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# Neutron flux mapping of the MSM reactor

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# NEUTRON FLUX MAPPING OF THE MSM REACTOR

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# ABSTRACT

This investigation presents a mean to determine thermal neutron flux of a reactor by irradiating copper wires inside the fuel elements. The activity recorded after decay correction, is the relative thermal neutron density. Thermal neutron flux is a measure of the neutron density at thermal energy, 0.025 ev.

Gold foils irradiated at National Bureau of Standards were used as the absolute neutron flux calibration standards. The average flux of the reactor with water as the reflector ranges from $7.24 \times 10^{10}$ neutrons/$cm^2$ - sec. to $7.87 \times 10^{10}$ neutrons/$cm^2$ - sec. as obtained from the calculations. This set of values compares favorably with the result as measured by the manufacturers.

In this investigation the thermal neutron flux in the MSM reactor was determined by irradiating copper wires inside the fuel elements.

## ACKNOWLEDGEMENT

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# I. INTRODUCTION

At the present, flux calculation for a given reactor remains a cumbersome and tedious process. At best the theoretical calculation is good as a first order approximation due to the assumptions required to make the problem practicable for solution by a computer. Thus the most accurate method of flux mapping relies on the various experimental techniques in which detectors or probes of some sort are extensively used.

A knowledge of the flux profile, although not essential in the operation of a reactor, is nonetheless important and has many uses. By the information gained from a mock-up reactor, designers can use the neutron flux profile to determine the power distribution, the locations for the control rods, thermal columns and other components which affect the neutron population. In a research reactor which is used as neutron source for radiation experiments, a knowledge of the neutron flux is most useful.

It is the purpose of the following investigation to make known the flux profiles for a few simple core arrangements. It is hoped that refinement of the present method will be made in the future. A system for automatic scan counting of the wire using a recorder will reduce the handling time and provide a continuous flux profile with minimum data processing required.

The selection of the copper wire as the detector in the activation experiments is based on its properties and handling safety. Copper-64 has as activation cross section 3.9 barns as compared to 96 barns for gold and 145 barns for indium, and is potentially safer for handling. Copper 65 has a half life of 4.3 minutes and will contribute insignificant radiation hazard after a decay time of several hours. It is estimated that a 14 gauge copper wire of 30 inches in length will give a radiation dosage of about

4 mr/hr at two feet distance when irradiated 20 minutes in a reactor of 10 kilowatt and after a waiting time of 4 half lifes. With the protection of lead shield, personnel can be safely exposed to the radioactive wire and stay within the maxium permissible exposure dosage of 100 mr per week. The commercially obtainable copper is better than 99.9% in purity and has small variation in diameter. If desired, the copper wire can be drawn into smaller diameter wire of uniform dimension with excellent surface smoothness.

## II. REVIEW OF LITERATURE

### 1. Slow Neutron Activation

Neutron flux measurements have been made successfully by radioactivation on many materials. The most commonly used materials are gold (1) and indium (2) foils.

In all such activation measurements, the procedure consists of exposing a foil of the material being used as a detector to the neutron flux for a known amount of time. Flux depression (3) due to the presence of the foil is small in most instances since the foil is of negligible thickness. The sample is removed and its radioactivity measured by observing the number of counts in a given time interval. If this procedure is repeated with a foil wrapped with cadmium (4), the foil will then be activated only by neutrons with energies above the cadmium cutoff, about 0.4 ev. The difference between the number of counts obtained from the two exposures can be related to the thermal flux if the detector's cross section is inversely proportional to the neutron velocity.

The number of capturing events or the activation response is proportional to $nv\sigma$, where n is the neutron density, v is the velocity of the neutrons, and $\sigma$ is the microscopic cross section of the detector, thus

$$\text{Thermal response} \propto (nv)_{th}\, \sigma_{th} \qquad (2\text{-}1)$$

and

$$\text{Resonance response} \propto \int_{0.4\ ev}^{\infty} \sigma_a(E)\ \phi\ (E)\ dE \qquad (2\text{-}2)$$

$\phi(E)$ is the resonance neutron flux per unit energy, and $\sigma_a$ (E) is the microscopic absorption cross section at energy E. For neutron flux in the resonance region which varies as 1/E, equation (2-2) can be represented as

$$\text{Resonance response} \propto \int_{0.4\ \text{ev}}^{\infty} \sigma_a \phi_{res} \, dE/E \qquad (2\text{-}3)$$

where $\phi_{res}$ is a constant.

The cadmium ratio, $R_{cd}$, is defined as the ratio of the sum of thermal and resonance response to the resonance response, it it evident that

$$R_{cd} - 1 = \frac{\text{thermal response}}{\text{resonance response}} = \frac{(nv)_{th} \quad \sigma_{th}}{\phi_{res} \int_{0.4\ \text{ev}}^{\infty} \sigma_a \ (E) \ dE/E} \qquad (2\text{-}4)$$

The actual cadmium ratio observed is a function of the sensitivity of the detector to resonance and thermal neutrons and does not lead to the true flux ratio unless this sensitivity is known. If the value for the thermal cross section and the resonance integral are known, then the ratio of the thermal and resonance fluxes can be obtained. As stated before, the thermal response can be found by the difference between the uncovered exposure which measures the total response, and the cadmium covered exposure which measures the resonance response. The absolute resonance flux can be obtained if some standard is available for converting thermal response to absolute thermal flux.

Some materials have one sharp resonance which predominates, and effectively all the resonance neutrons absorbed by the detector are neutrons which have energies grouped about the resonance peak. In such a case,

$$\int_{0.4\ \text{ev}}^{\infty} \sigma_a \ (E) \ \phi \ (E) \ dE = \phi \ (E_r) \quad \int_{0.4\ \text{ev}}^{\infty} \sigma_a \ (E) \ dE \qquad (2\text{-}5)$$

where $\phi\ (E_r)$ is the resonance flux per unit energy corresponding to the resonance peak, since the integral is largely determined by the energy interval in the neighborhood of the resonance peak. A flux spectrum over a considerable range of energies can be obtained by activating materials which have prominent resonance absorption at various energies.

Employing the activation principle, Battelle Memorial Institute (5) investigated a flux profile by the activation of magnesium-indium wire. A cadmium-alloy tubing was used to simulate the cadmium cover used in the foil-activation technique. A continuous counting device with gears and timer was developed. The method used is practicable under conditions of relatively high flux level and is more expeditious compared to the foil activation technique.

Another method of neutron detection is by means of a $BF_3$ counter. The reaction, $B^{10}(n,\alpha)Li^7$, enables the detection of neutrons by the ionization caused by alpha particles. The rate of neutron capture events in a volume, V, of $BF_3$ gas possessing N atoms of $B^{10}$ per $cm^3$ is

$$R = NV\int_0^{\infty} n(v)\,v\,\sigma(v)\,dv \qquad (2\text{-}6)$$

where n(v) is the neutron density per unit velocity interval at velocity v, and $\sigma(v)$ is the $B^{10}$ capture cross section at velocity v.

When detecting neutrons in the thermal region, $\sigma(v)$ is nearly proportional to 1/v, and it may be written as

$$\sigma(v) = \frac{\sigma_0 v_0}{v} \qquad (2\text{-}7)$$

where $\sigma_0$ is the thermal capture cross section for $B^{10}$ and $v_0$ is the most probable neutron velocity. Then the rate of neutron capture is

$$R = NV\sigma_0 v_0\int_0^{v_0} n(v)\,dv = NV\sigma_0 v_0 \rho \qquad (2\text{-}8)$$

where $\rho$ is the density of slow neutrons.

If the velocity spectrum, n(v) is well known about an average velocity $\bar{v}$, then the flux density is given by

$$\rho\bar{v} = \frac{R\bar{v}}{NV\sigma_0 v_0} \qquad (2\text{-}9)$$

The measurement of R, the rate of $B^{10}$ capture events, may be accomplished by pulse counting. The volume, V, is the sensitive volume of a proportional counter or of an ionization chamber.

The assumption in the foregoing is that slow-neutron absorption by the counter wall is negligible. The validity of the statement depends upon the material and the thickness of the walls. Important aspects of $BF_3$ proportional counters and pulse chambers can be found in an article by Fowler and Tunnicliffe (6).

A common method to measure R is by collecting the ionization current from the volume V. Since each capture event releases 2,34 mev as the kinetic energy of the alpha and $Li^7$ particles, and since this energy is lost by ionization and excitation with an energy of about 32.5 ev per ion pair, the ionization current due to neutrons will be (at saturation)

$$I = 1.6x10^{-19} \left( \frac{2.34x10^6}{32.5} \right) VR \left(1 - \frac{\Delta V}{5V}\right) \text{ Amperes} \tag{2-10}$$

$\Delta V$ is the volume reduction by moving the chamber walls inward by a distance equal to the range of the alpha in $BF_3$ gas. The volume correction factor, $\left( 1 - \frac{\Delta V}{5V}\right)$, approximately accounts for the capture events occurring near the walls which may not contribute their share of ionization to the gas. If there is a way to subtract that portion of ionization current contributed by gamma and other radiations, the neutron flux can be evaluated by equation (2-9) with the known value R from equation (2-10).

Developed at Oak Ridge National Laboratory, the compensated ionization chamber measures the neutron current alone. This device consists of a pair of ionization chambers, one is filled with dry $BF_3$ gas and the other is filled with a gas of argon or $CO_2$ which is insensitive to neutrons. The pressure in the second chamber is adjusted to give an identical ionization current when both chambers are exposed to the same intensity of gamma radiation. Since the $BF_3$

chamber is sensitive to gamma and neutron radiations, the difference current of the two chambers, as indicated by an electrometer, is the ionization current due to the neutrons. The application of fission chambers to detect neutrons is through the kinetic energy of the fission products. The ionization produced as the fission products are brought to rest is utilized to measure neutron densities.

Fission chambers containing the thermal-fissionable nuclei $U^{233}$, $U^{235}$, or $Pu^{239}$ are efficient thermal-neutron detectors. The large energy released per reaction makes it possible to discriminate against much larger fluxes of gamma rays than with detectors employing $(n,\alpha)$ or similar reactions. This property makes the fission chambers particularly useful for the measurement of small values of neutron flux which are present in the start up and shutdown of a reactor. The cross sections of $U^{233}$, $U^{235}$, and $Pu^{239}$ follow approximately 1/v dependence so the relationship between reaction rate and thermal flux for boron chambers applies here as a crude approximation.

## 2. Fast Neutron Activation

In most instances the detection of high energy neutrons, energies ranging from 10 kev to about 15 mev, relies on the modified slow neutron detection techniques. A survey of the detection methods for fast neutrons will be given in this section.

Since $B^{10}$ $(n,\alpha)$ has a decreasing cross section for the reaction as neutron energy increases, the sensitivity of the $B^{10}$ counter is quite small for fast neutrons. Much improvement can be had by surrounding the counter with a neutron moderator so the neutrons are slowed down before entering the counter tube. However, it is found such an arrangement is usually dependent on the neutron energy and the detector-source geometry. These factors make the interpretation of measurement quite difficult.

A detector system known as the "long counter", devised by Hanson and McKibben (7), is essentially independent of neutron energy from 10 kev to 3 mev. The arrangement consists of a paraffin cylinder about 10 inches outer diameter by 12 inches long surrounding a long boron trifluoride proportional counter. The response is flat within 10 percent for the neutron energies between 10 kev and 3 mev.

The application of fission chambers for slow neutron detection was discussed earlier. The underlying principle, threshold reaction, can be applied to detect fast neutrons by suitably selecting fissionable materials with higher threshold energies. Wiegand (8) has described the use of bismuth in a fission chamber which will monitor neutrons with energy greater than 50 mev, the threshold energy for the fission process of bismuth. A list of references (9-12) includes the various fission chamber constructions and characteristics.

The use of a pulse chamber to detect fast neutrons involves the (n,p) scattering process. The neutron in the scattering process transfers part of its energy to the recoil proton and the ionization produced by the protons is a measure of the neutron density.

The hydrogen which is required for the proton recoil counter can be introduced either in a solid or gaseous form. If one assumes that the pulse height produced by each recoil proton is proportional to the proton energy, an expression for the counting rate, $C(E_n, E_t)$, for neutrons with energy $E_n$ is

$$C(E_n, E_t) = \int_{E_t}^{E_n} N_p(E)\, dE \qquad (2\text{-}11)$$

where $E_t$ is the threshold energy of (n,p) reaction and $N_p(E)$ is the proton recoil energy distribution.

If a region contains $N_t$ protons in a uniform flux of monoenergetic neutrons with energy $E_n$, the number of recoil protons per unit time per unit neutron energy is

recoil protons per sec per unit energy =

$$\frac{N_t \phi_{E_n} \sigma(E_n)}{E_n} \qquad (2\text{-}12)$$

Since the recoil protons per second per unit energy is the recoil proton energy distribution, the relationship between the counting rate and flux is

$$C(E_n, E_t) = \int_{E_t}^{E_n} \frac{N_t \phi_{E_n} \sigma(E_n)\, dE}{E_n} = \frac{N_t \phi_{E_n} \sigma(E_n)(E_n - E_t)}{E_n} \qquad (2\text{-}13)$$

Designs of several different counters of this type can be found in the discussion by Rossi and Staub (9).

For sufficiently large neutron fluxes, the current in an ionization chamber containing hydrogen can be measured.

Again, if the ionization produced in the chamber by each recoil proton is proportional to the proton energy, the idealized saturation current can be written as

$$I = \frac{e}{w} \int_0^{E_n} E N_p(E)\, dE = \frac{e}{2w} N_t \phi_{E_n} \sigma(E_n) E_n \qquad (2\text{-}14)$$

In this expression, e is the electronic charge, and w is the energy required to produce one ion pair. The factor 1/2 is the fraction of the neutron energy imparted to proton assuming isotropic scattering.

Neutron induced reactions which have a threshold energy can be used to detect fast neutrons. A list of some common threshold detectors, their energies, and a discussion of their uses have been given by Cohen (13).

