2)$ versus r

QUESTIONS:

1. Why are cadmium covered indium foils used in this experiment and what do the foils actually measure?
2. How long is it necessary to irradiate the foils?
3. There are resonance regions at energies greater than 1.44 ev in indium. How will this affect the measurement?
4. When relating foil activations to neutron fluxes what additional precautions should be taken when beta counting rather than gamma counting techniques are employed? Explain.
5. In the methods suggested for analyzing the data:
 - a. What are the assumptions made in each case, concerning the method of obtaining the Fermi Age and/or the mean square slowing down distance?
 - b. Calculate the Fermi Age for graphite using Eq. 1. Include first and last flight corrections.
 - c. How is the slowing down density, q , and/or the neutron flux, ϕ , related to the activity produced? Analyze with respect to each method.
 - d. Derive Eqs. 2 and 3 for the mean square distance for slowing down.
 - e. Can either or both methods of analysis be applied in general? Calculate the Fermi Age for water using Eq. 1. Include first and last flight corrections.
6. How does an experiment measuring Fermi Age differ from one measuring diffusion length?

REFERENCES:

1. Holmes and Meghreblian, "Notes on Reactor Analysis, Part II, Theory", CF 54-7-88 (Pt. II) (1955).
2. Glasstone and Edlund, "The Elements of Nuclear Reactor Theory", D. Van Nostrand Company, Inc., Princeton, New Jersey (1952).
3. Roberts, Hill and McCommon, "A Study of the Slowing Down Distribution of Sb^{124} -Be Photo Neutrons in Graphite, and of the Use of Indium Foils", ORNL 201 (1950).

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 10

SHIM ROD CALIBRATION

OBJECT:

The purpose of this experiment is to determine the overall worth of the Ford Nuclear Reactor shim-safety rods.

DISCUSSION:

Calibration of the shim-safety rods can be accomplished by a point by point comparison with a previously calibrated control rod. In this experiment total negative excess reactivity available in each rod is measured. The total reactivity inserted if all the rods are dropped into the reactor during a scram is determined. The negative reactivity results from the insertion of the boron carbide rods into the water filled channels in the control elements.

PROCEDURE:

Two methods will be used and compared. The first method, described in reference 1, drops a rod from the position of 100% removal. This is done by decreasing the magnet-holding current. The trace of reactor power versus time is observed on the Log N and linear level recorders. Rod worth is calculated from the resulting data.

The second method uses subcritical multiplication and is described in reference 2. The calibrated control rod is used to determine the effective source strength. This source strength can be used to determine the magnitude of any other reactivity effects when the reactor is subcritical. In this case, it is used to calibrate the shim rods.

QUESTIONS:

1. What are the possible sources of error in each method?
2. a) Why should the rod worth as measured in the first method be stated in dollars rather than in $\% \Delta k/k$?
- b) Does the answer to the above hold for the second method as well? Explain.

REFERENCES:

1. Shapiro, J. L., et al, "Initial Calibration of the Ford Nuclear Reactor", MMPP 110-1, April 1958.
2. Cochran, R. G., et al, "Reactivity Measurements with the BSR", ORNL-1682, November 19, 1954.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

Experiment No. 11

Calibration of the Composite Safety Amplifier

OBJECT:

The purpose of this calibration is to acquire a conceptual understanding of the performance of the safety amplifiers used on the Ford Nuclear Reactor.

DISCUSSION:

The Composite Safety Amplifier, ORNL-Q-1565, is an assemblage, on one standard electronic chassis, of the electronic components of a safety channel of the MTR safety system¹. There are three safety channels in the FNR safety systems: one period and two level safety channels.

The two level-safety channels function in conjunction with the period safety channel to shut the reactor down. They cause all safety rods to drop whenever the power level increases beyond a preset value and/or an abnormally short period occurs. The period safety channel derives its signal from the log N channel².

In each level safety channel, a PCP (Parallel Circular Plate) ionization chamber supplies a current which is proportional to the reactor power level to the composite safety amplifiers. Because the current produced by neutron flux at high levels of operation is much greater than that produced by gamma radiation or other sources, this chamber is not compensated.

The output of the PCP chambers and the output of the log N channel feed preamplifiers in the composite safety amplifiers. The pre-amplifiers, in turn, feed sigma amplifiers whose outputs supply a bus, referred to as the "sigma bus." This bus serves as the input to all three magnet amplifiers, each of which supplies the current to an electromagnet holding a shim-safety rod.

When neither the two PCP ionization chambers nor the period channel puts out a signal, the sigma amplifiers maintain the potential of the sigma bus at a prescribed level. However, if the positive period becomes abnormally short, or if the power level becomes dangerously high, the sigma-bus potential increases. This quickly reduces the magnet current in all three magnet amplifiers (and therefore in the three electromagnets), thus dropping all three safety rods into the reactor. This is termed a "fast scram."

The system is designed so as to provide the same result if for any reason the sigma-bus potential decreases. Because the sigma bus connects to the input of each magnet amplifier, any one of the three safety channels can automatically initiate a scram. This

method is known as "auctioneering," the highest "bidder" causing a scram. The Ford Nuclear Reactor is "fast scrambled" whenever the level exceeds 150% of full power and/or the period becomes shorter than 3 seconds.

A procedure for testing and calibrating the Composite Safety Amplifier was published by the Oak Ridge National Laboratory³. This detailed procedure makes use of standard laboratory instrumentation but it is not convenient for routine testing and calibration of the safety amplifiers installed in a reactor control system. To overcome this disadvantage, a CSA Calibrator was built by P. Herman of the Phoenix Memorial Laboratory which combines in one instrument all the functions required to accomplish a calibration. The CSA Calibrator is simple to use since only a "cookbook" type procedure is needed. By the nature of this procedure, however, the student calibrating the instrument gains little or no insight as to the characteristics and functions of the safety amplifier. Experience has shown, however, that this disadvantage can be overcome if the student follows, point by point, the steps in both the ORNL and the FNR calibration procedures while calibrating the instrument.

PROCEDURE:

Calibrate a FNR Composite Safety Amplifier using the CSA Calibrator, the ORNL procedures³, and the FNR procedure. The latter procedure is given in Appendix B.

QUESTIONS:

1. What is the function of the Bus Protect circuit?
2. Describe the input-output characteristic of the Sigma Amplifier section of the CSA.
3. How and why is the CSA monitored?
4. Discuss conditions or circumstances where the safety amplifiers and/or the safety system appear to be operating correctly but an unsafe situation exists within the safety system.

REFERENCES:

1. T. E. Cole, E. E. St. John, and S. H. Hanauer, "The MTR Safety System and Its Components", ORNL-1139, April 4, 1952.
2. C. W. Ricker and H. J. Gomberg, "Control System of the Ford Nuclear Reactor", ISA Journal, pp. 496-501, November 1957.
3. J. B. Ruble and S. H. Hanauer, "Testing Procedures for Reactor Instrumentation, Section P, Composite Safety Amplifier, Q-1565", CF 56-5-30, March 7, 1955.

REACTOR LABORATORY
FORD NUCLEAR REACTOR

EXPERIMENT NO. 12

ELECTROMAGNET - SAFETY ROD PERFORMANCE

OBJECT:

The purpose of this experiment is to measure electromagnet - safety rod release times and to determine the force-current relationship for a Ford Nuclear Reactor electromagnet.

DISCUSSION:

In the evaluation of a reactor safety system, one important consideration is the overall response time of the system. This is usually measured from the time the neutron detectors sense a high level or a rapid rate of change of neutron level to the time that the shim-safety rods are able to bring a power excursion under control. Since the time required for a signal to pass from the neutron detectors (PCP Chambers) to the output of the Composite Safety Amplifiers is of the order of millimicroseconds¹, the major delay times are (1) the time required for the electromagnet to release the shim-safety rod and (2) the time for the shim-safety rod to be inserted sufficiently to bring the reactor excursion under control. The first part of this experiment will be concerned with (1), the determination of magnet-rod release times. The second delay, item (2), will not be measured in this experiment.

