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A PHYSICAL DETERMINATION OF THE CONVERSION RATIO OF THE
EXPERIMENTAL BREEDER REACTOR

by

C. D. Curtis, S. H. Klein, D. Okrent, W. C. Redman, S. Untermeyer

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ABSTRACT

Physical methods of measurement have been employed to determine the ratio of Pu^{239} production to U^{235} destruction in the Experimental Breeder Reactor (CP-4). Highly depleted U^{238} foils were irradiated throughout the core, inner blanket and outer blanket (cup), and the U^{238} neutron capture rates were determined by scintillation counting of the plutonium $K\alpha_1$ and $K\alpha_2$ X-rays which accompany the decay of Np^{239} . The observed activities required corrections for contributions by fission products and the decay of U^{237} formed by an $(n, 2n)$ threshold reaction of U^{238} . A U^{235} -coated fission chamber of the gamma-ray compensated type was used to establish the fission patterns in the core and inner blanket. These measurements were supplemented by the irradiation and counting of copper and U^{235} foils placed in those portions of the outer blanket which were inaccessible to the current chamber. The observations for Pu^{239} production and U^{235} fission were normalized by a comparison in the EBR thermal column of the response of the detectors to a thermal neutron flux for which pertinent cross sections are known. When combined with values for the ratio of captures to fissions in U^{235} , as determined by mass spectrometric analysis of fuel from the EBR, the measurements yielded a value for the conversion ratio which is in excellent agreement with that determined by radiochemical procedures. It was found that 91% of the U^{235} destruction occurs in the core, 3% in the inner blanket, and 6% in the outer blanket. One-half per cent of the Pu^{239} produced is found in the core, 33-1/2% in the inner blanket and 66% in the outer blanket. For the movable outer blanket in its position of maximum effectiveness, the physically determined conversion ratio is 1.01 ± 0.05 . Estimates based on these measurements indicate that a conversion ratio of 1.3 is possible for a fast converter of the EBR type.

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I. INTRODUCTION

The Experimental Breeder Reactor (EBR) is an experimental facility designed to test some of the features of an eventual large-scale reactor for the production of electric power and the generation of fissionable material. At the present time the knowledge of the pertinent nuclear parameters and the methods of reactor calculations are not sufficiently well established to permit prediction of the efficiency of the generation of fissionable material with the accuracy necessary to establish the economic feasibility of a proposed assembly. This situation was a contributing factor in the decision to construct the test reactor known as the EBR.

A. Definition of Conversion Ratio

If the components of a critical assembly are such that the same fissionable species is both consumed and produced during operation, the unit is termed a breeder. The term converter is applied to a reactor in which the type of fissionable material produced differs from that which is destroyed. The initial loading of the EBR was a core of enriched uranium surrounded by a blanket of natural uranium. Since Pu^{239} is produced in this assembly at the expense of U^{235} and U^{238} destroyed, this reactor is a converter.

The term conversion ratio is used as a measure of the efficiency of a conversion process. For the initial loading of the EBR, the conversion ratio (CR) is the ratio of plutonium production to enriched uranium destruction. The loss of U^{238} , either by capture or fission, is neglected.

B. Description of the EBR

The mechanical design of the EBR is described in detail in ANL-4356.¹ Only those features which are of importance in connection with the conversion ratio measurements will be considered here.

A horizontal section of the nuclear portion of the EBR is shown in Figure 1. The enriched section consists of cylindrical rods of U^{235} assembled in a close-packed array to form a hexagon. A sodium-potassium alloy coolant flows in the interstices between the rods. The enriched region is surrounded by a tamper or blanket of normal uranium. This, in turn, is divided into two portions: (1) that part which immediately surrounds the enriched reactor is in the form of rods and is also cooled by the NaK alloy; (2) the remainder of the natural uranium is in the form of bricks which are located outside of the NaK-filled tank and are air-cooled. The latter portion of the blanket may be moved as a unit for control purposes.