The saturation activity of a threshold detector is given by the well known equation

$$A_s = N_t \int_0^{\infty} \sigma_a(E) \phi(E)\, dE \qquad (2\text{-}15)$$

where $N_t$ is the total number of target atoms in the detector and $\sigma_a(E)$ is the cross section for activation at energy E. In the case of the $P^{31}$ (n,p) and $S^{32}$ (n,p) reactions, there is a fortunate occurrence of resonances and the cross sections rise quite rapidly and remain rather constant thereafter. In this special case, the actual cross section can be replaced by an idealized cross section, $\sigma_c$, whose value is constant from $E_t$ to infinity. Thus saturation activity is given as

$$A_s = N_t \sigma_c \int_{E_t}^{\infty} \phi(E)\, dE \qquad (2\text{-}16)$$

where $\sigma_c$ is set as the mean value above the threshold. By the use of two foils with threshold energies $E_{t-1}$ and $E_{t-2}$, the total flux in the energy interval $E_{t-1}$ and $E_{t-2}$ can be found. Hurst et al (14) have utilized threshold detectors in this fashion for determining neutron spectra.

The central problem in neutron counting by the use of scintillation detectors is the discrimination against gamma rays. Because of the high density of the scintillation detectors, the secondary electrons released by the gamma rays often dissipate their entire energies in the detectors. Therefore, the scintillator outputs for the gamma rays are often at least as large as those for the neutrons.

Bollinger (15) has described a boron-loaded liquid scintillation counter which minimizes the discriminator problems. The cell containing the scintillator is viewed by four photomultiplier tubes mounted in a circle on one side of the container. The tubes are paired by joining the anodes of the diagonally opposite, the signal from each pair being independently amplified. The electronic system requires coincidence between two amplifier outputs, thus eliminating tube-noise counts. Gamma ray background is minimized by requiring that the sum of the amplifier outputs be in a given pulse-height range.

When a fast neutron enters the liquid scintillator containing boron, two light pulses may be produced, one by the protons scattered by the neutrons and the other upon the capture of the neutrons by the boron. The two pulses should be separated by about 0.5 $\mu$sec, the time required for the capture of neutron in the boron. Since the individual pulses are quite short (around $5 \times 10^{-9}$ sec), they can be resolved. Thus the fast neutron can be identified by the appearance of two pulses. By the use of a delayed coincidence circuit, the fast neutrons can be separated from the gamma rays and the slow neutrons, each of which gives one signal pulse.

An ingenious application of organic scintillators has been developed (16) which is insensitive to gamma radiation and for which the detection efficiency is strongly dependent on neutron energy. The counting medium consists of spheres of a plastic scintillator immersed in nonhydrogeneous optically inert material (glass or trifluorochloroethylene liquid). The sphere diameter is chosen large enough that, for a particular neutron energy, most recoil protons dissipate their energy within the scintillator. However, it must be a small enough to prevent the pulses of maximum size caused by gamma rays from being in the same pulse-height range as those due to the neutrons.

Nuclear emulsions have been found satisfactory for neutron energy distribution measurements of neutrons in the energy range from about 0.5 to 15 mev. The lower limit arises since the track ranges become too short for accurate measurements while the upper limit comes from a practical limit of emulsion thickness.

Several techniques have been developed for the measurement of neutron energy and spectra through the use of nuclear emulsions. Extensive review of the nuclear emulsion techniques has been given by Rosen (17). The choice of method depends on several factors such as the degree of collimation of the neutrons, the energy region in which the measurement is required, and the facilities and time available for measuring the tracks.

One technique commonly used is that of measuring the range of proton recoils in the emulsion within a small angle from the forward direction. This technique requires the knowledge of the direction of the primary neutrons. Through the use of the range-energy relationship, readily attainable through the suppliers of the emulsions, the energies associated with the proton recoils can be determined.

A considerable amount of work has been devoted to the establishment of precise range-energy relationship for various types of nuclear emulsions (18). Since changes in emulsion composition affect range measurement, it is a common practice to calibrate emulsions under the conditions of exposure and development to be employed in the experiment. This can be done by using particles of known range.

## III THEORY AND EXPERIMENTAL PROCEDURE

A detector placed in a uniform neutron flux, $\phi$, has a rate of change of radioactive atoms given by the difference between the rate of radioactive formation and the rate of decay, assuming negligible loss due to neutron capture. If the decay constant is $\lambda$, the rate of change of radioactive atoms, $\frac{dN}{dt}$, is

$$\frac{dN}{dt} = \sigma_a N_d S_d \phi - \lambda N \qquad (3\text{-}1)$$

The rate of radioactive formation is $\sigma_a N_d S_d \phi$ where $\sigma_a$ is the activation cross section of the detector, $N_d$ and $S_d$ are the molecular surface density and the surface area of the detector respectively. It follows from equation (3-1) that N, the number of radioactive atoms present at time t is.

$$N = \frac{\sigma_a N_d S_d \phi}{\lambda} \left(1 - e^{-\lambda t}\right) \qquad (3\text{-}2)$$

where time is measured from the commencement of the irradiation.

When a detector is irradiated for a duration of $t_1$, the number of radioactive atoms decaying for a length of time T after removal from the flux for a period of $t_2$ is

$$N_T = \frac{\sigma_a N_d S_d \phi}{\lambda} \left(1 - e^{-\lambda t_1}\right) \left(1 - e^{-\lambda T}\right) e^{-\lambda t_2} \qquad (3\text{-}3)$$

If the counter efficiency is $e_c$ and the fractional counts due to the geometry is $e_g$, then the total count, C, registered for the interval T is

$$C = e_c e_g N_T \qquad (3\text{-}4)$$

For a particular counter with a constant counting geometry it is evident that the flux $\phi$, is directly proportional to the registered counts after the correction. If the absolute flux is known for any one count, the absolute flux profile can be obtained.

In 19W loading, (19 represents the loading arrangement and W stands for the water reflector) 14 copper wires of gauge number 14, each 30 inches long, were positioned into the center of the fuel elements. A plastic holder for the copper wire was designed to rest between the top edges of any two fuel plates. The holders and the wires, each numbered for identification, were lowered into the fuel elements by nylon strings, positioned as shown in figure 2a. The reactor was brought to a power level of 10 kilowatts at a constant period and operated for 20 minutes as the total duration of the irradiation. The contribution to the radioactivity, N', while the reactor is approaching 10 kilowatts can be represented by

$$\frac{dN'}{dt} = \sigma_a N_d S_d \phi_o \, e^{\frac{t}{T}} - \lambda N' \qquad (3\text{-}5)$$

where $\phi_o$ is the flux when the reactor is critical, T is the reactor period, and t is the time between critical and final steady power of the reactor. As the calculation shows in appendix 2, the contribution to the radioactivity is negligible and is well within the error of the National Bureau of Standards flux source.

In order to minimize the radiation hazard, the radioactive wires were allowed to decay at least 4 half lives before handling. Counting was done at two inch intervals for one minute periods starting at the 30 inch mark of the wire, a position corresponding to the bottom portion of the fuel element. As the water reflecting wing at the top appears as part of the 2 inch interval count, an extra reading at the 29th inch was necessary to locate the reflecting wing at the bottom. Counting was done with the G-M tube, model 10106, by Radiation Counter Lab, Inc. It was attached to a scalar model DS-5B by Technical Associated and operated at

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 |
| B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 |
| C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 |
| D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
| E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 |
| F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 |

FIGURE 1a CORE ARRANGEMENT

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | | | | S | | | | |
| | | | F-12 | F-8 | HR-1 | | | |
| | | F-22 | C-1 | F-15 | C-4 | F-18 | | |
| | | F-5 | C-2 | F-13 | C-3 | F-3 | | |
| | | F-2 | F-21 | F-10 | F-7 | F-14 | | |

FIGURE 1b SOURCE, S, AND FUEL POSITIONS

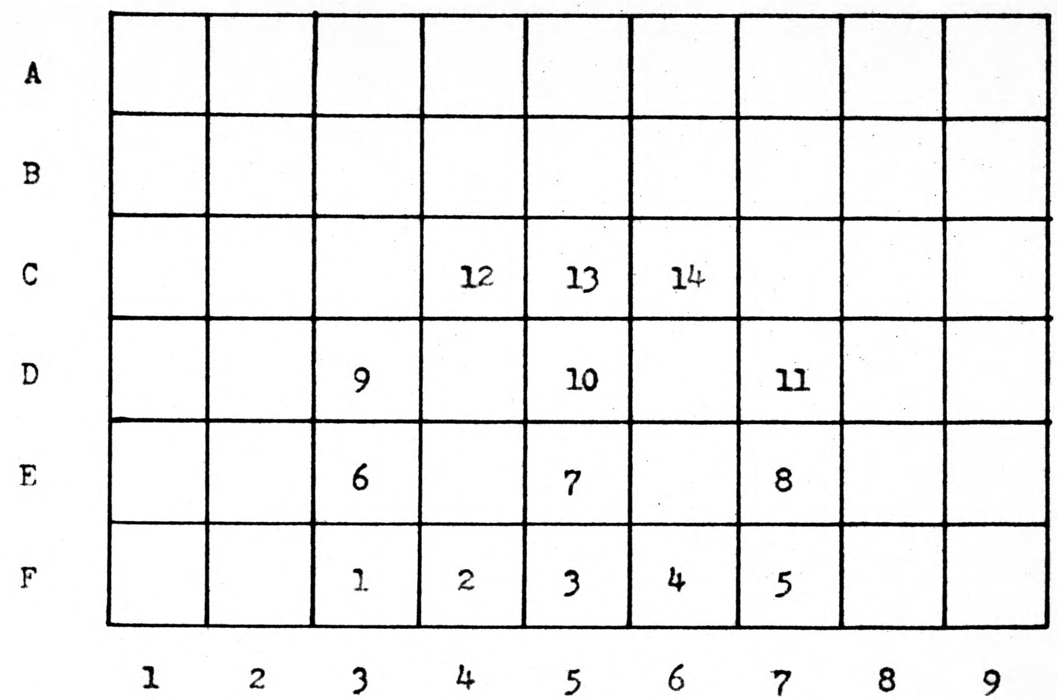


FIGURE 2a WIRE POSITIONS FOR 19W

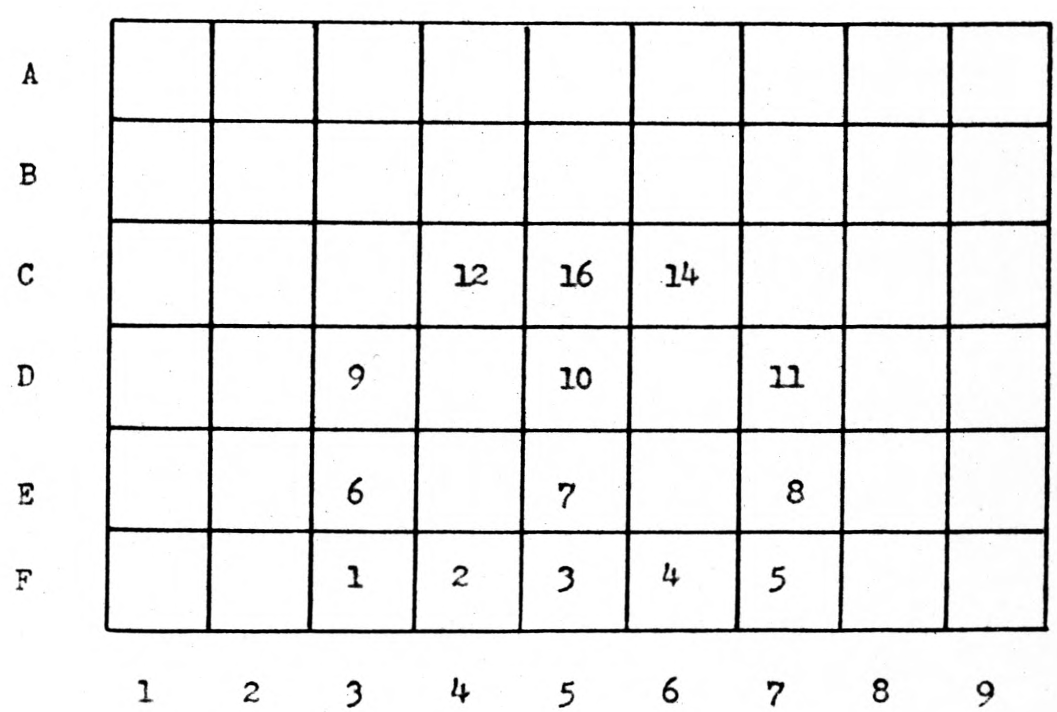


FIGURE 2b WIRE POSITIONS FOR 19T

1320 volts, the middle of the G-M tube plateau. The counting arrangement with the lead bricks as shield provides constant geometry and is arranged as in figure 3.

Four gold foils, irradiated in the thermal neutron pile of the National Bureau of Standards, were used as the absolute neutron flux standard for the calibration. Using gold foils of known masses, two foils were positioned inside each fuel element at core position F-6 and F-4 at a known distance along the length of the element. These foils were irradiated for ten minutes at a reactor power of 10 watts. Subsequently four identical foils with cadmium covers were irradiated under the same conditions. The difference between the saturation counts of the bare and cadmium covered foils is proportional to the thermal neutron flux. Saturation count is the number of radioactive atoms present when the decay time is zero and the sample is irradiated for an infinite time. A sample calculation to determine the absolute flux at a point in the reactor is done in appendix 3.

A plastic strip, 1 1/4 inches by 32 inches, was used as the foil holder. Six holes spaced 4 inches apart starting from the 26th inch were drilled to fit the round cadmium covers. Commercially obtainable black electrical tape was employed to hold the foils and the covers secure. Again, nylon string was used to lower the plastic strip into the fuel element. It was found that lead weights must be added to the strip to make positioning possible.

A scintillation tube positioned inside a lead shield was used to count the radioactivity of the gold foils. A plateau run indicated the best operating voltage is 1120 volt. For reproducible geometry, shelf number 1 of the standard counting set-up was used for all the foil counting. Fifteen minute counts were taken for all the foils except the standard foils where counting was done for a period of 50 minutes. The foil counting set-up is arranged as in fugure 4.