The release time measurements will be made using a Magnet Pulser¹, a Composite Safety Amplifier², an oscilloscope, and a FNR electromagnet. The output of the Magnet Pulser is a low frequency square wave pulse whose frequency, amplitude and width may be varied.

A "DC Level" adjustment is provided for adjusting the zero of the instrument. A "Pulse Height" adjustment is used for setting the pulse amplitude. The pulse output is fed to the input of a Composite Safety Amplifier. The latter supplies the current to an electromagnet. The pulser simulates a "scram" or shutdown signal of variable duration. The duration of the scram signal sufficient to allow the shim-safety rod to be released from the electromagnet is a measure of the magnet-rod release time.¹ The pulser is initially adjusted for the smallest possible pulse width, or pulse duration, with an amplitude sufficient to decrease the magnet current to zero. The pulse duration is slowly increased by suitable adjustments on the pulser until the simulated shim-safety rod is released from the electromagnet. A calibrated oscilloscope provides the means for measuring the pulse duration.

This method of measuring magnet-rod release times, developed by L. C. Oakes at the Oak Ridge National Laboratory¹,

has the advantage that the measurements can be made on a reactor without disassembly or removal of reactor components. For this experiment, however, a special electromagnet test facility, separate from the reactor, has been set-up in the laboratory. This facility simulates the magnet-rod conditions that exist in the reactor.

In order to provide for continuous operation of the reactor under normal conditions, it is necessary that the electromagnets hold the rods with sufficient excess holding force to insure that vibrations or mechanical shock will not drop the rods thus causing the reactor to be shut down needlessly. This implies that the electromagnet design must provide for this dependability without compromising the specification of short release times. To determine the excess holding force, a measurement of the force to current relation for a Ford Nuclear Reactor electromagnet will be made as the second part of this experiment.

PROCEDURE:

1. Set-up and calibrate the Composite Safety Amplifier (See Experiment 11 and reference 2).
2. Calibrate the Magnet Pulser (See procedure on instrument and reference 1).
3. Measure the magnet-rod release times for rod weights of 6 lbs. and 12 lbs. with the electromagnet and rod in air.
4. Measure the magnet-rod release times for rod weights of 6 lbs. and 12 lbs. with the electromagnet and rod submerged in water.
5. Measure the electromagnet force-current relationship for increasing currents (0 to 100 milliamperes) and decreasing currents (100 to 0 milliamperes).

QUESTIONS:

1. What techniques or procedures were developed for making the measurements in this experiment? Explain.
2. Discuss the overall problem of reactor safety system response and the relationship of this experiment to that problem.
3. Assume that a positive excess reactivity of 1.3% were suddenly inserted into the Ford Nuclear Reactor when the power is one (1) milliwatt. Assume the total worth of the shim-safety rods to be 10% and the rod acceleration to be 15 feet per second per second.
 - (a) If the Log N Channel comes on scale 6 decades below full power (1 megawatt) and the period signal is seen following a rise of power of $e^{0.4}$ after the Log N comes on scale, will the period channel scram the reactor before the

level channels? (NOTE: For the FNR, the reactor is scrammed for a period of 3 seconds or less and/or a level signal of 150% of full power.)

(b) Calculate the peak power level of the excursion when the reactor is scrammed only by (1) the period channel and (2) the level channels. (See references 3 - 7 for other pertinent data).

REFERENCES:

1. Green, F. P., ed., "Reactor Safety System Response," ORNL-2318, February 14, 1958.
2. Ruble, J. B., and Hanauer, S. H., "Testing Procedures for Reactor Instrumentation, Section P, Composite Safety Amplifier, Q-1565," CF 56-5-30, March 7, 1955.
3. Cole, T. E., St. John, E. E., and Hanauer, S. H., "The MTR Safety System and Its Components," ORNL-1139, April 4, 1952.
4. "Ford Nuclear Reactor Manual, Description and Operation", Michigan Memorial-Phoenix Project, University of Michigan, 1957.
5. Shapiro, J. L., et al, "Initial Calibration of the Ford Nuclear Reactor," MMPP-110-1, April 1958.
6. Good, E. G., "Subpower Range Start-up Transients," WAPD-TM-1, March 1956.
7. Schroeder, F., et al, "Experimental Study of Transient Behavior in a Subcooled, Water-Moderated Reactor," Nuclear Science and Engineering: 2, 96-115 (1957).

REACTOR LABORATORY
FORD NUCLEAR REACTOR
DEMONSTRATION EXPERIMENT NO. 1

HEALTH PHYSICS - SURVEY TECHNIQUES AND EQUIPMENT

OBJECT:

The object of this demonstration is to present a summary of various survey techniques applicable to the evaluation of radiation hazards. It is proposed that the students be introduced to the various pieces of survey equipment and taught the fundamentals of their utilization. Such items as, protective clothing, supply air masks, respirators, ion chambers, geiger counters and neutron counters, will be demonstrated and discussed.

DISCUSSION:

Without proper electronic and photographic radiation responding equipment it is possible to work in a radiation environment for hours, days, or weeks, and accumulate a lethal dose of radiation without being aware of the fact. The presence of proper instrumentation for the registering of radiation levels is a necessity for an operating reactor.

All personnel directly involved in the operation, maintenance and experimental utilization of the reactor should be equipped with photographic film badges, as a minimum, for the registration of radiation exposures. It is suggested that the individual wear pocket chambers, or dosimeters, when it is known that he will be subjected to radiation exposure during the working day. These two devices, the film badge and the pocket chamber, are called personnel monitors in that they are worn by the individual and record the individuals's exposure during the period of wearing.

There are additional instruments available which are used to measure the radiation environment which will be occupied by staff and experimenters. These instruments are usually grouped under the heading of "area survey meters", and includes such items as ion chamber survey meters, geiger survey meters, and neutron survey meters.

The ion chamber survey meter is utilized to measure dose rates in the vicinity of radiation sources. In its usual form it covers the range of from zero to five roentgens per hour and permits one to prescribe permissible operation times in a radiation field.

The Geiger type survey meter, with its associated error due to gamma energy dependence, is extremely useful for measuring contamination existent in experimental areas. It is not to be used to prescribe permissible operation times since its response is highly energy dependent. Its high sensitivity in the range of zero to twenty milliroentgens per hour makes it extremely useful for the localization of contamination.

It is often desirable to check for the presence of contamination in a region where the general radiation level is higher than the expected contamination level. For example, it might be desired to survey for the presence of contamination on the floor in front of a hood while a relatively large radiation source is contained within the hood. It is not possible to perform such a survey with the Geiger-type survey instrument since the instrument response is not directional and it sees the relatively large source located in the hood. In such instances it is possible to miss the contamination spots located adjacent to or in front of the hood. The most common procedure is to use a "smear" technique for the evaluation of this contamination.

In this technique the health physicist, or the experimenter, takes small discs of filter paper and rubs them over suspected areas of contamination. He then removes these discs to a location distant from the radiation source and counts them on an end-window Geiger counter or a scintillation well-type counter. He relates the activity that has rubbed off onto the disc of filter paper to the contamination level existing in front of the hood or on door knobs, faucets, desks, etc.

The application of instruments such as the ion chambers, pocket chambers and the neutron survey meters requires that these units be calibrated at least quarterly. Ion chambers, which include the pocket chambers or dosimeters, are usually calibrated by taking a known source of radium or cobalt-60 and placing it at a known distance from the survey instrument. The output of the source is calculated on the basis of the known radiation output for a source of a given size. The instrument is placed at various distances away from the source and adjustments made in the instrument such that it reads the dose rate calculated at that distance. When it is not possible to adjust the instrument to read correctly the usual procedure is to construct a graph of the instrument reading versus the true radiation reading. It is not normal procedure to calibrate a Geiger-type survey meter for quantitative work. As mentioned earlier, the Geiger survey meter is used primarily as a qualitative device for the detection of contamination.