The EBR core is composed of 217 rods which contain 58.4 kg of uranium with a 93.4% enrichment. A standard rod, of which there are 150, contains 4-3/4 in. of natural uranium below and 8 in. above an enriched

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portion of 7.5 in. in height. Near the periphery of the core are located 63 rods of slightly larger fuel diameter which contain an enriched region of 10 in. in height. A thermocouple rod containing slightly less U^{235} than a standard rod and three rods with provision for the irradiation of samples complete the complement of core rods. The oversized rods represent a deviation from the description given in the feasibility report¹ and were required to obtain sufficient reactivity.

The enriched region is surrounded by 138 rods, each of which contains 0.9 in. diameter slugs of natural uranium totaling 20-1/4 in. in length. Figure 2 contains the rod identity numbers which are used in this report to indicate the positions at which measurements were made in the core and inner blanket.

The air-cooled outer blanket of natural uranium has an inside diameter of 17-7/8 in., an outside diameter of 34 in., a height of 27-1/8 in., and a total weight of approximately 4.1 tons. The blanket is formed with 84 bricks similar in structure to the special irradiation brick shown in Figure 8. Each brick has five holes which are fitted with finned tubes for air cooling and a sixth hole for insertion of a control or safety rod. Each brick is protected from oxidation by a 0.020-in. stainless steel jacket. A uranium brick of special design fills the opening at the bottom of the shell, and the entire cup rests on an hydraulically-motivated pedestal.

The relation of the nuclear portion to other components of the reactor is shown in Figures 3 and 4. Also shown are the beam holes and air ducts which pierce the structure and contribute significantly to certain asymmetries in the experimental observations. The layer and column coordinates for the cup bricks are also indicated in these figures.

C. Outline of Measurement

The plutonium production pattern in the EBR was established by scintillation counting of irradiated U^{238} foils. Both foils and a compensated fission chamber were used to determine the distribution of U^{235} fissions. These sets of observations were interrelated by a comparison of the response of the detectors in a neutron flux for which the pertinent cross sections were known. The Pu^{239} production and U^{235} fission measurements and their normalization are discussed in Sections II, III, and IV, respectively.

The results of mass spectrometric analysis of fuel from the EBR must be combined with the measured U^{235} fission pattern to yield the U^{235} destruction. The point by point integration of the experimental data, properly weighted for capture in the case of the U^{235} measurements, is described in Section V. These integrated results are then compared region by region with radiochemical data on the conversion ratio.² The results are in good agreement, but the physical and chemical methods of measurement are not completely independent in that each must utilize the mass spectrometric data for the ratio of captures to fissions of the enriched uranium.

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II. MEASUREMENT OF Pu^{239} PRODUCTION PATTERNS

Scintillation counting techniques have been applied for the measurement of the plutonium production pattern of the Experimental Breeder Reactor (CP-4). The plutonium K_{α_1} and K_{α_2} X rays which accompany the 2.3-day decay of Np^{239} were used to determine the plutonium production in depleted uranium foils irradiated in the core, inner and outer blankets of the EBR. Corrections have been applied for the natural activity of the foils and the activity associated with the decay of fission products and U^{237} formed during the irradiation.

A. Detection of Pu^{239} Production

The applicability of scintillation counting of uranium foils to the measurement of plutonium- and fission-producing flux has been demonstrated by Axtmann and Stutheit.³ Detection of the K_{α} X rays associated with the decay of Np^{239} provides a measure of the plutonium production, and the fission flux activation is determined by the detection of the high-energy gamma rays present. Plutonium production in the EBR has been detected in this manner.

Plutonium production in a reactor proceeds in the following manner:

The decay scheme for the 2.3-day Np^{239} is complex. One proposed pattern of energy levels in Pu^{239} , consistent with observations⁴ of the beta decay of Np^{239} and the alpha decay of Cm^{243} , is shown in Figure 5. The high-energy gamma rays are in part internally converted, resulting in the emission of X rays which are characteristic of plutonium.