FIGURE 3 WIRE COUNTING GEOMETRY

A: Copper Wire

B: G-M Tube

C: Lead Shield

D: Scalar

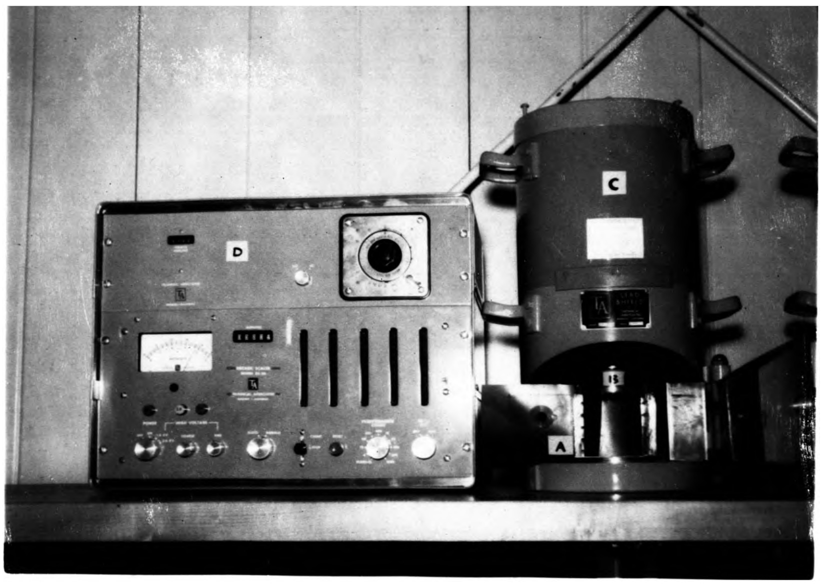


FIGURE 4 FOIL COUNTING GEOMETRY

A: Gold Foil, Shelf, and Counting Stand

B: Scintillation Tube

C: Lead Shield

D: Scalar

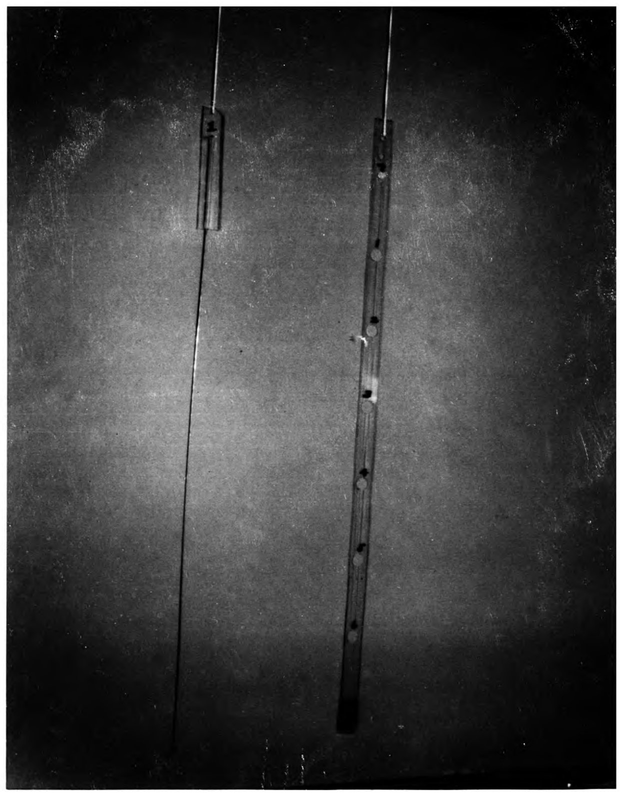

FIGURE 5  FOIL AND WIRE HOLDERS

The same procedure was used for the 19T core arrangement where the reactor is moved against the thermal column, The data together with the correction can be found on Tables I and IV.