In addition to the instrumentation discussed in the preceding paragraphs, the reactor health physicist must have available suitable equipment for the entry and decontamination

of a radiation hazardous area. Such equipment should include items such as dust respirators, supply air masks, coveralls, boots, gloves, hats, copious quantities of masking tape, and blotting paper. It is proposed that the utilization of these various pieces of equipment will be demonstrated to the student.

PROCEDURES:

The demonstration will open with a discussion of the various survey instruments available and their applications to reactor surveys. This discussion will include film badges, pocket chambers, ion chamber survey instruments, Geiger survey instruments, respirators and protective clothing.

It is proposed that one of the beam ports on the reactor will be opened such as to allow the escape of a mixed gamma-neutron field into the beam port floor area. The group will then witness the application of the ion chamber and neutron survey instruments to delineate the boundaries of radiation fields surrounding the open beam port.

Following the demonstration of the evaluation of fields in the vicinity of the beam port, the students will move to the area immediately behind number two hot cell in the Phoenix Memorial Laboratory. This area will have been subjected to radioactive contamination on the day preceding the health physics demonstration. Two staff members will demonstrate survey techniques utilizing Geiger survey instruments and smears to localize radiation contamination areas. The area under surveillance will have been contaminated with sodium-24, (fifteen hour half-life) and will be isolated to prevent entry by unauthorized personnel.

CONCLUSIONS:

It is recommended that minimum health physics equipment for a one megawatt swimming pool reactor should include the following:

1. film badges for all personnel
2. twenty self-reading pocket chambers and charger
3. four ion chamber survey instruments
4. four Geiger-Mueller survey instruments
5. two slow-fast neutron survey instruments
6. six dust-type respirators
7. two supply air masks
8. coveralls (assorted sizes)
9. shoe covers (or rubber boots)
10. canvas and rubber gloves
11. masking tape
12. hats
13. blot (absorbent) paper
14. scaler-counter assembly

REFERENCES:

1. East, E., et al, "A Survey of the Materials Testing Reactor Shield", 38 pages, Contract AT(10-1)-205, May 27, 1953, Decl, Oct. 11, 1954.
2. Smith, James A. Jr., "Radiation Safety for a Reactor" Nucleonics, Vol. 11, No. 6, June, 1953.
3. Sulit, R. A., "Radiological Monitoring During a Water Boiler-Type Reactor Startup", LRL-99, March, 1954, 38 p. Contract AT(11-1)-74.
4. Whipple, G. Hoyt, "Health Physics Instrumentation for a Power Reactor", Paper No. 57-NESC-34, Published by the Amer. Soc. of Mech. Eng., 29 West 39th St., N. Y. 18, N. Y. (1957)

REACTOR LABORATORY
FORD NUCLEAR REACTOR

DEMONSTRATION EXPERIMENT No. 2

SEPARATION OF FISSION PRODUCTS

OBJECT:

The purpose of this experiment is to acquaint the student with the problems of separating the uranium fission products from each other.

DISCUSSION:

This experiment will consist of a demonstration of the separation of barium and iodine from neutron irradiated uranyl nitrate (fission products).

U^{235} , comprising 0.72% of natural uranium has a cross section of about 500 barns toward neutron absorption. When a U^{235} nucleus captures a neutron it forms a very unstable U^{236} nucleus which undergoes fission into two nuclei of usually unequal mass. The fission process leads to a statistical distribution among fragments of masses from about 70 to 160 with maximum fission yields of about 6% for masses near 95 and 140. Figure 1 shows a plot of fission yield versus mass numbers of U^{235} fission products.¹ Each primary nuclide formed undergoes on the average three decays before reaching a stable state. Since U^{235} has a higher neutron-proton ratio than the lighter nuclides, the fission process produces elements having a neutron excess. This leads to beta decay through various stages until a stable nuclide is formed. Table 1 shows some of the various fission products with corresponding fission yields.²

Table 1
Yields of Fission Products of U^{235}

(2)

Activity isolated	Mass No.	Fission yields	Activity isolated	Mass No.	Fission yields
49h Zn	72	0.000015	17m Se	81	0.133
5h Ga	(73)	0.00010	25m Se	83	0.21
12h Ge	77	0.0037	2.4h Br	83	0.40
40h As	77	0.0091	33m Br	84	0.65
2.1h Ge	(78)	0.02	53d Sr	89	4.6

Activity isolated	Mass No.	Fission yields	Activity isolated	Mass No.	Fission yields
9.7h Sr	91	5.0	90d Te	127	0.033
57d Y	91	5.9	4.2h Sb	129	
2.7h Sr	(92)	5.0	32d Te	129	0.19
20m Y	(94)	~5	8.0d I	131	2.8 ^e
65d Zr	95	~6	77h Te	(132)	3.4
17h Zr	97	>4.5 ^c	22h I	133	4.6
67h Mo	99	6.2	54m I	(134)	~5.7
42d Ru	103	3.7	6.7h I	135	5.6
4.5h Ru	105	0.9	9.2h Xe	135	5.9
36.5h Rh	105		85m Ba	139	6.3
1.0y Ru	106	0.52	12.8d Ba	140	6.1 ^{d,g}
13h Pd	109	0.028 ^e	28d Ce	141	5.7
7.6d Ag	111	0.018 ^e	33h Ce	143	5.4
21h Pd	112	0.011	275d Ce	144	5.3
2.33d Cd	115	{0.011	11d Nd	147	2.6
43d Cd			{0.0008		
2.83h Cd	117	0.01	47h Pm	149	1.3
62h Sn	(123)	0.014 ^f	47h Sm	(153)	0.15 ^e
10d Sn	(123)	0.0044 ^f	2y Eu	155	0.03
70m Sn	(126)	0.1	15.4d Eu	(156)	0.013
93h Sb	127		15.4h Eu	(157)	0.0074
			60m Eu	(158)	0.002

PROCEDURE:

In this experiment a few milligrams of uranyl nitrate, $\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, sealed in a Lusteroid tube will be irradiated for a period of 1 hour, using the pneumatic tube system of the reactor at a power level of 100 kilowatts. The neutron flux in the pneumatic tubes at this power level is of the order of 5×10^{10} to 2×10^{11} neutrons per square centimeter per second. The irradiated uranyl nitrate has an activity level, after this irradiation, of about 2 milliroentgen per hour per milligram of uranyl nitrate used. It will be left untouched for about one hour in order to let the short half-lived nuclides decay.

The problem of separating these isotopes from each other is a difficult one as more than 200 fission product nuclides are formed. Separations can be performed with or without the addition of inactive carrier, depending on the difficulty of the separation without carrier, and the specific activity of the product desired. However, the general procedure for the separation of fission products is by use of carrier