Also shown in Figure 5 is the gamma-ray energy distribution observed for the Np^{239} decay by means of a NaI scintillation counter used in conjunction with a single channel differential pulse height analyzer. A uranium foil, depleted to about 500 ppm of isotopes other than U^{238} , was irradiated in a thermal flux in the Argonne Heavy Water Reactor (CP-3'). The resulting activity was observed with the same scintillation counting equipment used for the Np^{239} measurements in the EBR conversion ratio experiments. Thus Figure 5 depicts the Np^{239} decay spectrum free from any other significant contribution and indicates the magnitude of resolution existing in this experiment. The principal peak, at a channel level of 32, is ascribable to the K_{α} radiation of Pu^{239} resulting from internal conversion of those gamma rays greater than 122 keV which follow the beta decay of Np^{239} . The most prominent X rays associated with the K_{α} level of plutonium are those resulting from the allowed transitions K-L_{III} and K-L_{II}. The energies⁵ of these so-called K_{α_1} and K_{α_2} X rays are $121.75 - 18.06 = 103.69$ keV and $121.75 - 22.25 = 99.50$ keV respectively. The location of the peak for

photolines resulting from radiation of these energies agrees with the energy scale established by means of Ce^{141} and Au^{198} sources. The broad peak in the vicinity of a 70-volt channel level results from the unresolved photolines of 210-, 227- and 276-keV gamma rays which are not internally converted. The hump on the low energy side of the 100-keV peak is a combined effect of the 44-, 49-, 57-, 61- and 67-keV gamma rays shown in the energy level diagram.

A NaI (Tl) crystal, 1/2 in. thick and 1-1/4 in. diameter, was used with an RCA 5819 photomultiplier in these measurements. For this combination the resolution, defined as the ratio of full energy width at half maximum to the peak energy, was 25% for the photoline of the 146-keV radiation from Ce^{141} .

B. Summary of Foil Irradiations

The initial determination of the plutonium production pattern in the EBR by physical methods of measurement was based on the observed activities of 129 uranium foils which were irradiated in three separate exposures, as described in Table I. The simultaneous activation of copper foils at each of the 45 cup positions used in Run 1 is discussed in Section III in connection with the determination of the U^{235} fission patterns. Additional information on plutonium production was provided by 37 uranium foils which were irradiated in two subsequent experiments. These irradiations are summarized in Table II. Observations on the U^{235} -Al and Cu foils included in these latter experiments are presented as a part of the U^{235} fission pattern measurements. The Pu^{239} -Al foils mentioned in the summary of the fifth irradiation were included in the irradiation to provide information which is not pertinent to the subject of this report, and so only their effect on shielding of the foils of interest will be considered.

All of the uranium foils used for the detection of plutonium contained only 500 ppm of isotopes other than U^{238} . Each foil used in the initial measurements was approximately 1/4 x 1/4 x 0.003 in. thick. Ten foils from Run 1, selected on the basis of low residual activity and minimum weight variation, were quartered to provide the U^{238} foils used in the supplemental irradiations designated in Table II as No. 4 and No. 5.

In the first irradiation foils were placed in: (1) the core and inner blanket, by insertion between uranium slugs in special thimbles which replaced the central rod and one rod in each of the four rings of the inner blanket; (2) the outer blanket (cup), within milled depressions in a 1/16 in. thick stainless steel sheet positioned vertically between adjacent columns of the uranium bricks which form the cup; and (3) the thermal column, where a sandwich of three foils was contained in a special holder which simulated a current chamber of the type used for the determination of the EBR fission patterns. The relative positions of the foils located in rods No. 1, 235, 268,

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308 and 343, between the G and H columns of cup bricks and in the thermal column may be seen in Figures 2 and 4. Coordinate locations of the core and blanket foils are included in Table III.

The second irradiation involved a repetition of the thermal column irradiation with the addition of a 30-mil thick cadmium cover to the foil sandwich. This irradiation was performed to provide information on a correction needed in the normalization of the plutonium production and uranium fission patterns, as discussed in Section IV.