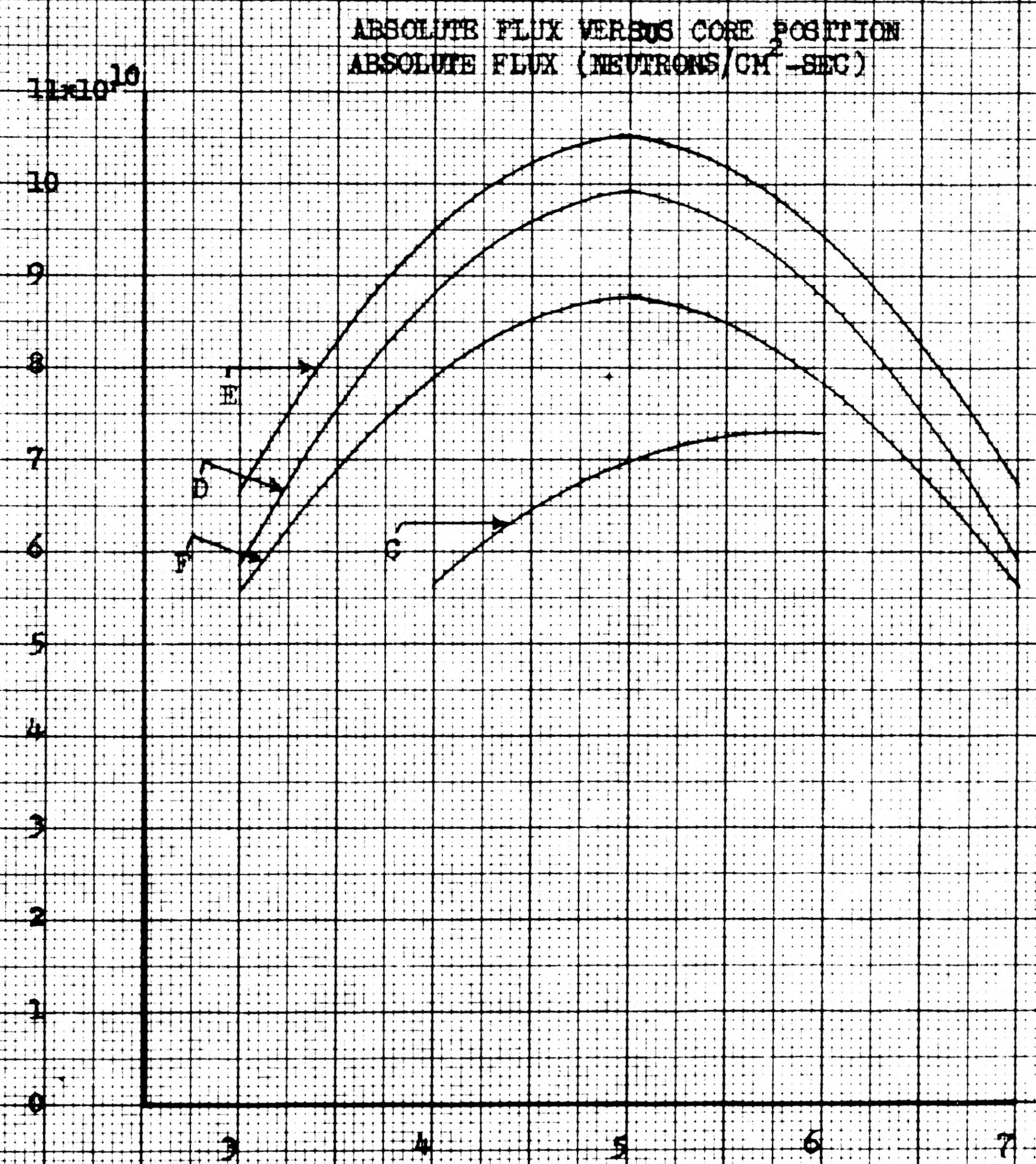


FIGURE 6 FLUX DISTRIBUTION OF THE CORE FOR 19W

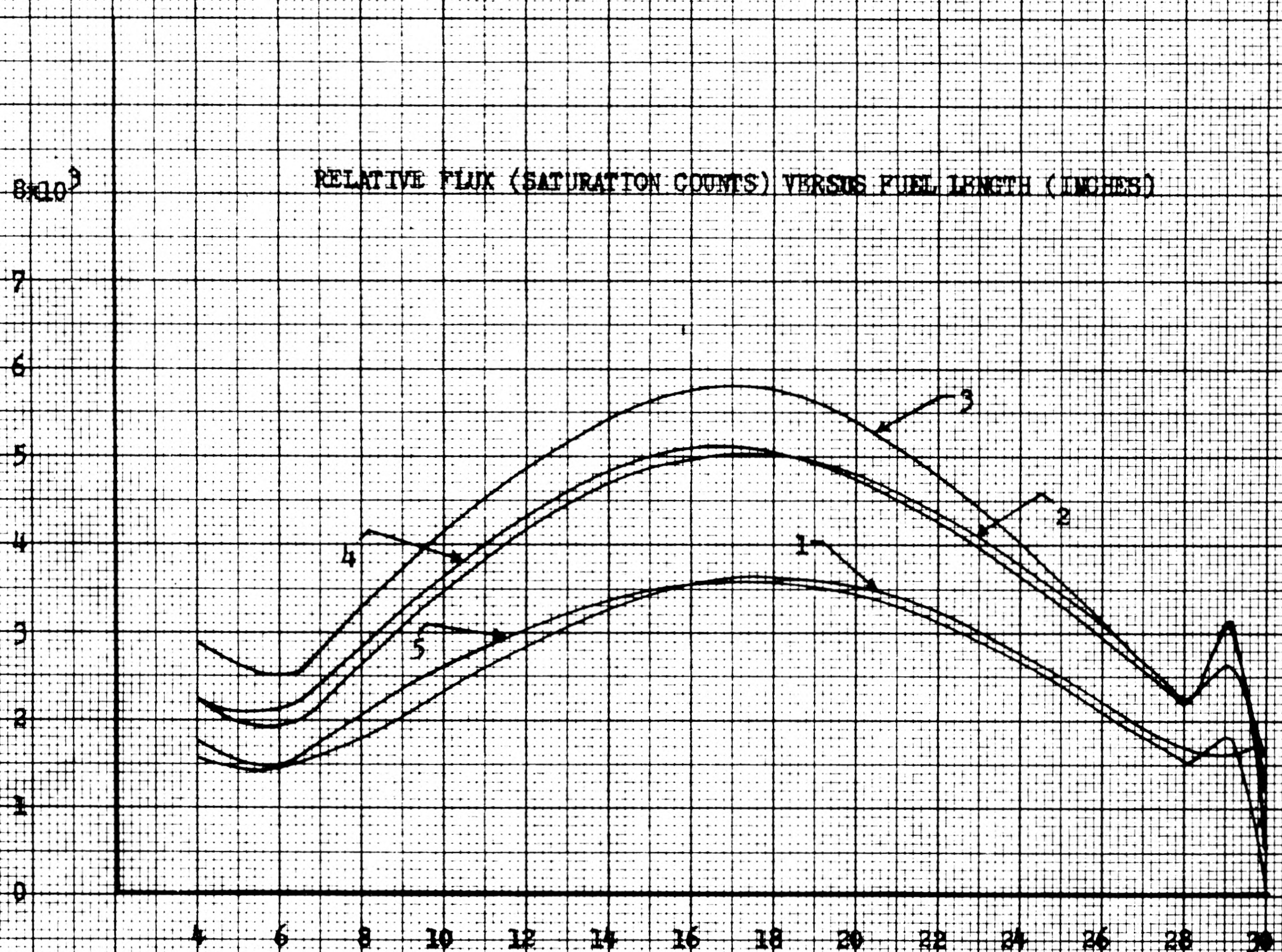


FIGURE 6a FLUX DISTRIBUTION OF FUEL IN ROW F FOR 15W

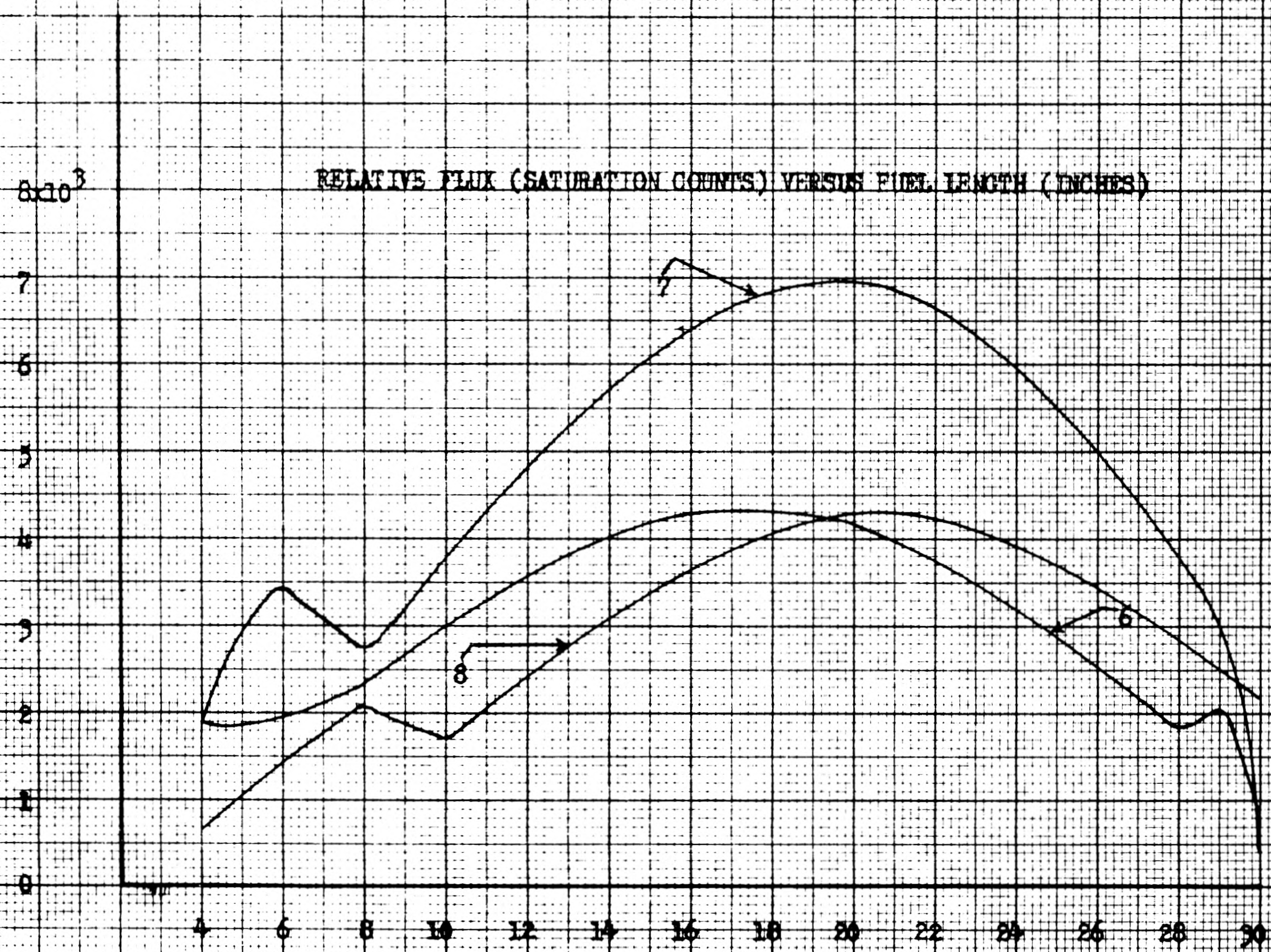


FIGURE 6b FLUX DISTRIBUTION OF FUEL IN ROW E FOR 19W

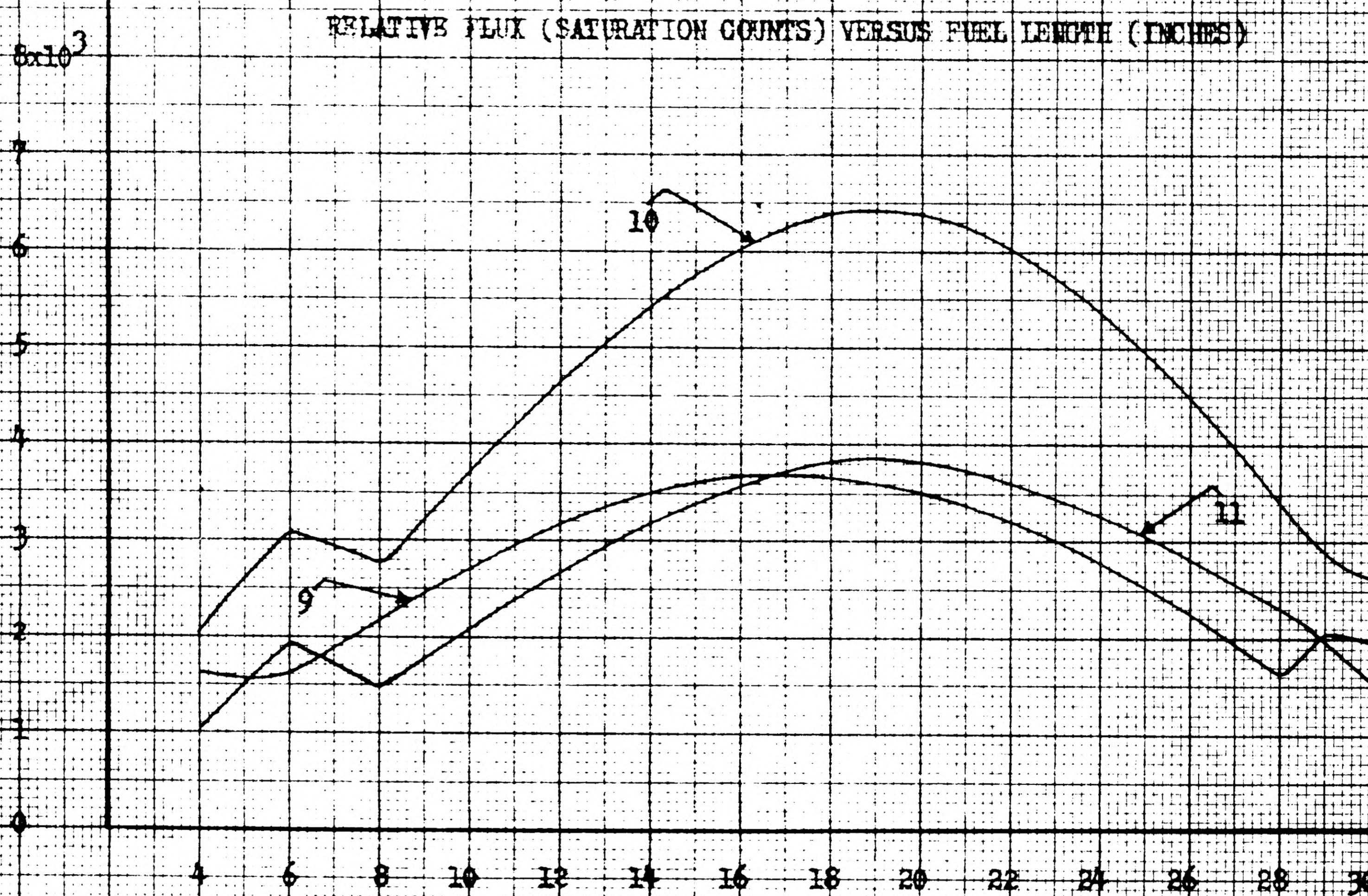


FIGURE 6c FLUX DISTRIBUTION OF FUEL IN ROW D FOR 19W

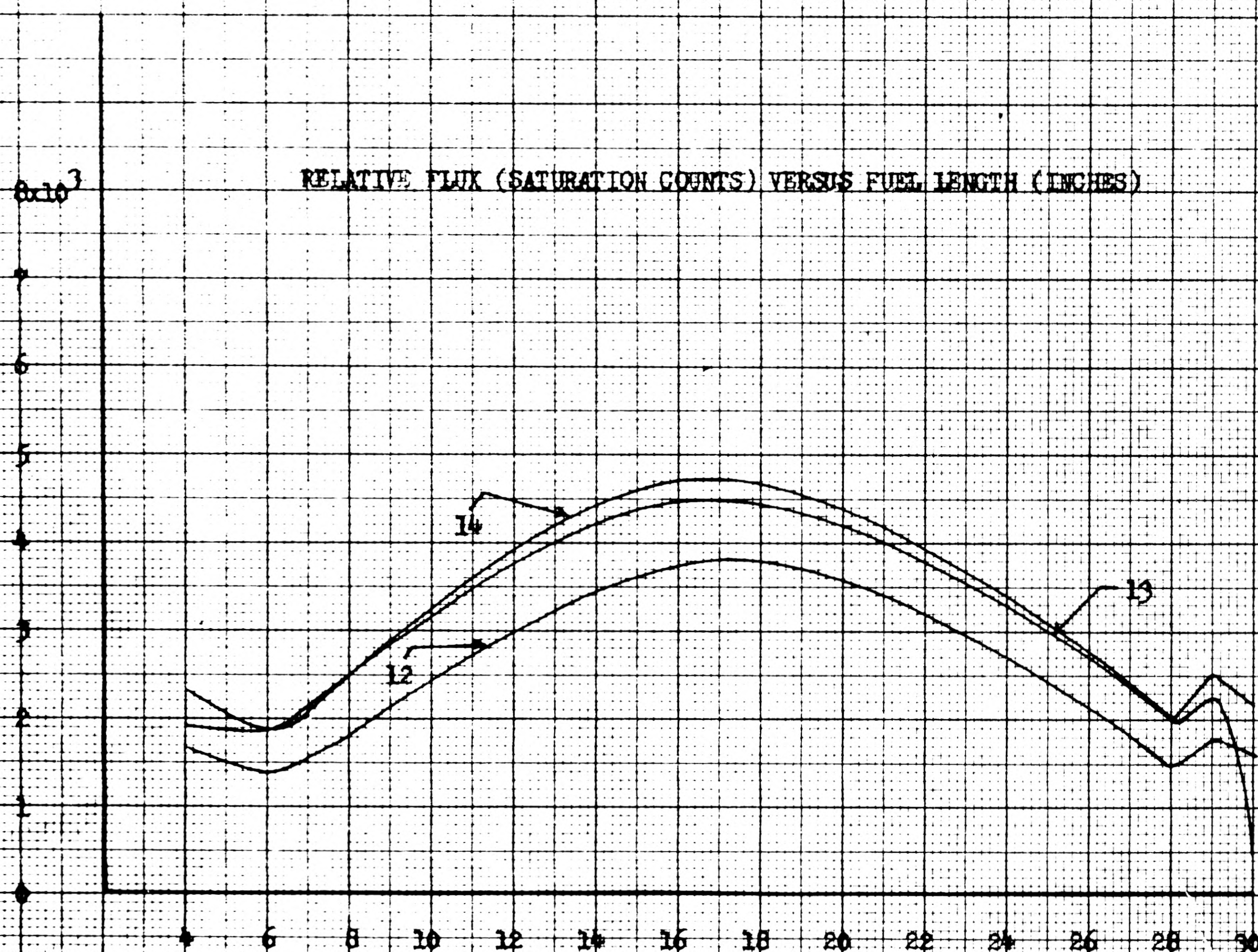


FIGURE 6d FLUX DISTRIBUTION OF FUEL IN ROW C FOR 19W

## TABLE I WIRE ACTIVATION FOR 19W

General Information :

Irradiation date : May 5, 1962

Reactor power : 10 kilowatts

Critical time : 10:30 A.M.

Level time : 10:41 A.M.

Period of the reactor : 70 seconds

Scram time : 11:01 A.M.

Irradiation time : 20 minutes

Wire No. 1

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 1261 | 5 hr. 13 min. | .7555 | 1669 |
| 29 | 1567 | " 14 " | .7548 | 2077 |
| 28 | 1287 | " 16 " | .7535 | 1708 |
| 26 | 1710 | " 17 " | .7528 | 2272 |
| 24 | 2092 | " 18 " | .7521 | 2782 |
| 22 | 2292 | " 19 " | .7514 | 3050 |
| 20 | 2648 | " 20 " | .7508 | 3527 |
| 18 | 2736 | " 21 " | .7500 | 3648 |
| 16 | 2657 | " 22 " | .7494 | 3546 |
| 14 | 2461 | " 23 " | .7487 | 3287 |
| 12 | 2157 | " 24 " | .7480 | 2884 |
| 10 | 1803 | " 25 " | .7473 | 2413 |
| 8 | 1327 | " 27 " | .7459 | 1779 |
| 6 | 1079 | " 28 " | .7453 | 1448 |
| 4 | 1146 | " 32 " | .7426 | 1543 |
| Average | | | | 2799 |

Wire No. 2

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 1368 | 3 hr. 4 min. | .8481 | 1613 |
| 29 | 2291 | " 6 " | .8466 | 2707 |
| 28 | 1907 | " 7 " | .8458 | 2254 |
| 26 | 2562 | " 9 " | .8443 | 3034 |
| 24 | 3222 | " 10 " | .8435 | 3820 |
| 22 | 3769 | " 11 " | .8428 | 4473 |
| 20 | 3981 | " 12 " | .8420 | 4728 |
| 18 | 4192 | " 13 " | .8413 | 4984 |
| 16 | 4201 | " 15 " | .8397 | 5004 |
| 14 | 4093 | " 17 " | .8382 | 4884 |
| 12 | 3538 | " 18 " | .8374 | 4225 |
| 10 | 2881 | " 19 " | .8367 | 3443 |
| 8 | 2272 | " 20 " | .8359 | 2718 |
| 6 | 1561 | " 21 " | .8352 | 1869 |
| 4 | 1845 | " 22 " | .8344 | 2211 |
| Average | | | | 3947 |

Wire No. 3

| | | | | |
|---|---|---|---|---|
| 30 | 476 | 2 hr. 46 min. | .8618 | 552 |
| 29 | 2678 | " 47 " | .8611 | 3110 |
| 28 | 1923 | " 49 " | .8595 | 2237 |
| 26 | 2690 | " 50 " | .8588 | 3132 |
| 24 | 3439 | " 51 " | .8580 | 4008 |
| 22 | 3989 | " 52 " | .8572 | 4653 |
| 20 | 4577 | " 53 " | .8565 | 5344 |

Wire No. 3

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 18 | 4839 | 2 hr. 54 min. | .8557 | 5655 |
| 16 | 4733 | " 56 " | .8542 | 5541 |
| 14 | 4697 | " 57 " | .8534 | 5503 |
| 12 | 4145 | " 58 " | .8527 | 4862 |
| 10 | 3589 | " 59 " | .8519 | 4212 |
| 8 | 2785 | 3 hr. | .8512 | 3272 |
| 6 | 2080 | 1 min. | .8504 | 2445 |
| 4 | 2460 | 2 " | .8496 | 2895 |
| Average | | | | 4415 |

Wire No. 4

| | | | | |
|---|---|---|---|---|
| 30 | 1165 | 45 " | .9604 | 1213 |
| 29 | 2497 | 47 " | .9587 | 2604 |
| 28 | 2160 | 46 " | .9596 | 2251 |
| 26 | 2844 | 48 " | .9579 | 2969 |
| 24 | 3558 | 49 " | .9570 | 3718 |
| 22 | 3947 | 50 " | .9562 | 4128 |
| 20 | 4357 | 51 " | .9553 | 4560 |
| 18 | 4759 | 52 " | .9545 | 4986 |
| 16 | 5001 | 53 " | .9536 | 5244 |
| 14 | 4527 | 54 " | .9528 | 4751 |
| 12 | 4181 | 56 " | .9511 | 4395 |
| 10 | 3554 | 58 " | .9494 | 3743 |
| 8 | 2656 | 59 " | .9485 | 2800 |

Wire No. 4

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 6 | 1124 | 22 hr. 13 min. | .3031 | 3708 |
| 4 | 1012 | " 14 " | .3029 | 3341 |
| Average | | | | 6721 |

Wire No. 5

| | | | | |
|---|---|---|---|---|
| 30 | 266 | 2 hr. 30 min. | .8740 | 304 |
| 29 | 2523 | " 31 " | .8733 | 2890 |
| 28 | 3162 | " 32 " | .8725 | 3624 |
| 26 | 3995 | " 33 " | .8717 | 4583 |
| 24 | 4584 | " 35 " | .8702 | 5268 |
| 22 | 4920 | " 36 " | .8694 | 5659 |
| 20 | 5047 | " 37 " | .8687 | 5810 |
| 18 | 4775 | " 37 " | .8671 | 5506 |
| 16 | 4728 | " 40 " | .8664 | 5457 |
| 14 | 4061 | " 41 " | .8656 | 4691 |
| 12 | 3177 | " 42 " | .8649 | 3674 |
| 10 | 2530 | " 43 " | .8641 | 2928 |
| 8 | 1659 | " 45 " | .8626 | 1924 |
| 6 | 2496 | " 46 " | .8618 | 2897 |
| 4 | 1549 | " 47 " | .8610 | 1800 |
| Average | | | | 4393 |

Wire No. 6

| | | | | |
|---|---|---|---|---|
| 30 | 1898 | 5 hr. 18 min. | .7521 | 2524 |
| 29 | 2951 | " 19 " | .7513 | 3928 |
| 28 | 3590 | " 20 " | .7508 | 4782 |