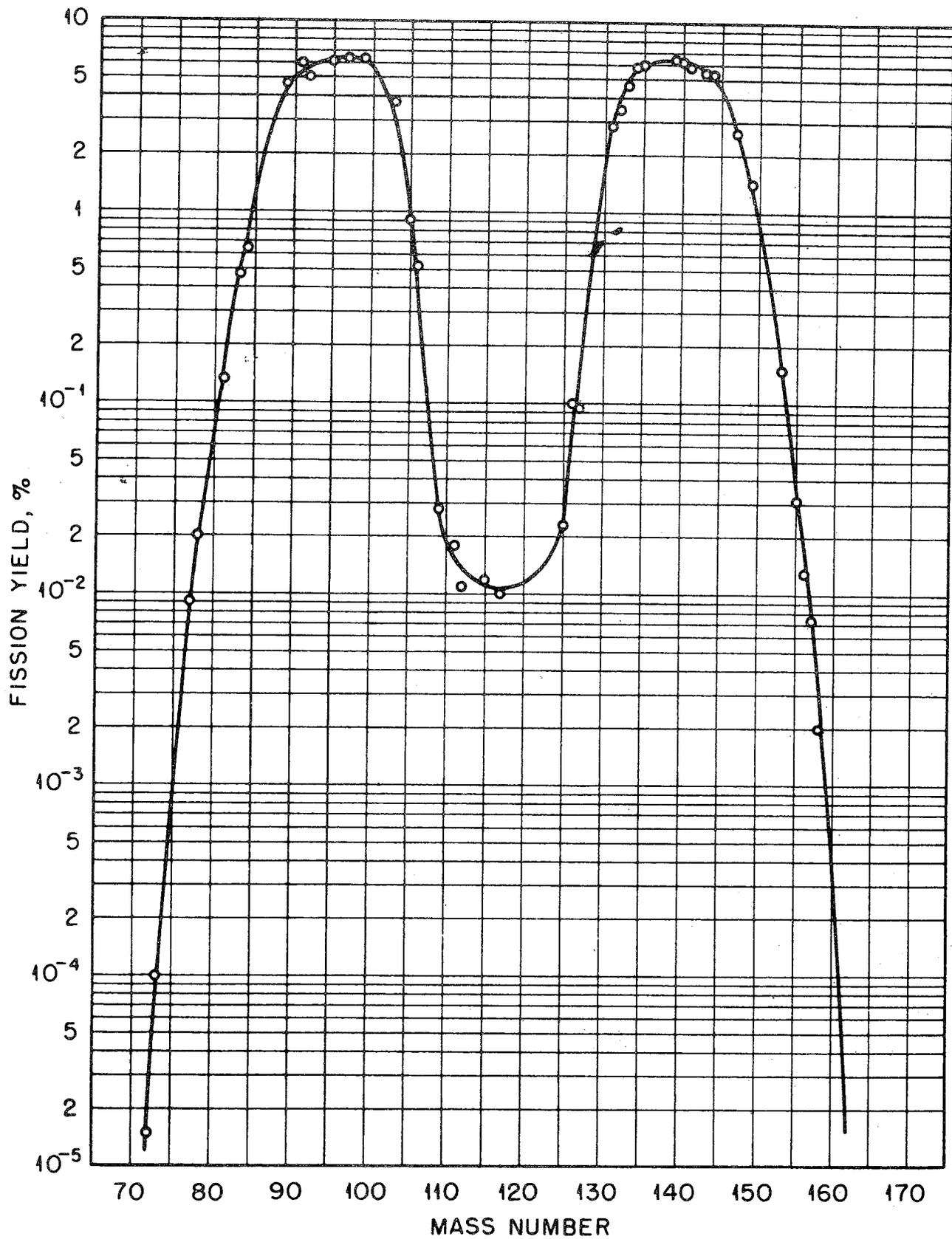


Figure 1. Yield-mass curve for the fission of U^{235} by thermal neutrons

(weighable amount of inactive element added). The carrier and radioisotope are then processed to ensure complete exchange and existence of identical oxidation states.

There are various analytical techniques available for optimum separations. They may involve precipitations, volatilization, ion-exchange, and solvent extraction. In this experiment solvent extraction and precipitation methods will be demonstrated in the separation of iodine and barium from fission products.

SEPARATION OF IODINE:

Iodine is separated from the other fission products by the oxidation of I^- carrier to I_2 with HNO_2 and by the extraction of the I_2 with CCl_4 .³ The I_2 is then removed from the CCl_4 by shaking with water containing $NaHSO_3$ to reduce the I_2 to I^- . The aqueous solution is further purified by three or more extraction cycles. The iodine is finally precipitated as AgI for mounting. The chemical yield is about 90% and the time required for analysis is about 1.5 hours. The detailed procedure is as follows:

- Step 1. Place into a small beaker 5 ml. of 6 M HNO_3 and 20 mg. of I^- carrier, add 1 ml. of the active $UO_2(NO_3)_2$ solution. Transfer the solution to a separatory funnel, and add 15 ml. of CCl_4 and 4 or 5 drops of 0.1 M $NaNO_2$ and shake.
- Step 2. Extract the I_2 four or five times with successive 10-ml portions of CCl_4 .
- Step 3. Add 10 ml. of H_2O to the CCl_4 solution of I_2 , transfer to another separatory funnel, and add 0.1 M $NaHSO_3$ drop by drop with shaking until no color of the I_2 remains in the CCl_4 layer.
- Step 4. Reoxidize the I^- with 2 ml. of 6 M HNO_3 and 5 drops of 0.1 M $NaNO_2$, and extract the I_2 with four 15-ml. portions of CCl_4 . Reduce the I_2 to I^- by drop-by-drop addition of $NaHSO_3$ solution as above. Discard the CCl_4 layer.
- Step 5. Add 1 or 2 drops of HNO_3 to the aqueous layer of the last extraction. Precipitate AgI by the addition of 0.1 M $AgNO_3$ and boil the solution to prevent colloid formation. Filter, wash, and dry the precipitate (use alcohol). Mount the AgI filter paper on cardboard, tape down with cellophane over the AgI .

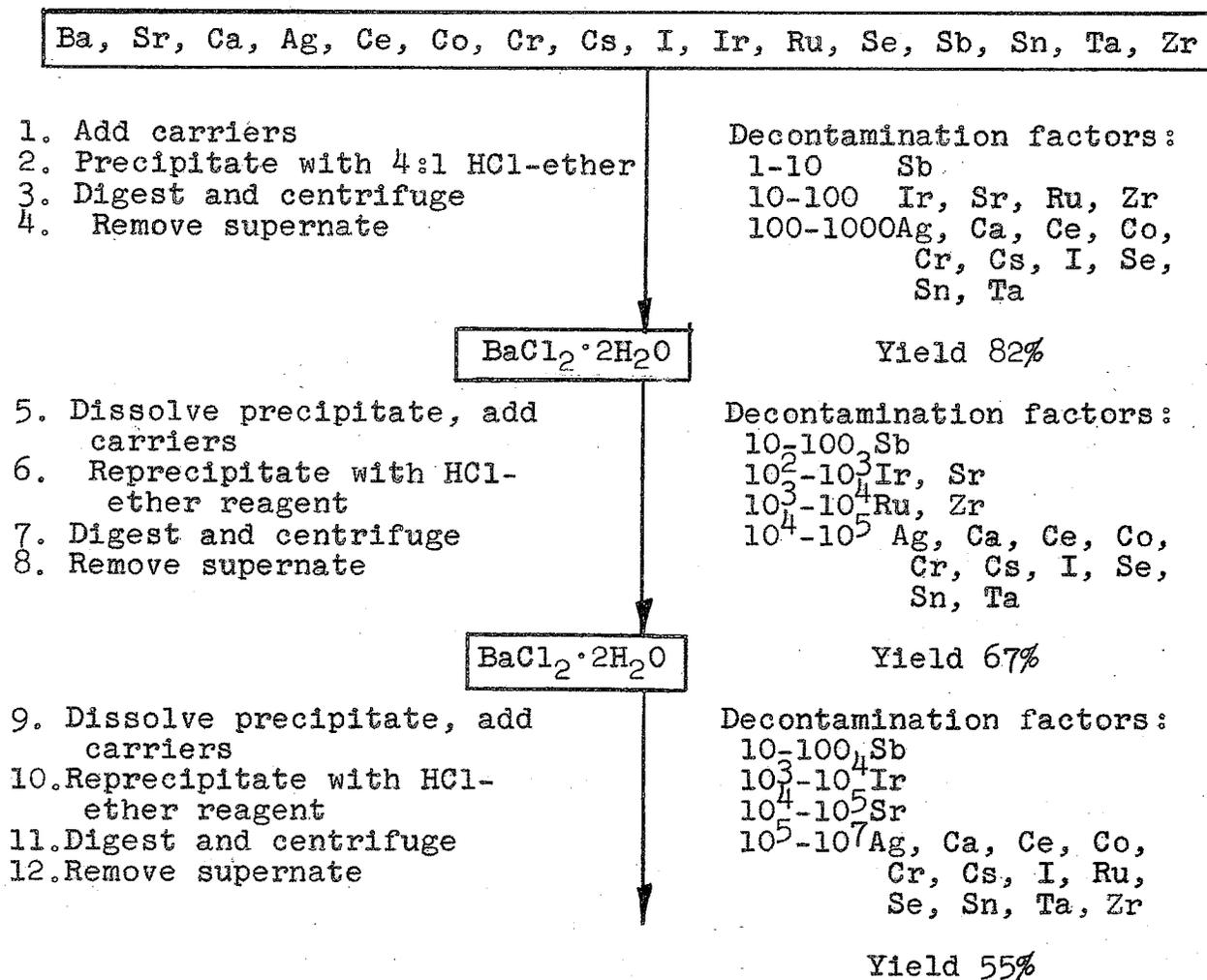
Separation from bromine is afforded by the extraction of I_2 after oxidation with HNO_2 ; this does not oxidize Br^- contamination by the other fission products. It should be mentioned that this procedure does not separate all the iodine activity since some of the active atoms formed in nuclear processes seem to be found in species that are not readily exchangeable with the stable valence forms of the iodine that may be used as carrier. Glendenin⁴ showed that oxidation by hypochlorite in alkaline solution in the presence of carrier with hydroxylamine reduction to I_2 will achieve complete exchange. Because of the length of time required for this procedure, it could not be incorporated in the experiment.