Wire No. 6

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 24 | 2830 | 10 min. | .8901 | 3179 |
| 22 | 3322 | 11 " | .8893 | 3736 |
| 20 | 3557 | 13 " | .8877 | 4008 |
| 18 | 3658 | 14 " | .8869 | 4125 |
| 16 | 3793 | 15 " | .8861 | 4281 |
| 14 | 3492 | 16 " | .8853 | 3945 |
| 12 | 3180 | 17 " | .8845 | 3599 |
| 10 | 2706 | 19 " | .8829 | 3065 |
| 8 | 1959 | 20 " | .8821 | 2221 |
| 6 | 1712 | 21 " | .8813 | 1943 |
| 4 | 1644 | 22 " | .8804 | 1867 |
| Average | | | | 3337 |

Wire No. 7

| | | | | |
|---|---|---|---|---|
| 30 | 332 | 3 hr. 24 min. | .8329 | 398 |
| 29 | 2776 | " 25 " | .8321 | 3336 |
| 28 | 3327 | " 27 " | .8306 | 4006 |
| 26 | 4325 | " 28 " | .8298 | 5212 |
| 24 | 4936 | " 29 " | .8290 | 5954 |
| 22 | 5482 | " 30 " | .8283 | 6619 |
| 20 | 5788 | " 31 " | .8276 | 6994 |
| 18 | 5622 | " 32 " | .8268 | 6800 |
| 16 | 5289 | " 34 " | .8254 | 6408 |
| 14 | 4886 | " 35 " | .8247 | 5925 |

Wire No. 7

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 12 | 4041 | 3 hr. 36 min. | .8240 | 4905 |
| 10 | 3083 | " 37 " | .8232 | 3745 |
| 8 | 2242 | " 39 " | .8218 | 2728 |
| 6 | 2801 | " 40 " | .8211 | 3418 |
| 4 | 1475 | " 41 " | .8203 | 1798 |
| Average | | | | 5288 |

Wire No. 8

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 2123 | 25 min. | .9776 | 2172 |
| 29 | | | | |
| 28 | 2932 | 26 " | .9767 | 3002 |
| 26 | 3311 | 28 " | .9749 | 3396 |
| 24 | 3737 | 29 " | .9740 | 3837 |
| 22 | 4144 | 30 " | .9731 | 4259 |
| 20 | 3986 | 31 " | .9723 | 4100 |
| 18 | 3925 | 32 " | .9714 | 4041 |
| 16 | 3576 | 34 " | .9698 | 3688 |
| 14 | 3002 | 35 " | .9689 | 3098 |
| 12 | 2435 | 36 " | .9681 | 2516 |
| 10 | 1641 | 37 " | .9672 | 1696 |
| 8 | 2002 | 38 " | .9664 | 2072 |
| 6 | 1443 | 39 " | .9655 | 1494 |
| 4 | 627 | 41 " | .9638 | 650 |
| Average | | | | 3390 |

Wire No. 9

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 1523 | 4 hr. 52 min. | .7699 | 1978 |
| 29 | 1595 | " 53 " | .7692 | 2073 |
| 28 | 1248 | " 55 " | .7678 | 1625 |
| 26 | 1763 | " 56 " | .7672 | 2298 |
| 24 | 2145 | " 57 " | .7665 | 2798 |
| 22 | 2485 | " 58 " | .7658 | 3245 |
| 20 | 2530 | " 59 " | .7651 | 3307 |
| 18 | 2793 | 5 hr. 1 min. | .7637 | 3658 |
| 16 | 2835 | " 2 " | .7630 | 3716 |
| 14 | 2708 | " 3 " | .7624 | 3552 |
| 12 | 2456 | " 5 " | .7610 | 3227 |
| 10 | 2102 | " 6 " | .7603 | 2764 |
| 8 | 1699 | " 7 " | .7596 | 2237 |
| 6 | 1186 | " 8 " | .7589 | 1562 |
| 4 | 1219 | " 10 " | .7576 | 1609 |
| Average | | | | 2948 |

Wire No. 10

| | | | | |
|---|---|---|---|---|
| 30 | 2289 | 2 hr. 24 min. | .8788 | 2605 |
| 29 | 2446 | " 25 " | .8780 | 3421 |
| 28 | 2889 | " 26 " | .8772 | 3293 |
| 26 | 4076 | " 28 " | .8756 | 4655 |
| 24 | 4660 | " 33 " | .8717 | 5345 |
| 22 | 5220 | " 34 " | .8710 | 5993 |

Wire No. 10

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 20 | 5585 | 2 hr. 35 min. | .8702 | 6401 |
| 18 | 5643 | " 36 " | .8694 | 6490 |
| 16 | 5263 | " 37 " | .8687 | 6058 |
| 14 | 4643 | " 38 " | .8679 | 5350 |
| 12 | 4070 | " 40 " | .8664 | 4698 |
| 10 | 3356 | " 41 " | .8656 | 3877 |
| 8 | 2369 | " 42 " | .8649 | 2740 |
| 6 | 2668 | " 43 " | .8641 | 3087 |
| 4 | 1773 | " 44 " | .8634 | 2053 |
| Average | | | | 4989 |

Wire No. 11

| | | | | |
|---|---|---|---|---|
| 30 | 1440 | 1 hr. 6 min. | .9426 | 1528 |
| 29 | 1792 | " 8 " | .9409 | 1905 |
| 28 | 2152 | " 9 " | .9401 | 2289 |
| 26 | 2687 | " 10 " | .9392 | 2861 |
| 24 | 3213 | " 11 " | .9384 | 3424 |
| 22 | 3342 | " 12 " | .9375 | 3565 |
| 20 | 3591 | " 13 " | .9367 | 3834 |
| 18 | 3551 | " 14 " | .9358 | 3795 |
| 16 | 3349 | " 16 " | .9341 | 3585 |
| 14 | 3003 | " 17 " | .9333 | 3218 |
| 12 | 2519 | " 18 " | .9324 | 2702 |
| 10 | 1883 | " 19 " | .9316 | 2021 |

Wire No. 11

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 8 | 1376 | 1 hr. 20 min. | .9308 | 1479 |
| 6 | 1820 | " 21 " | .9299 | 1957 |
| 4 | 950 | " 23 " | .9282 | 1023 |
| Average | | | | 2967 |

Wire No. 12

| | | | | |
|---|---|---|---|---|
| 30 | 1224 | 5 hr. 35 min. | .7407 | 1652 |
| 29 | 1345 | " 36 " | .7400 | 1816 |
| 28 | 1104 | " 38 " | .7387 | 1494 |
| 26 | 1416 | " 40 " | .7374 | 1920 |
| 24 | 2077 | " 41 " | .7368 | 2819 |
| 22 | 2306 | " 42 " | .7361 | 3132 |
| 20 | 2478 | " 43 " | .7355 | 3369 |
| 18 | 2800 | " 45 " | .7342 | 3814 |
| 16 | 2671 | " 46 " | .7335 | 3641 |
| 14 | 2577 | " 47 " | .7329 | 3517 |
| 12 | 2213 | " 48 " | .7322 | 3022 |
| 10 | 1828 | " 49 " | .7316 | 2498 |
| 8 | 1344 | " 50 " | .7309 | 1838 |
| 6 | 1014 | " 51 " | .7303 | 1388 |
| 4 | 1249 | " 52 " | .7296 | 1712 |
| Average | | | | 2822 |

Wire No. 13

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 1976 | 1 hr. 27 min. | .9248 | 2137 |
| 29 | 2319 | " 28 " | .9239 | 2510 |
| 28 | 1892 | " 29 " | .9231 | 2050 |
| 26 | 2431 | " 30 " | .9222 | 2636 |
| 24 | 3095 | " 32 " | .9207 | 3362 |
| 22 | 3553 | " 33 " | .9198 | 3863 |
| 20 | 3857 | " 34 " | .9190 | 4198 |
| 18 | 4082 | " 35 " | .9182 | 4446 |
| 16 | 4188 | " 36 " | .9174 | 4565 |
| 14 | 3939 | " 37 " | .9166 | 4297 |
| 12 | 3502 | " 38 " | .9158 | 3824 |
| 10 | 2871 | " 40 " | .9142 | 3140 |
| 8 | 2275 | " 41 " | .9134 | 2491 |
| 6 | 1709 | " 42 " | .9126 | 1872 |
| 4 | 2112 | " 43 " | .9118 | 2342 |
| Average | | | | 3529 |

Wire No. 14

| | | | | |
|---|---|---|---|---|
| 30 | 158 | 1 hr. 45 min. | .9102 | 173 |
| 29 | 2071 | " 46 " | .9094 | 2277 |
| 28 | 1814 | " 47 " | .9086 | 1996 |
| 26 | 2574 | " 50 " | .9062 | 2840 |
| 24 | 3209 | " 51 " | .9054 | 3544 |
| 22 | 3471 | " 52 " | .9046 | 3837 |
| 20 | 3920 | " 54 " | .9030 | 4341 |

Wire No. 14

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 18 | 4183 | 1 hr. 55 min. | .9022 | 4637 |
| 16 | 4267 | " 56 " | .9014 | 4734 |
| 14 | 3938 | " 57 " | .9006 | 4373 |
| 12 | 3653 | " 58 " | .8998 | 4060 |
| 10 | 3070 | 2 hr. | .8981 | 3418 |
| 8 | 2225 | " 1 min. | .8973 | 2480 |
| 6 | 1678 | " 2 " | .8965 | 1871 |
| 4 | 1731 | " 3 " | .8957 | 1932 |
| Average | | | | 3662 |

# TABLE II GOLD FOIL ACTIVATION FOR 19W

A. Bare Gold Foils

General Information :

Irradiation date : May 25, 1962

Reactor power : 10 watts

Critical time : 10:51 A.M.

Level time : 10:55:30 A.M.

Period of the reactor : 47.5 seconds

Scram time : 11:05:30 A.M.

Irradiation time : 10 minutes

| Core Position | Vertical Position (inches) | Foil Mass (grams) | N(counts per 15 min.) | $t_2$ (decay time) | Saturation Counts |
|---|---|---|---|---|---|
| F-4 | 18 | .1082 | 134,141 | 3 days 16 min. | $6.115 \times 10^{10}$ |
| F-4 | 14 | .1084 | 127,988 | 3 days | $5.818 \times 10^{10}$ |
| F-6 | 18 | .1085 | 124,841 | 3 days 33 min. | $5.708 \times 10^{10}$ |
| F-6 | 14 | .1090 | 123,845 | 3 days 49 min. | $5.679 \times 10^{10}$ |

B. Cadmium Covered Gold Foils

General Information :

Irradiation date : May 25, 1962

Reactor power : 10 watts

Critical time : 1:38 P.M.

Level time : 1:43:20 P.M.

Period of the reactor : 53 seconds

Scram time : 1:53:20 P.M.

Irradiation time : 10 minutes

| Core Position | Vertical Position (inches) | Foil Mass (grams) | N(counts per 15 min.) | $t_2$ (decay time) | Saturation Counts |
|---|---|---|---|---|---|
| F-4 | 18 | .1082 | 85,888 | 5 hr. 2 min. | $1.867 \times 10^{10}$ |
| F-4 | 14 | .1084 | 78,873 | 2 hr. 28 min. | $1.704 \times 10^{10}$ |
| F-6 | 18 | .1085 | 83,217 | 1 hr. 53 min. | $1.787 \times 10^{10}$ |
| F-6 | 14 | .1090 | 85,942 | 2 hr. 46 min. | $1.863 \times 10^{10}$ |

TABLE III NATIONAL BUREAU OF STANDARDS GOLD FOILS

General Information :

Irradiation start : 9:55 A.M. EST, May 7, 1962

Irradiation end : 2:15 P.M. EST, May 14, 1962

Irradiation time : 7 days 4 hours and 20 minutes

Standard pile flux : $4.23 \times 10^3$ neutrons per $cm^2$ per second ( $\pm$ 1.5 per cent )

| Foil Mass (grams) | N(counts per 50 min.) | $t_2$ (decay time) | Saturation Counts |
|---|---|---|---|
| .1168 | 6,599 | 2 days 18 hr. 21 min. | $1.7972 \times 10^6$ |
| .1122 | 6,514 | 2 days 19 hr. 24 min. | $1.7941 \times 10^6$ |
| .1119 | 6,396 | 2 days 20 hr. 18 min. | $1.7786 \times 10^6$ |
| .1078 | 6,131 | 2 days 21 hr. 15 min. | $1.7222 \times 10^6$ |