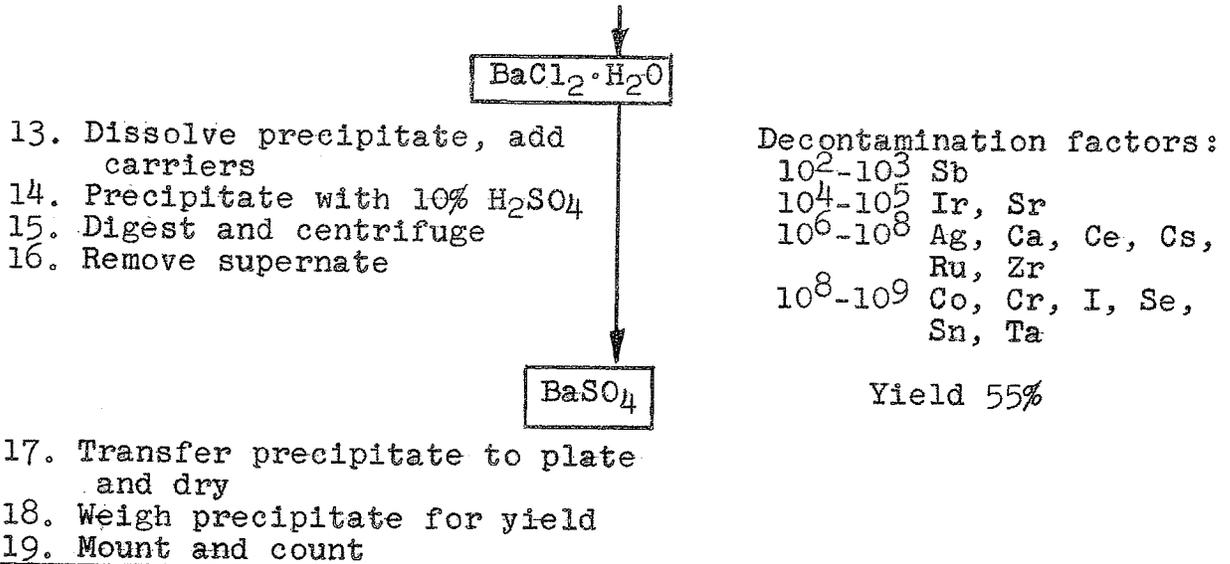
SEPARATION OF BARIUM:

Coryell and Sugarman⁵ give a procedure for barium in their book on studies of the fission products. This procedure and others like it have been studied and improved by Sunderman and Meinke who give an optimum radiochemical determination for barium.¹⁰ This procedure is outlined below in Table 2.

Table 2

Radiochemical Determination of Barium





RESULTS:

In the laboratory handling and separation techniques of two fission products were demonstrated. Another aspect to fission product chemistry is that of identification. In order to identify and determine the efficiency of the separation, several methods are available. The three most widely used are construction of either a decay or an absorption curve of the product and gamma scintillation spectrometry. Table 3 lists various characteristics of the isotopes of barium and iodine fission products.⁶

Table 3
FISSION PRODUCT NUCLEAR CHARACTERISTICS OF BARIUM AND IODINE ⁶

Z	A	Half-life	Energy of particle or photon (Mev.)	
			Beta	Gamma
56	Ba-139	85.0 min.	2.27	0.163
	Ba-140	12.8 d.	0.48, 1.02	0.16, 0.306, 0.540
	Ba-141	18 min.	2.8	
53	I-131	8.0 d.	0.6	0.363
	I-132	2.4 hr.	0.9, 2.2	0.68, 1.48
	I-133	22.4 hr.	1.4	0.53
	I-134	52.8 min.	3.5-4.2	
	I-135	6.68 hr.	1.0	2.4
	I-136	86 sec.	6.5	2.9

QUESTIONS:

1. What is the purpose of allowing an hour prior to opening the container of fission products?
2. What are some advantages and disadvantages of solvent extraction ion exchange and precipitation as seen from the demonstration?
3. What are the meanings of the following terms?
 - a. carrier
 - b. scavenging precipitations
 - c. absorption curve
 - d. radiocolloid
 - e. holdback carrier

REFERENCES:

1. C. B. Coryell and N. Sugarman, Radiochemical Studies: The Fission Products, Book 3, pp. 1381-2, McGraw-Hill (1951)
2. Ibid., p. 1383.
3. Ibid., p. 1623.
4. Ibid., p. 1625.
5. Ibid., p. 1460.
6. Ibid., pp. 2048-9.
7. Ibid., p. 989.
8. Ibid., p. 1102.
9. Ibid., p. 1106.
10. D. N. Sunderman, W. W. Meinke, Anal. Chem. 29, 1587 (1957).

APPENDIX A

THERMAL NEUTRON FLUX MEASUREMENTS IN A
NUCLEAR REACTOR USING ACTIVATION TECHNIQUES

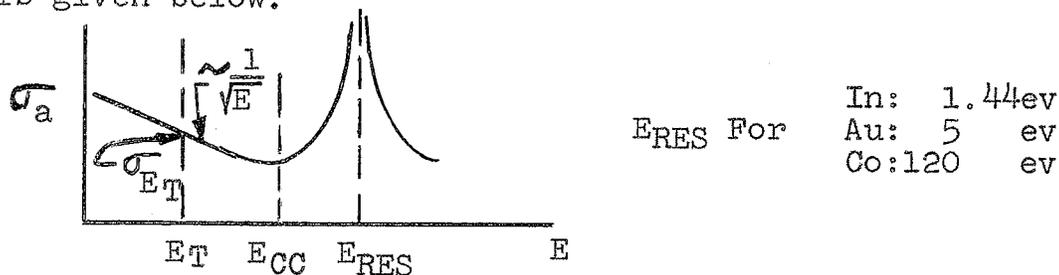
The activation method of neutron flux measurement makes use of the production of radioactive nuclei by the absorption of neutrons in a detecting material. The radioactive nuclei so produced decay with the emission of nuclear radiation and can thus be detected. The most widely used detecting materials are indium and gold in the form of foils or wires.

The rate of production, R , of the radioactive nuclei depends on the absorption cross section of the detecting material and on the neutron flux in the following manner:

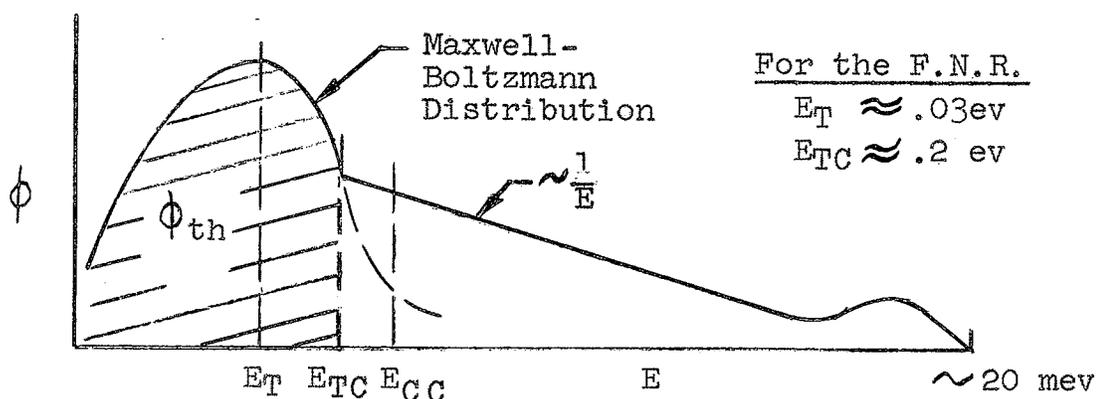
$$R = N_D \int_0^{\infty} \sigma_a(E) \phi(E) dE$$

where N_D is the number of nuclei in the detector, σ_a the absorption cross section, ϕ the neutron flux, and E the neutron energy.