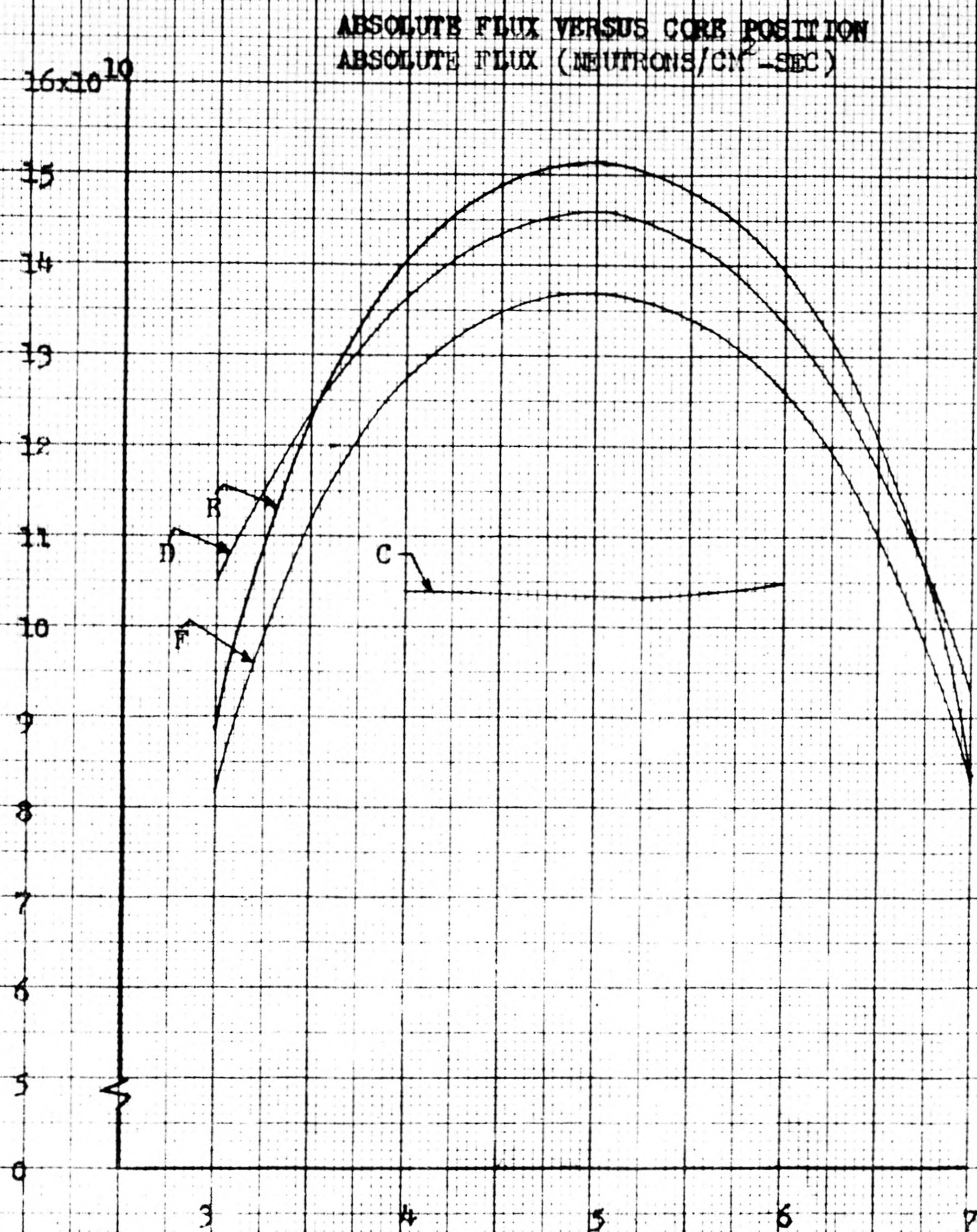


FIGURE 7 FLUX DISTRIBUTION OF THE CORE FOR 19T


FIGURE 7a FLUX DISTRIBUTION OF FUEL IN ROW F FOR 19T

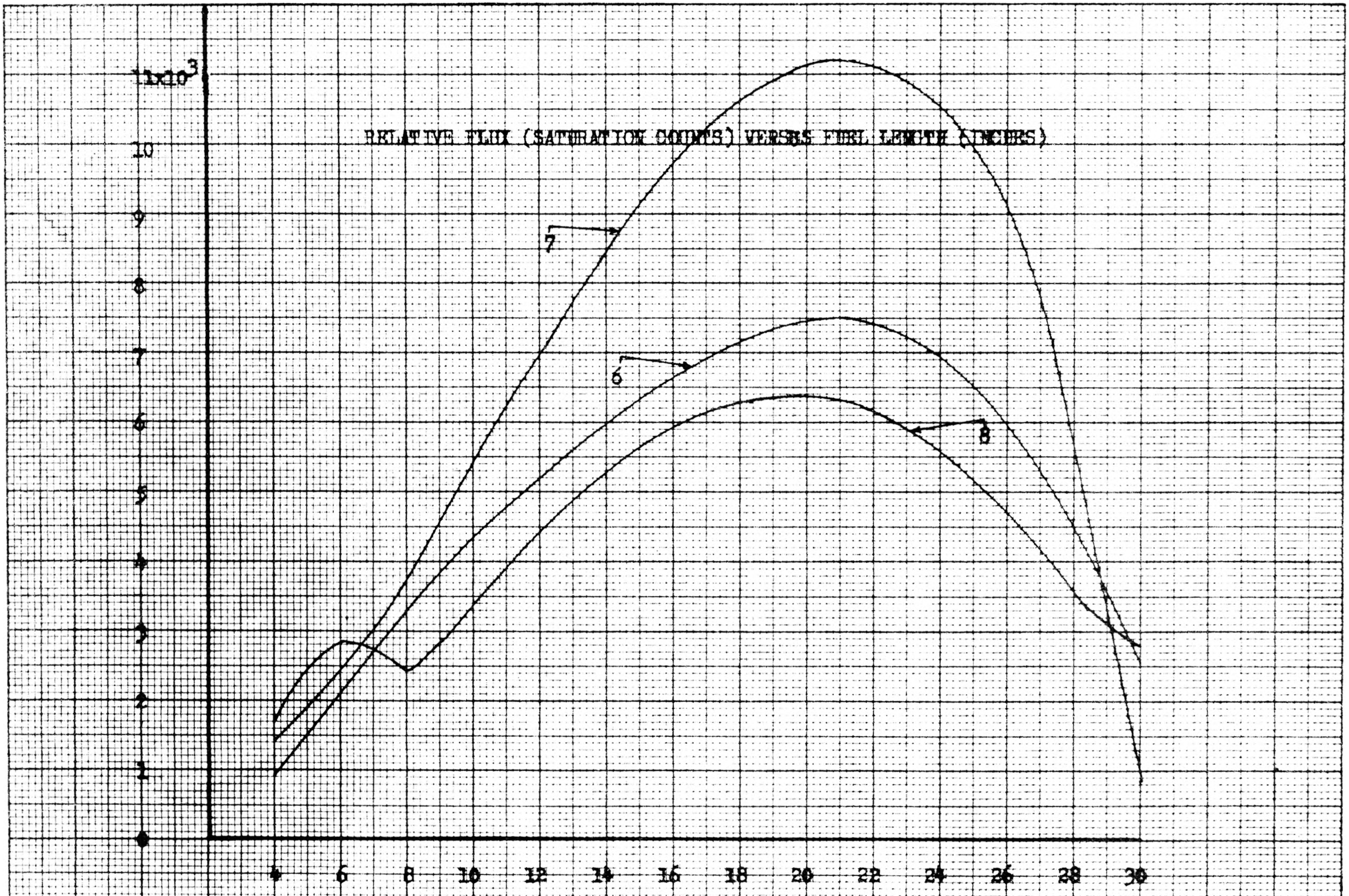


FIGURE 7b FLUX DISTRIBUTION OF FUEL IN ROW E FOR 19T

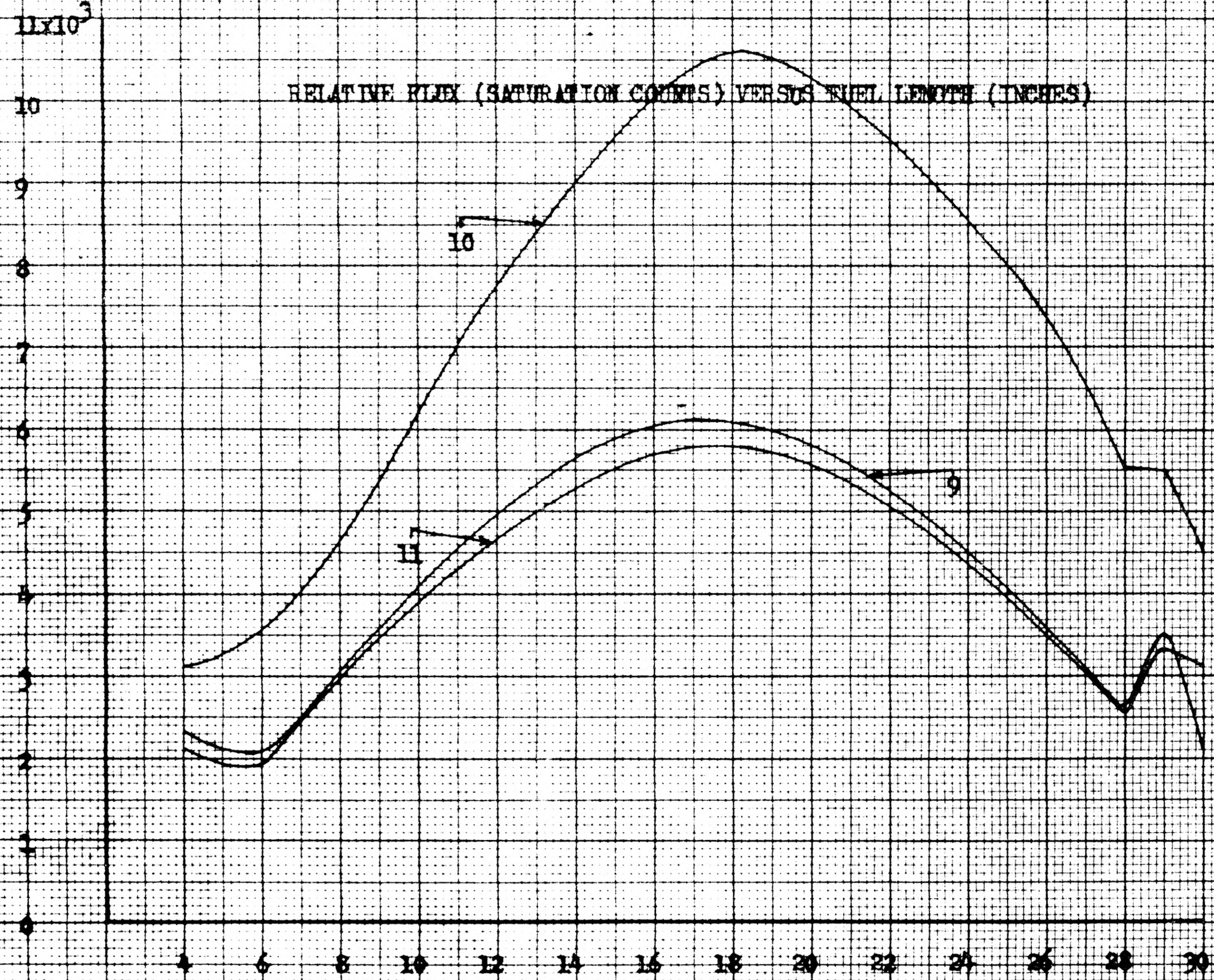


FIGURE 7c FLUX DISTRIBUTION OF FUEL IN ROW D FOR 19T

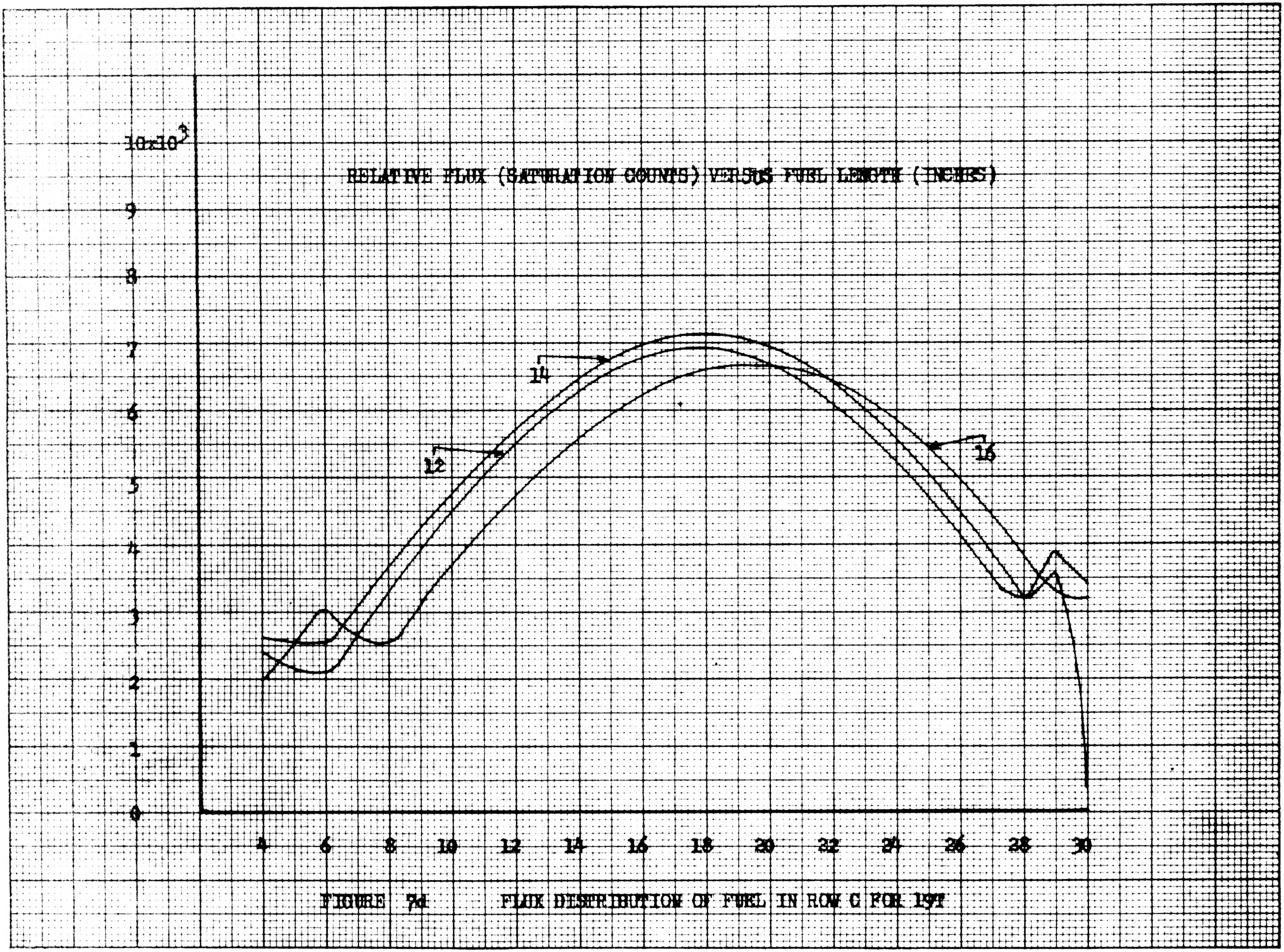


FIGURE 7d FLUX DISTRIBUTION OF FUEL IN ROW C FOR 1ST

TABLE IV WIRE ACTIVATION FOR 19T

General Information :

Irradiation date : May 22, 1962

Reactor power : 10 kilowatts

Critical time : 9:02 A.M.

Level time : 9:11:10 A.M.

Period of the reactor : 62 seconds

Scram time : 9:31:10 A.M.