A rough plot of σ_a for low energies (in general) is given below.



A rough plot of ϕ for a thermal reactor is shown below.

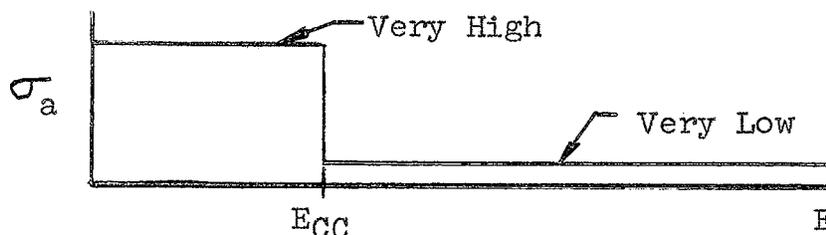


Here E_T is the most probable energy of the thermal neutrons, E_{TC} is the thermal cutoff energy, and E_{CC} will be discussed below.

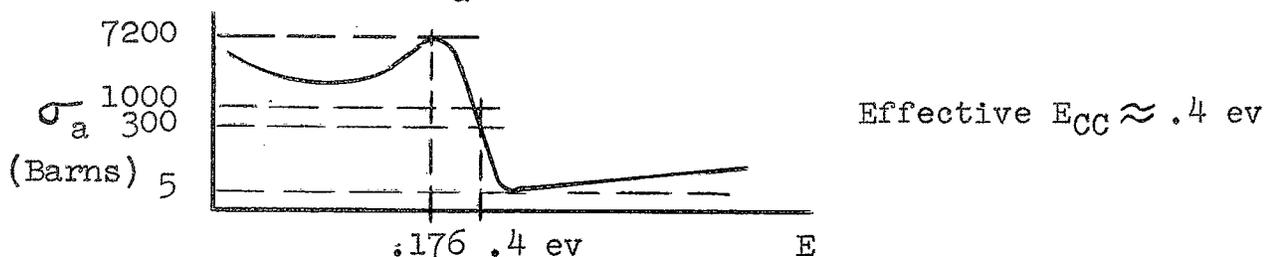
We may now write

$$R = N_D \left[C_M \sigma_{E_T} \phi_{th} + \int_{E_{TC}}^{\infty} \sigma_a(E) \phi(E) dE \right]$$

where C_M is a factor which is applied to σ_{E_T} so that $C_M \sigma_{E_T}$ gives the average cross section for the thermal flux. In order to measure ϕ_{th} , one must somehow differentiate between the quantities of radioactive nuclei produced by slow and fast neutrons. This can be done by first making measurements with a cover placed over the detecting material. This will screen out one of the two neutron groups. A material for which σ_a varies as shown below is needed.



Here E_{CC} is the cutoff energy. We would like to have $E_{CC} \approx E_{TC}$. A rough plot of σ_a for cadmium is shown below.



Now if we assume that no neutrons with $E < E_{CC}$ get through the cover, and that all neutrons with $E > E_{CC}$ go through it, we have:

$$R_C = N_D \int_{E_{CC}}^{\infty} \sigma_a(E) \phi(E) dE.$$

With a bare detector, that is, with no cover, we have

$$R_b = N_D \left[c_M \sigma_{E_T} \phi_{th} + \int_{E_{TC}}^{E_{CC}} \sigma_a(E) \phi(E) dE + \int_{E_{CC}}^{\infty} \sigma_a(E) \phi(E) dE \right].$$

R_b/R_c is called the cadmium ratio.

Taking the difference of the two rates:

$$R_b - R_c = N_D \left[c_M \sigma_{E_T} \phi_{th} + \int_{E_{TC}}^{E_{CC}} \sigma_a(E) \phi(E) dE \right].$$

Let us now look at the integral term. For the energy range

$E_{TC} < E < E_{CC}$ let $\sigma_a(E) \approx \frac{\sigma_0}{\sqrt{E}}$ and $\phi(E) \approx \frac{\phi_0}{E}$, where σ_0 and ϕ_0 are appropriate constants.

We now may write:

$$\begin{aligned} \int_{E_{TC}}^{E_{CC}} \frac{\sigma_0}{\sqrt{E}} \frac{\phi_0}{E} dE &= \sigma_0 \phi_0 \int_{E_{TC}}^{E_{CC}} E^{-3/2} dE \\ &= \sigma_0 \phi_0 \left[-2E^{-1/2} \right]_{E_{TC}}^{E_{CC}} = 2\sigma_0 \phi_0 \left[\frac{1}{\sqrt{E_{TC}}} - \frac{1}{\sqrt{E_{CC}}} \right]. \end{aligned}$$

But $\sigma_{th} = \frac{\sigma_0}{\sqrt{.025}}$, so that $\sigma_0 = \sqrt{.025} \sigma_{th}$

where σ_{th} is the value of $\sigma_a(E)$ at .025 ev.

Also, $\sigma_{E_T} = \frac{\sqrt{.025}}{\sqrt{E_T}} \sigma_{th}$, so that

$$R_b - R_c = N_D \left[c_M \sqrt{\frac{.025}{E_T}} \sigma_{th} \phi_{th} + 2 \sqrt{.025} \sigma_{th} \phi_0 \left(\frac{1}{\sqrt{E_{TC}}} - \frac{1}{\sqrt{E_{CC}}} \right) \right]$$

If we define $\bar{\sigma}_{th} = C_M \sigma_{E_T} = C_M \sqrt{\frac{.025}{E_T}} \sigma_{th}$, we get

$$R_b - R_c = N_D \left[\bar{\sigma}_{th} \phi_{th} + \frac{2}{C_M} \sqrt{E_T} \bar{\sigma}_{th} \phi_0 \left(\frac{1}{\sqrt{E_{TC}}} - \frac{1}{\sqrt{E_{CC}}} \right) \right]$$

So that finally we may write

$$R_b - R_c = N_D \bar{\sigma}_{th} (\phi_{th} + k \phi_0)$$

where k is a constant. For example, for $E_T = .03$ ev, $E_{TC} =$

$$.2 \text{ ev, } E_{CC} = .4 \text{ ev, } C_M = \sqrt{\frac{\pi}{4}},$$

$$k = .258$$

Now if $\phi_{th} \gg k \phi_0$, and it usually is, we may take

$$R_b - R_c \approx N_D \bar{\sigma}_{th} \phi_{th}$$

One should, however, distinguish between the thermal flux and the subcadmium flux at least in principle. Reference 1 discusses the determination of E_T and E_{TC} , and reference 2 the determination of the effective E_{CC} .

Up to this point we have dealt with the rates of the production of the radioactive nuclei. Now we must relate this quantity to one that we can measure. The quantity that we measure is the rate of disintegration of the radioactive nuclei at the time of measurement, which is some time after the removal of the detector from the neutron flux.

The buildup of the radioactive nuclei during irradiation is described by the equation

$$\frac{dN_R}{dt} = R - \lambda N_R$$

If $N_R(t = 0) = 0$:

$$N_R = \frac{R}{\lambda} (1 - e^{-\lambda t})$$

Here t is the time of irradiation, R the rate of production of the radioactive nuclei, N_R the number of such nuclei, and λ their decay constant. The rate of disintegration A during irradiation is

$$A = \lambda N_R = R(1 - e^{-\lambda t})$$

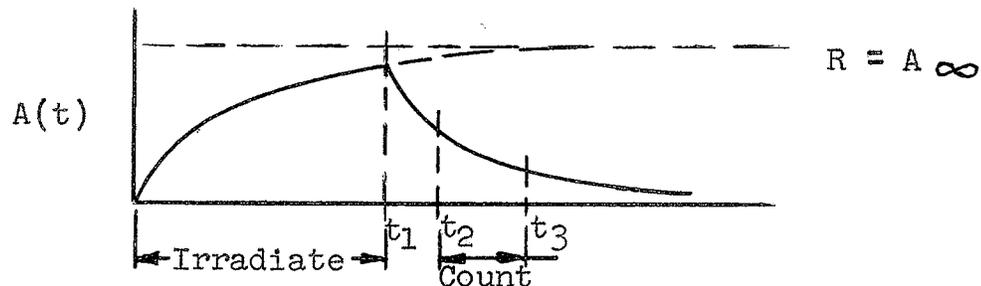
As $t \rightarrow \infty$, $A \rightarrow R$, the so called saturated activity A_∞ .

$$A_\infty = R = \frac{A}{1 - e^{-\lambda t}}$$

After removing the detector from the neutron flux at $t = t_1$, A will fall exponentially:

$$A = A(t_1)e^{-\lambda(t - t_1)} = A(t_1)e^{\lambda t_1} e^{-\lambda t}$$

The time behavior of A is sketched below:



Counting the decaying nuclei with counting efficiency f from t_2 to t_3 , the number of counts, C , is:

$$C = f \int_{t_2}^{t_3} A(t_1) e^{\lambda t_1} e^{-\lambda t} dt + \text{background}$$

$$= f A(t_1) e^{\lambda t_1} \left[-\frac{1}{\lambda} e^{-\lambda t} \right]_{t_2}^{t_3} + \text{background}$$

$$= f A(t_1) e^{\lambda t_1} \frac{1}{\lambda} (e^{-\lambda t_2} - e^{-\lambda t_3}) + \text{background}$$

but $A(t_1) = R(1 - e^{-\lambda t_1})$,

and if we define $C_{\text{corrected}} \equiv C - \text{background}$,

then $C_{\text{corrected}} = f R \frac{1}{\lambda} (e^{\lambda t_1} - 1) (e^{-\lambda t_2} - e^{-\lambda t_3})$

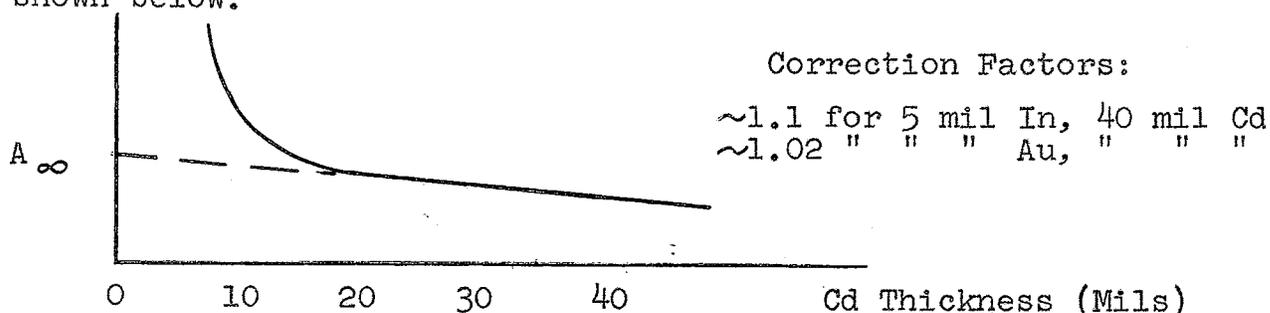
so that

$$R = \frac{C_{\text{corr}}/f}{\frac{1}{\lambda} (e^{\lambda t_1} - 1) (e^{-\lambda t_2} - e^{-\lambda t_3})}$$

The analysis up to this point has neglected the following facts:

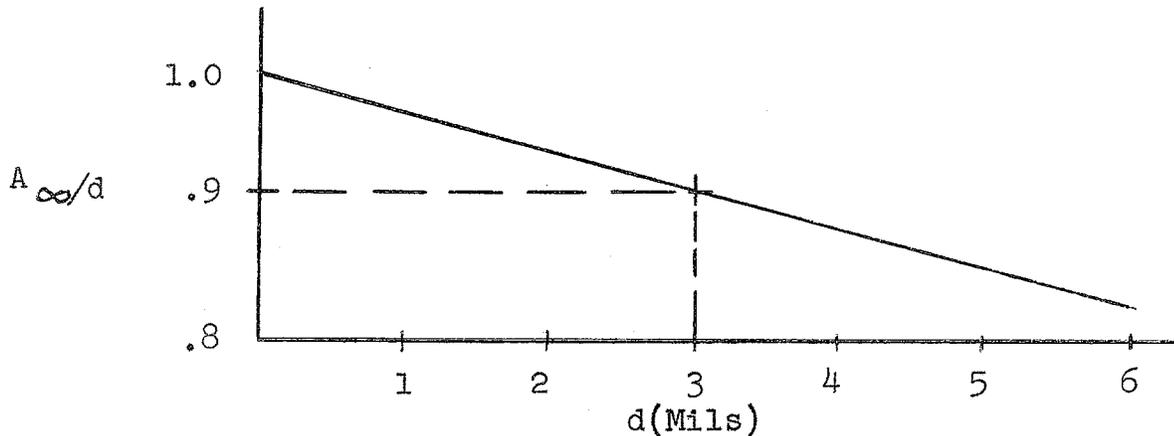
- 1) Some neutrons with $E < E_{CC}$ pass through the Cd cover
- 2) The Cd cover stops some of the neutrons with $E > E_{CC}$
- 3) The presence of the detector with its relatively high absorption cross section depresses the neutron flux
- 4) The detector has a finite thickness, and therefore the inner volume elements are shielded by the outer ones, that is, the activity per unit volume is not uniform. A detailed discussion of the above factors is beyond the scope of this paper. Only an indication of the results of some experimental investigations will be shown. References 3 through 6 should be consulted for further information.

The first two effects mentioned above can be investigated by irradiating detectors with different thicknesses of Cd cover. A typical plot of A_{∞} vs. Cd cover thickness is shown below.



The shape of the curve depends on several factors, such as the material and dimensions of the detector, the medium in which the measurements are made, and the Cd ratio. The steep slope at and below 10 mils of Cd thickness shows that more than a negligible number of sub-Cd neutrons reach the detector. More than about 20 mils of Cd seems to reduce this leakage enough so that only a small slope remains indicating the absorption of epi-Cd neutrons. For thicknesses greater than 20 mils, therefore, one can correct for the absorption of the epi-Cd neutrons by simply extrapolating the slope to zero Cd cover thickness.

Effects 3 and 4 can be investigated by irradiating detectors of different thicknesses, plotting the activity per unit thickness against detector thickness, d , and again extrapolating to zero thickness. The slope of such a curve will depend on the detector material and dimensions, and the medium in which the measurements are made. A typical plot is shown below.



Correction Factors:

$\sim 1/.845$ for .75" dia. 5 mil In.
 $\sim 1/.84$ " 1.5 " " " " "
 $\sim 1/.86$ " 1.5 " " " " Au.

REFERENCES:

1. Deutsch, R. W., "Computing Three-Group Constants for Neutron Diffusion", *Nucleonics*, Vol. 15, No. 1 (1957).
2. Dayton, I. E., and Pettus, W. G., "Effective Cadmium Cutoff Energy", *Nucleonics*, Vol. 15, No. 12 (1957).
3. Tittle, C. W., "Slow Neutron Detection by Foils" I and II, *Nucleonics*, Vol. 8, No. 6 and Vol. 9, No. 1 (1951).
4. Martin, D. H., "Correction Factors for Cd-Covered Foil Measurements", *Nucleonics*, Vol. 13, No. 3 (1955).
5. Gallagher, T. L., "Foil Depression Factors for Indium Disc Detectors", *Nuclear Science and Engineering*, Vol. 3, No. 1 (1958).
6. Klema, E. D., and Ritchie, R. H., "Thermal Neutron Flux Measurements in Graphite Using Gold and Indium Foils", *Phys. Rev.*, 87, 167 (1952).