Irradiation time : 20 minutes

Wire No. 1

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 1991 | 4 hr. 41 min. | .7774 | 2561 |
| 29 | 2680 | " 42 " | .7767 | 3450 |
| 28 | 2085 | " 43 " | .7761 | 2687 |
| 26 | 2762 | " 44 " | .7754 | 3562 |
| 24 | 3430 | " 45 " | .7747 | 4428 |
| 22 | 4025 | " 46 " | .7740 | 5200 |
| 20 | 4381 | " 48 " | .7726 | 5670 |
| 18 | 4226 | " 49 " | .7719 | 5475 |
| 16 | 3993 | " 51 " | .7706 | 5181 |
| 14 | 3863 | " 52 " | .7699 | 5018 |
| 12 | 3465 | " 53 " | .7692 | 4505 |
| 10 | 2739 | " 54 " | .7685 | 3564 |
| 8 | 2035 | " 55 " | .7678 | 2651 |
| 6 | 1473 | " 56 " | .7672 | 1921 |
| 4 | 1709 | " 57 " | .7665 | 2230 |
| Average | | | | 4324 |

Wire No. 2

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 393 | 22 hr. 21 min. | .3009 | 1306 |
| 29 | 1298 | " 23 " | .3004 | 4322 |
| 28 | 1622 | " 24 " | .3001 | 5404 |
| 26 | 2139 | " 25 " | .2998 | 7136 |
| 24 | 2444 | " 26 " | .2996 | 8157 |
| 22 | 2633 | " 27 " | .2993 | 8796 |
| 20 | 2690 | " 30 " | .2985 | 9012 |
| 18 | 2632 | " 31 " | .2982 | 8826 |
| 16 | 2435 | " 33 " | .2977 | 8179 |
| 14 | 2200 | " 35 " | .2972 | 7402 |
| 12 | 1634 | " 37 " | .2967 | 5507 |
| 10 | 1262 | " 38 " | .2964 | 4258 |
| 8 | 1218 | " 39 " | .2962 | 4112 |
| 6 | 874 | " 40 " | .2959 | 2954 |
| 4 | 417 | " 41 " | .2956 | 1411 |
| Average | | | | 6869 |

Wire No. 3

| | | | | |
|---|---|---|---|---|
| 30 | 346 | 2 hr. 11 min. | .8893 | 388 |
| 29 | 4786 | " 12 " | .8885 | 5386 |
| 28 | 5450 | " 13 " | .8877 | 6139 |
| 26 | 6816 | " 16 " | .8853 | 7699 |
| 24 | 7530 | " 17 " | .8845 | 8513 |
| 22 | 8007 | " 18 " | .8837 | 9061 |
| 20 | 8130 | " 19 " | .8829 | 9209 |

Wire No. 3

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 18 | 7689 | 2 hr. 20 min. | .8821 | 8717 |
| 16 | 7358 | " 21 " | .8813 | 8350 |
| 14 | 6585 | " 23 " | .8796 | 7486 |
| 12 | 4509 | " 24 " | .8788 | 5131 |
| 10 | 3741 | " 25 " | .8780 | 4261 |
| 8 | 3703 | " 26 " | .8772 | 4221 |
| 6 | 3078 | " 27 " | .8764 | 3512 |
| 4 | 1595 | " 28 " | .8756 | 1822 |
| Average | | | | 7267 |

Wire No. 4

| | | | | |
|---|---|---|---|---|
| 30 | 248 | 21 hr. 56 min. | .3078 | 806 |
| 29 | 1271 | " 57 " | .3075 | 4133 |
| 28 | 1229 | " 59 " | .3070 | 4003 |
| 26 | 1726 | 22 hr. | .3067 | 5628 |
| 24 | 2107 | " 1 min. | .3064 | 6877 |
| 22 | 2353 | " 2 " | .3062 | 7685 |
| 20 | 2624 | " 3 " | .3059 | 8578 |
| 18 | 2711 | " 5 " | .3053 | 8880 |
| 16 | 2610 | " 6 " | .3051 | 8555 |
| 14 | 2374 | " 9 " | .3042 | 7804 |
| 12 | 2138 | " 10 " | .3040 | 7033 |
| 10 | 1674 | " 11 " | .3037 | 5512 |
| 8 | 1172 | " 12 " | .3034 | 3863 |

Wire No. 4

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 6 | 1991 | 60 min. | 9477 | 2101 |
| 4 | 2057 | 62 " | .9460 | 2173 |
| Average. | | | | 3956 |

Wire No. 5

| | | | | |
|---|---|---|---|---|
| 30 | 59 | 0 | 1 | |
| 29 | 1842 | 1 min. | .9991 | 1843 |
| 28 | 1495 | 4 " | .9964 | 1500 |
| 26 | 2093 | 5 " | .9955 | 2102 |
| 24 | 2600 | 6 " | .9946 | 2613 |
| 22 | 3215 | 7 " | .9937 | 3235 |
| 20 | 3413 | 8 " | .9928 | 3438 |
| 18 | 3449 | 10 " | .9919 | 3480 |
| 16 | 3560 | 11 " | .9901 | 3596 |
| 14 | 3347 | 12 " | .9893 | 3383 |
| 12 | 3051 | 13 " | .9884 | 3087 |
| 10 | 2585 | 14 " | .9875 | 2617 |
| 8 | 2090 | 15 " | .9867 | 2118 |
| 6 | 1419 | 17 " | .9848 | 1440 |
| 4 | 1694 | 18 " | .9839 | 1721 |
| Average | | | | 2834 |

Wire No. 6

| | | | | |
|---|---|---|---|---|
| 30 | 652 | 2 hr. 5 min. | .8941 | 729 |
| 29 | 1839 | " 7 " | .8925 | 2060 |
| 28 | 1665 | " 8 " | .8917 | 1667 |
| 26 | 2327 | " 9 " | .8909 | 2612 |

Wire No. 6

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 26 | 4379 | 5 hr. 21 min. | .7500 | 5839 |
| 24 | 5208 | " 23 " | .7487 | 6956 |
| 22 | 5563 | " 26 " | .7466 | 7451 |
| 20 | 5570 | " 27 " | .7459 | 7467 |
| 18 | 5398 | " 28 " | .7453 | 7243 |
| 16 | 5109 | " 29 " | .7446 | 6861 |
| 14 | 4653 | " 30 " | .7439 | 6255 |
| 12 | 3584 | " 31 " | .7433 | 4822 |
| 10 | 2690 | " 32 " | .7426 | 3622 |
| 8 | 2241 | " 34 " | .7413 | 3023 |
| 6 | 1538 | " 35 " | .7407 | 2076 |
| 4 | 706 | " 36 " | .7387 | 954 |
| Average | | | | 5584 |

Wire No. 7

| | | | | |
|---|---|---|---|---|
| 30 | 711 | 3 hr. 19 min. | .8367 | 850 |
| 29 | 5200 | " 20 min. | .8359 | 6221 |
| 28 | 6013 | " 21 " | .8352 | 7199 |
| 26 | 7633 | " 22 " | .8344 | 9148 |
| 24 | 8266 | " 24 " | .8329 | 9924 |
| 22 | 9346 | " 25 " | .8321 | 11,232 |
| 20 | 9275 | " 26 " | .8314 | 11,156 |
| 18 | 8931 | " 27 " | .8306 | 10,752 |
| 16 | 8234 | " 28 " | .8298 | 9923 |
| 14 | 6893 | " 29 " | .8290 | 8315 |
| 12 | 5083 | " 30 " | .8283 | 6137 |

Wire No. 7

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 10 | 3085 | 3 hr. 32 min. | .8268 | 3731 |
| 8 | 3145 | " 33 " | .8260 | 3806 |
| 6 | 2348 | " 37 " | .8232 | 2852 |
| 4 | 1150 | " 38 " | .8225 | 1398 |
| Average | | | | 7767 |

Wire No. 8

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 2671 | 48 min. | .9579 | 2788 |
| 29 | 2978 | 49 " | .9570 | 3112 |
| 28 | 3436 | 50 " | .9562 | 3593 |
| 26 | 4541 | 52 " | .9545 | 4757 |
| 24 | 5174 | 53 " | .9536 | 5426 |
| 22 | 5884 | 54 " | .9528 | 6175 |
| 20 | 5987 | 55 " | .9519 | 6289 |
| 18 | 5898 | 56 " | .9511 | 6201 |
| 16 | 5876 | 58 " | .9494 | 6189 |
| 14 | 5142 | 59 " | .9485 | 5422 |
| 12 | 4267 | 1 hr. 00 " | .9477 | 4502 |
| 10 | 3301 | " 01 " | .9469 | 3485 |
| 8 | 2287 | " 02 " | .9460 | 2417 |
| 6 | 2698 | " 03 " | .9452 | 2854 |
| 4 | 1601 | " 06 " | .9426 | 1698 |
| Average | | | | 4972 |

Wire No. 9

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 2535 | 3 hr. 40 min. | .8211 | 3087 |
| 29 | 2733 | " 41 " | .8202 | 3332 |
| 28 | 2065 | " 42 " | .8195 | 2520 |
| 26 | 2925 | " 43 " | .8188 | 3572 |
| 24 | 3693 | " 45 " | .8173 | 4519 |
| 22 | 4431 | " 46 " | .8167 | 5425 |
| 20 | 4773 | " 47 " | .8160 | 5849 |
| 18 | 4975 | " 48 " | .8153 | 6102 |
| 16 | 4964 | " 50 " | .8138 | 6105 |
| 14 | 4714 | " 51 " | .8131 | 5798 |
| 12 | 4099 | " 52 " | .8124 | 5046 |
| 10 | 3193 | " 53 " | .8117 | 3934 |
| 8 | 2463 | " 55 " | .8102 | 3041 |
| 6 | 1527 | " 56 " | .8095 | 1887 |
| 4 | 1716 | " 57 " | .8088 | 2122 |
| Average | | | | 4691 |

Wire No. 10

| | | | | |
|---|---|---|---|---|
| 30 | 4584 | 0 min. | 1.0000 | 4584 |
| 29 | 5468 | 1 " | .9991 | 5472 |
| 28 | 5508 | 2 " | .9982 | 5518 |
| 26 | 7474 | 3 " | .9973 | 7494 |
| 24 | 8697 | 4 " | .9964 | 8728 |
| 22 | 9585 | 6 " | .9946 | 9637 |
| 20 | 10,299 | 7 " | .9937 | 10,364 |

Wire No. 10

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 18 | 10594 | 8 min. | .9928 | 10671 |
| 16 | 9312 | 9 " | .9919 | 9388 |
| 14 | 8938 | 11 " | .9893 | 9027 |
| 12 | 7682 | 12 " | .9893 | 7765 |
| 10 | 6273 | 13 " | .9884 | 6347 |
| 8 | 4368 | 14 " | .9875 | 4423 |
| 6 | 3629 | 15 " | .9867 | 3678 |
| 4 | 3104 | 18 " | .9839 | 3155 |
| Average | | | | 8048 |

Wire No. 11

| | | | | |
|---|---|---|---|---|
| 30 | 1816 | 1 hr. 52 min. | .9046 | 2008 |
| 29 | 3207 | " 53 " | .9038 | 3548 |
| 28 | 2432 | " 54 " | .9030 | 2694 |
| 26 | 3175 | " 55 " | .9022 | 3519 |
| 24 | 3879 | " 56 " | .9014 | 4303 |
| 22 | 4453 | " 58 " | .8998 | 4949 |
| 20 | 4850 | " 59 " | .8990 | 5406 |
| 18 | 5253 | 2 hr. | .8981 | 5849 |
| 16 | 5062 | " 1 min. | .8973 | 5641 |
| 14 | 4665 | " 2 " | .8965 | 5204 |
| 12 | 4165 | " 4 " | .8949 | 4654 |
| 10 | 3414 | " 5 " | .8941 | 3819 |
| 8 | 2647 | " 6 " | .8933 | 2964 |

Wire No. 11

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|---|
| 6 | 1821 | 1 hr. | 7 min. | .8925 | 2040 |
| 4 | 2117 | " | 9 " | .8909 | 2376 |
| Average | | | | | 4425 |

Wire No. 12

| | | | | | |
|---|---|---|---|---|---|
| 30 | 2598 | 5 hr. | | .7644 | 3399 |
| 29 | 2936 | " | 1 min. | .7637 | 3845 |
| 28 | 2406 | " | 2 " | .7630 | 3153 |
| 26 | 3127 | " | 3 " | .7624 | 4102 |
| 24 | 4071 | " | 5 " | .7610 | 5350 |
| 22 | 4629 | " | 6 " | .7603 | 6088 |
| 20 | 5034 | " | 7 " | .7596 | 6627 |
| 18 | 5177 | " | 8 " | .7589 | 6822 |
| 16 | 5211 | " | 9 " | .7582 | 6873 |
| 14 | 4605 | " | 10 " | .7576 | 6078 |
| 12 | 4142 | " | 12 " | .7562 | 5478 |
| 10 | 3293 | " | 13 " | .7555 | 4360 |
| 8 | 2325 | " | 14 " | .7548 | 3080 |
| 6 | 1565 | " | 15 " | .7541 | 2075 |
| 4 | 1805 | " | 17 " | .7528 | 2398 |
| Average | | | | | 5226 |

Wire No. 14

| | | | | | |
|---|---|---|---|---|---|
| 30 | 293 | 2 hr. | 49 min. | .8595 | 340 |
| 29 | 3046 | " | 50 " | .8587 | 3547 |

Wire No. 14

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 28 | 2750 | 2 hr. 51 min. | .8580 | 3205 |
| 26 | 3797 | " 52 " | .8572 | 4430 |
| 24 | 4853 | " 54 " | .8557 | 5671 |
| 22 | 5480 | " 55 " | .8549 | 6410 |
| 20 | 5980 | " 56 " | .8542 | 7001 |
| 18 | 6011 | " 57 " | .8534 | 7043 |
| 16 | 5950 | " 58 " | .8527 | 6978 |
| 14 | 5461 | " 59 " | .8519 | 6411 |
| 12 | 5028 | 3 hr. 1 min. | .8504 | 5913 |
| 10 | 4122 | " 2 min. | .8496 | 4852 |
| 8 | 3109 | " 3 " | .8488 | 3663 |
| 6 | 2140 | " 5 " | .8473 | 2526 |
| 4 | 2230 | " 6 " | .8466 | 2635 |
| Average | | | | 5569 |

Wire No. 16

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 30 | 2935 | 1 hr. 11 min. | .9384 | 3128 |
| 29 | 3086 | " 12 " | .9375 | 3292 |
| 28 | 3595 | " 13 " | .9367 | 3838 |
| 26 | 4704 | " 15 " | .9350 | 5031 |
| 24 | 5631 | " 16 " | .9341 | 6028 |
| 22 | 6043 | " 18 " | .9324 | 6481 |
| 20 | 6175 | " 19 " | .9316 | 6628 |
| 18 | 5939 | " 20 " | .9308 | 6381 |
| 16 | 5617 | " 21 " | .9299 | 6041 |

Wire No. 16

| Position (inches) | N(counts per min.) | $t_2$ (decay time) | $e^{-\lambda t_2}$ | $\frac{N}{e^{-\lambda t_2}}$ |
|---|---|---|---|---|
| 14 | 5252 | 1 hr. 22 min. | .9291 | 5653 |
| 12 | 4466 | " 23 " | .9282 | 4811 |
| 10 | 3437 | " 25 " | .9265 | 3709 |
| 8 | 2301 | " 26 " | .9257 | 2485 |
| 6 | 2821 | " 27 " | .9248 | 3050 |
| 4 | 1787 | " 28 " | .9239 | 1934 |
| Average | | | | 5292 |

# TABLE V GOLD FOIL ACTIVATION FOR 19T

A. Bare Gold Foils

General Information :

Irradiation date : May 25, 1962

Reactor power : 10 watts

Critical time : 9:30 A.M.