APPENDIX B

FORD NUCLEAR REACTOR CALIBRATION PROCEDURE
FOR THE
COMPOSITE SAFETY AMPLIFIER

- 1.* Remove Sigma Bus, Remote Meter, Trouble, Operation Transfer, and 3" PCP connectors from rear of Composite Safety Amplifier (CSA).
2. Connect the Calibrator to the CSA. Make sure all connections are made correctly.
3. Short the Sigma Bus female connector on CSA chassis shell to ground (on CSA chassis).
4. Plug Calibrator into 110 volt A.C. outlet and turn power switch on.
- 5.* Turn on Amplifier, Magnet Power and Control Circuit switches located on control console.
- 6.* After time delay relay has cut in, press Scram Reset button on control console. (If scram level abnormal light on CSA is on, press scram reset button on CSA).

Sigma Amplifier

7. Set up the Calibrator as follows:

Operation switch	- position 1
Test switch	- position A
Potentiometer switch	- off
Potentiometer range	- zero
8. Adjust input voltage control to indicate 22 volts on input signal meter.

Sigma bus voltage meter should read 37 ± 1 volts.
 All lights on CSA should show normal.
 Amplifier trouble light on calibrator should be on.

If the sigma bus voltage is not within the tolerance, this indicates malfunctioning of the sigma amplifier. Check tubes V3 and V4 in a tube checker. Should the sigma bus voltage still not be within the tolerance, check resistor R33, 15K, on the plate side of the V3 tube.

9. Set monitor switch on CSA to position 1. In this position the meter, M1, measures power level. (Meter M1 is located at the lower left of the CSA panel).

10. Adjust the Recorder Zero potentiometer on CSA so that the meter, M1, reads zero.
11. Set potentiometer switch on Calibrator to the Meter position. The Potentiometer should read ± 1 divisions. This insures that if a recorder is used it will read zero at zero power level.
12. Decrease the input voltage slowly until the Preamp-Grid-Offset light on CSA shows abnormal.

Amplifier trouble light on Calibrator should go out, showing an open circuit.
Input voltage meter on Calibrator should indicate not less than 13 volts.
13. Slowly increase the input voltage until the Preamp-Grid-Offset light on CSA shows normal and the amplifier trouble light on the Calibrator comes on.

Input meter should indicate not more than 21 volts.
14. Adjust input voltage control to indicate 32 volts on input signal meter.
15. Set potentiometer range switch to 53.3 millivolts, to simulate a recorder load.
16. Adjust Recorder Gain potentiometer on CSA until the potentiometer reads zero. When potentiometer (bridge circuit) reads zero, the recorder gain is set at full scale (6.67 mv).

Meter M1 on CSA should read between 0.95 and 1.05. If it doesn't, replace resistor R46 and recheck. It may be necessary to do this several times since it is a fine adjustment between the resistor and the remainder of the circuit.
17. Remove tube V4 (inside CSA) from its socket.

Sigma Amplifier light should show abnormal.
Preamp-Grid-Offset Abnormal light should also come on.
18. Replace V4 in its socket. Meter readings (M1 and input voltage) should return to those values indicated in steps 14 and 16.
19. Increase input voltage until input signal meter on the Calibrator reads 37 volts. This simulates 150% of full power.

Scram Level Abnormal Light on CSA should come on.

Power level meter M1 should read $1.5 P_F$
 Sigma Bus voltage meter on Calibrator must read
 43.5 ± 1 volts.

If the above conditions are not satisfied, it is an indication of low gain in the system. Check tubes V3 (for short circuit) and V4.

Sigma Preamplifier

20. Decrease the input voltage to a nominal value of 15 volts. Set operation switch on Calibrator to position 2.
21. Adjust input voltage control on Calibrator to make meter M1 on CSA read zero. Push scram reset button on CSA.

Input signal meter on calibrator should read approximately 12 volts.

22. Adjust input signal meter to read 29 volts.

Meter M1 should read at least $1.5 P_F$ (full power).

23. Decrease the input voltage to a nominal value of 15 volts. Set test switch on Calibrator to position B. This disconnects the input voltage.
24. Adjust Preamp-Grid-Offset potentiometer on CSA to make meter M1 read zero.
25. Press the recessed test scram button on CSA.

Meter M1 should read at least $1.5 P_F$. If not, check resistor R23.

Period Amplifier

26. Set operations switch on Calibrator to position 3. This connects the period amplifier to the sigma amplifier and feeds power to the period amp.
27. Set input voltage at zero and adjust the Period D.C. Level potentiometer so that meter M1 on CSA reads zero. Adjust input signal meter to read 37.5 which corresponds to an input voltage of 0.75 volts.

Meter M1 should read at least $1.35 P_F$.
 Scram Level Abnormal light should come on.

Magnet Amplifier

28. Decrease the input voltage to a nominal value of 15 volts. Set test switch on Calibrator to position A.

29. Set operations switch on Calibrator to position 4. This interconnects the period, sigma, and magnet amplifiers.
30. Adjust input voltage on Calibrator so that meter M1 on CSA reads zero.
31. Turn the Bus Protect potentiometer on CSA fully clockwise.
32. Adjust Magnet Current potentiometer on CSA so that magnet current meter (M2) on CSA reads 50 ma.
33. Adjust Bus Protect potentiometer on CSA until meter M2 on CSA decreases by 1 ma.
34. Adjust Magnet Current potentiometer until M2 reads 50 ma.
35. Adjust input voltage on Calibrator so that M1 reads $0.75 P_F$.
Meter M2 should read not less than 40 ma.
36. Adjust input voltage on Calibrator so that M1 reads $1.5 P_F$.
M2 should read 25 ma or lower.
Scram Level Abnormal light should come on.
37. Adjust input voltage on Calibrator so that M1 reads $1.0 P_F$.
Reset the Scram Level light to normal.

Positions 2,3,4,5,6,10,11 of the monitor switch on CSA should read within two large divisions of the center of the green mark on M1.

Positions 7 and 8 measure the cathode current of the magnet tubes. The absolute value of the readings in positions 7 and 8 is not significant, but they should be within 20% of each other.

Position 9 will show greater variation since feedback takes effect here and neutralizes drifts occurring elsewhere in the circuit, but should give an up-scale reading. This indicates that the feedback is operative.

If positions 7 and 8 are not within 20%, check tubes V7 and V8. If this does not correct the trouble, check resistors R91 and R96.

38. Set monitor switch on CSA to position 1.
39. Turn the Calibrator power off and return all switches to original positions.
40. Remove Calibrator cable connectors from CSA.
- 41.* Connect the CSA interconnecting cables behind control cubicle.

- 42.* Repeat steps 1 through 41 for the other safety amplifiers.

Final System Check

- 43.* Press the recessed test scram button on CSA (A).

The magnet current should decrease to at least 25 ma as indicated on meters M2 of all three CSA's.

- 44.* Repeat step 43 for CSA (B).

- 45.* Adjust Period D. C. Level potentiometer on CSA (C) until M1 reads 1.5 Pf.

The magnet current should drop to at least 25 ma as indicated on M2 of all three CSA's.

46. Adjust Period D. C. Level potentiometer on CSA (C) until M1 reads zero.

*. Omit for Bench Test

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- Exp. No. 2 - The Critical Experiment
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- Exp. No. 3 - Scintillation Counting Techniques
 Director - J. I. Trombka
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- Exp. No. 4 - Reactor Operation
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- Exp. No. 5 - The Subcritical Experiment
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- Exp. No. 10 - Shim Rod Calibration
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- Exp. No. 11 - Calibration of the Composite Safety
 Amplifier
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- Exp. No. 12 - Electromagnet-Safety Rod Performance
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