Level time : 9:34:30 A.M.

Period of the reactor : 48 seconds

Scram time : 9:44:30 A.M.

Irradiation time : 10 minutes

| Core Position | Vertical Position (inches) | Foil Mass (grams) | N(counts per 15 min.) | $t_2$ (decay time) | Saturation Counts |
|---|---|---|---|---|---|
| F-4 | 18 | .1088 | 153,626 | 3 days 30 min. | $7.021 \times 10^{10}$ |
| F-4 | 14 | .1142 | 153,217 | 3 days 13 min. | $6.981 \times 10^{10}$ |
| F-6 | 18 | .1144 | 162,538 | 3 days 46 min. | $7.449 \times 10^{10}$ |
| F-6 | 14 | .1144 | 148,563 | 3 days 63 min. | $6.829 \times 10^{10}$ |

B. Cadmium Covered Gold Foils

General Information :

Irradiation date : May 25, 1962

Reactor power : 10 watts

Critical time : 10:09 A.M.

Level time : 10:12:40 A.M.

Period of the reactor : 57.5 seconds

Scram time : 10:22:40 A.M.

Irradiation time : 10 minutes

| Core Position | Vertical Position (inches) | Foil Mass (grams) | N(counts per 15 min.) | $t_2$ (decay time) | Saturation Counts |
|---|---|---|---|---|---|
| F-4 | 18 | .1088 | 25,495 | 5 hr. 5 min. | $5.664 \times 10^9$ |
| F-4 | 14 | .1142 | 30,558 | 4 hr. 54 min. | $6.776 \times 10^9$ |
| F-6 | 18 | .1144 | 27,151 | 3 hr. 57 min. | $5.959 \times 10^9$ |
| F-6 | 14 | .1144 | 25,946 | 4 hr. 24 min. | $5.722 \times 10^9$ |

# IV CONCLUSIONS

From the results of this investigation, the flux of the reactor at 10 kilowatt lies between $7.24 \times 10^{10}$ and $7.87 \times 10^{10} \frac{\text{neutrons}}{\text{cm}^2 \text{ sec}}$ for 19W arrangement, and for 19T, the flux lies between $10.71 \times 10^{10}$ and $11.89 \times 10^{10} \frac{\text{neutrons}}{\text{cm}^2 \text{ sec}}$. This discrepancy of the average flux for the two core geometries is understandable since the power level calibration is true for only one arrangement. In the calculation for the average flux, the flux contribution of fuel elements at D-4, E-4, E-6, and D-6 were neglected. Due to the flux depressions by the control rods, the inclusion of the flux contribution from the above fuel elements would lower the average flux of the 19T arrangements. The effect of the 19T geometry to the compensated ionization chamber is uncertain. In this geometry the proximity of the chamber to the thermal column and wall apparently produced a net effect of smaller ionization current.

The appearance of the two water wings, grouped about 6 inches and 28 inches, shows the effect of water as the neutron reflector. The less pronounced wing is at 6 inches; this is due to the absorption of neutrons by the wire holder. It is apparent the fuel plates are approximately 22 inches long, the distance between the water wings. This is verified by the x-ray photographs of the fuel elements.

All the flux distributions closely approximate cosine curves. Noting this and the core symmetry, it is possible to map the flux distribution by locating 15 inch wires at strategic positions. The result is less accurate but the saving of labor and time may justify this approach.

It is found that the largest uncertainty is the positioning of the wires inside the fuel elements. Due to the difficulties in maneuverability and visibility, it is extremely difficult to place wires at the identical position in each fuel element. However, this problem is not a hindrance if average flux of the core is needed. To overcome the lengthy procedure of counting and data processing, a system of automatic counting which feeds the data into the computer is needed. The automatic counting set-up can be devised with the aid of gears, drums and timers. The scalar output and the wire position are fed into the computer simultaneously to determine the flux and its position in the core. This information can be graphically plotted by a recorder and the average power of the reactor can be acquired. A very sophisticated wire activation set-up is discussed by Kompanek and Tarnuzzer (20).

The pure copper wire activation is practicable for thermal neutron flux between $10^8 \frac{\text{neutrons}}{\text{cm}^2\ \text{sec}}$ to $10^{12} \frac{\text{neutrons}}{\text{cm}^2\ \text{sec}}$. For lower neutron flux, the radioactivity induced would give poor counting statistic for reasonable counting time.

For higher thermal neutron flux, $10^{12} \frac{\text{neutrons}}{\text{cm}^2\ \text{sec}}$ to $10^{15} \frac{\text{neutrons}}{\text{cm}^2\ \text{sec}}$, a dilute alloy of copper, copper titanium could be used. Titanium has a small cross section for thermal neutrons and a fast decay half life, 5.8 minutes, for the induced activity, titanium-51. Thus the achieved activity is low and exposure to personnel handling will not be excessive without the need for lengthy storage.

# APPENDIX 1 SOLUTION OF THE NEUTRON ACTIVATION EQUATION

$$\frac{dN}{dt} = \sigma_a N_d S_d \phi - \lambda N$$

$N$ : number of radioactive atoms at time t

$\sigma_a$ : activation cross section of the detector for thermal neutrons

$N_d$ : molecular surface density of the detector

$S_d$ : surface area of the detector

$\phi$ : neutron flux of the reactor

$\lambda$ : decay constant of the detector

let $k = \sigma_a N_d S_d \phi$

$$\frac{dN}{k - \lambda N} = dt$$

$$- \frac{\ln(k - \lambda N)}{\lambda} = t + c$$

$$-\ln(k - \lambda N) = \lambda t + c'$$

$$k - \lambda N = e^{-\lambda t} e^{c'} = A e^{-\lambda t}$$

when $t = 0$, $N = 0$

thus $A = k$ and $N = \frac{k}{\lambda}(1 - e^{-\lambda t})$

According to the decay law:

$$N_{t_2} = N e^{-\lambda t_2} \quad \text{and} \quad N_{t_2 + T} = N e^{-\lambda t_2} e^{-\lambda T}$$

$N_{t_2}$ : number of radioactive atoms present at time $t_2$

$N_{t_2+T}$: number of radioactive atoms present at time $t_2+T$

$t_2$ : time elasped after the detector is removed from the flux

$$N_T = N_{t_2} - N_{t_2+T} = \frac{\sigma_a N_d S_d \phi}{\lambda} (1-e^{-\lambda t_1}) (1-e^{-\lambda T}) e^{-\lambda t_2}$$

$N_T$ : number of radioactive atoms decayed between $t_2$ and $t_2+T$

$t_1$ : time of irradiation

## APPENDIX 2 RADIOACTIVITY CORRECTION FOR REACTOR START-UP

### A. Solution of the Radioactivity Correction Equation for Reactor Start-Up

$$\frac{dN'}{dt} = \sigma_a N_d S_d \phi_o \, e^{\frac{t}{T}} - \lambda N'$$

$N'$ : contribution of radioactive atoms by reactor start-up

$\sigma_a$ : activation cross section of the detector for thermal neutrons

$N_d$ : molecular surface density of the detector

$S_d$ : surface area of the detector

$\phi_o$ : flux when the reactor is critical

$t$ : time when the reactor is between critical and final power

$T$ : period of the reactor while approaching final power

$\lambda$ : decay constant of the detector

let $k' = \sigma_a N_d S_d \phi_o$

$$\frac{dN'}{dt} + \lambda N' = k' e^{\frac{t}{T}}$$

$$\frac{dN'}{dt} + \lambda N' = 0$$

$N'_c = N'_o \, e^{-\lambda t}$ complimentary solution

$N'_p = A \, e^{\frac{t}{T}}$ particular solution

$$\left(\frac{d}{dt} + \lambda\right) A \, e^{\frac{t}{T}} = k' \, e^{\frac{t}{T}}$$

$$A\left(\frac{1}{T} + \lambda\right) = k' \quad \text{or} \quad A = \frac{k'}{\frac{1}{T} + \lambda}$$

$$N' = N'_c + N'_p = N'_o e^{-\lambda t} + \frac{k'}{\frac{1}{T} + \lambda} e^{\frac{t}{T}}$$

when $t = 0$, $N' = 0$

$$\text{thus } N'_o = \frac{-k'}{\frac{1}{T} + \lambda}$$

$$N' = \frac{k'}{\frac{1}{T} + \lambda} \left( e^{\frac{t}{T}} - e^{-\lambda t} \right)$$

$$N'_T = \frac{\sigma_a N_d S_d \phi_o}{\frac{1}{T} + \lambda} \left( e^{\frac{t}{T}} - e^{-\lambda t} \right)\left( 1 - e^{-\lambda t} \right) e^{-\lambda t_2}$$

$N'_T$: number of radioactive atoms contributed by the reactor start-up in the interval T after a decay time $t_2$

B. Percentage Contribution of Radioactivity due to the Reactor Start-Up

For 19W wire run:

$t$ (time between critical and final power): 11 minutes

$T$ (period of the reactor while approaching critical) 70 seconds

$\phi_o$ (flux when the reactor is critical at $\frac{1}{10}$ watt) $\propto \phi(10\ kw) \times 10^{-5}$

$\frac{N'_T}{N_T}$ : percentage of radioactive contribution due to the reactor start-up

$$\frac{N'_T}{N_T} = \frac{\frac{\sigma_a N_d S_d \phi(10\ kw)}{\frac{1}{T} + \lambda} 10^{-5} \left( e^{\frac{t}{T}} - e^{-\lambda T} \right) \left(1 - e^{-\lambda T}\right) e^{-\lambda t_2}}{\frac{{}_a N_d S_d \phi(10\ kw)}{\lambda} \left(1 - e^{-\lambda t_1}\right) \left(1 - e^{-\lambda T}\right) e^{-\lambda t_2}}$$

$$\frac{N_T'}{N_T} = \frac{10^{-5}\left(e^{\frac{t}{T}} - e^{-\lambda t}\right)}{\left(\frac{1}{T} + \lambda\right)\left(1 - e^{-\lambda t_1}\right)}$$

$$\frac{N_T'}{N_T} = \frac{1.492 \times 10^{-5} \times 10^{-5} \times 1.23 \times 10^{4}}{1.43 \times 10^{-1} \times 1.79 \times 10^{-2}} = 0.07\ \%$$

# APPENDIX 3 SAMPLE COMPUTATIONS

A. Standard Foil Computation

standard gold foil: 1/2 inch diameter, 0.002 inch thick, and $m_s$(mass) 0.1168 gram

$\phi_s$(standard flux of National Bureau of Standards):

$4.23 \times 10^3 \ \frac{\text{neutrons}}{\text{cm}^2 - \text{sec}}$

time in: May 7, 1962 at 9:55 A.M. EST

time out: May 14, 1962 at 2:15 P.M. EST

$t_1$(total time of irradiation): 7 days, 4 hours and 20 minutes

T (total counting time): 50 minutes

$t_2$(total decay time): 2 days, 18 hours, and 21 minutes

half life of gold activity: 2.7 days

decay constant, $\lambda$, : $\frac{0.693}{2.7}$ days$^{-1}$

N (total number of counts less background): 6599

$N_s$ (saturation number of counts for 100% counting geometry and 100% counter efficiency):

$$N_s = \frac{6599}{(1 - e^{-\lambda t_1})\ (1 - e^{-\lambda T})\ e^{-\lambda t_2}} = 1.7972 \times 10^6$$

B. Absolute Flux Calculation of Core Position F-6 at 18 Inches

Since $N_s \propto m_s \phi_s$, it follows that the saturation counts registered in the same scalar and counting geometry for any gold foil of similar physical dimension is also proportional to the mass and flux.

$$\phi' = \phi_s \frac{N_s' m_s}{N_s m'} = 4.23 \times 10^3 \ \frac{N_s' \ 0.1168}{1.7972 \times 10^6 \ m'}$$

N' (saturation counts of bare gold foil) : $5.7083 \times 10^{10}$

m' (mass): 0.1085 gram in the reactor operating at 10 watts

$t_1$ (irradiation time) : 10 minutes

T (counting time) : 15 minutes

$t_2$ (decay time) : 3 days and 33 minutes

$N'_s$ (saturation counts of cadmium covered gold foil) : $1.7866\text{x}10^{10}$

$t_1$ (irradiation time in the reactor operating at 10 watts) : 10 minutes

T (counting) : 15 minutes

$t_2$ (decay time) : 1 hour and 53 minutes

$N'_s$ (saturation counts due to thermal neutrons) =

$5.7083\text{x}10^{10} - 1.7866\text{x}10^{10} = 3.9217\text{x}10^{10}$

$$\phi' \text{ (10 watts)} = 4.23\text{x}10^3 \; \frac{3.9217\text{x}10^{10} \quad 0.1168}{1.7972\text{x}10^6 \quad 0.1085}$$

$$= 9.94\text{x}10^7 \text{ neutrons/cm}^2\text{-sec}$$

C. Average Absolute Flux Calculation of the core

For the identical position, the saturation counts of the wire irradiation experiment for the reactor at 10 kilowatts is 4991.

thus 4991 counts $\propto 9.945\text{x}10^{10}$ neutrons/cm$^2$-sec

$\bar{\phi}$(10 kw) (average thermal flux of the reactor at 10 kilowatts and 19W geometry) = $9.945\text{x}10^{10} \; \frac{3645}{4991}$ = $7.24\text{x}10^{10}$ neutrons/cm$^2$-sec

3645 is the average saturation counts of the reactor at 19W.

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