The third irradiation was made to determine the plutonium production in the lower part of the cup and to establish the magnitude of the fission product correction. Two foils were placed in each of five positions in the central rod and five in one of the blanket rods. A foil sandwich was again placed at the thermal column position. These locations duplicated positions used in the first irradiation, thereby making possible both a comparison of physical and chemical determinations of the necessary correction of the observed activities for a fission product contribution, and the normalization of the lower cup data. The locations of the 15 foils irradiated simultaneously in the lower cup are shown in Figure 6. Coordinates for these foils are included in Table III.

The activities observed for the U^{238} foils involved in the three irradiations were used in the initial determination of the conversion ratio for the EBR. However, a comparison of the values obtained by physical and chemical methods revealed certain discrepancies in the data for the outer portion of the cup. It was suspected that neutron streaming between the columns of cup bricks, holes in the graphite reflector surrounding the cup, and the assumption of equivalence in neutron response for U^{235} and copper were all contributors to the disagreement. These effects were investigated in irradiation No. 4 described in Table II.

The fifth irradiation was performed to clarify some of the results obtained in the fourth irradiation, to establish the Pu^{239} fission rate patterns needed for the computation from mass spectrographic measurements of the U^{235} fission patterns with results obtained by counters and current chambers. Both of these supplemental irradiations are described in Table II, but only those results applicable to the determination of plutonium production are presented in this section.

The possibility of effects due to streaming and reflector structure on the activity induced in the outermost foils during the first irradiation is revealed by Figure 7, which is a detail of the region in the immediate vicinity of the column of foils located at radius $R = 38.6$ cm. The inhomogeneity of the graphite reflector is more apparent in Figures 3 and 4. The latter figures also reveal the differences in the reflector homogeneity near the K column of cup bricks which were used in the initial radiochemical

analysis, the E column from which was taken the brick used for subsequent radiochemical measurements of the cup production and fission, and the G and H columns between which was inserted the foil holder used in the initial determination of the conversion ratio.

Two special cup bricks, of the type shown in Figure 8, were used to replace conventional bricks in the fourth and fifth irradiations. Each brick contains two foil holders which fit between the cooling and control rod holes in the brick. Foils are located in milled depressions at the ends of uranium cylinders which fill the holders at 0, 1/4, 1/2, 1, 2 and 3 in. from the outer face of the uranium cup.

The special bricks were positioned at the cup coordinate locations K-5 and G-5 for Run No. 4. U^{238} and U^{235} -Al alloy foils were placed at each of the six positions in both holders of the brick located at K-5 and in the G-5 brick holder adjacent to the regular brick at H-5, to provide detailed Pu^{239} production and U^{238} and U^{235} fission patterns, and to reveal perturbations caused by holes in the graphite. Pairs of Cu and U^{235} -Al alloy foils were placed in the fourth holder, adjacent to F-5, to compare the neutron response of Cu and U^{235} . All foils were approximately $1/8 \times 1/8 \times 0.003$ in. At each position, the U^{235} -Al foil was closer to the outer face of the cup, and the foils were separated from each other and from the uranium cylinders by three aluminum foils ($3/16$ in. diameter, 1 mil thick) which prevented the transfer of fission fragments during irradiation. Such a foil sandwich completely fills the 10-mil deep hole in the uranium cylinder. To interrelate this irradiation with those performed earlier, U^{238} , U^{235} -Al and Cu normalization foils were located at the reactor mid-plane in a uranium-filled thimble which replaced rod No. 268 ($R = 5.20$ in.). A summary of this foil loading is included in Table IV.

Fifty-one foils were loaded and irradiated in the EBR for 100 kwh on September 9, 1953. This irradiation was performed in the following manner: 10 kwh with cup at 0.2 in., power 128 kw; 15 kwh with cup at 0.3 in., power 93 kw; and 75 kwh with cup at 0.0 in. (requested position), power 175 kw. The uranium control rods in the G and K columns, which contained the special bricks, were inserted during the irradiation.

The foil loading for the fifth irradiation is included in Table V. One of the special bricks was again positioned at K-5 in order to check an anomalous behavior observed in the fourth irradiation for the foils located at the outermost position in the holder adjacent to the brick at L-5. U^{238} foils were placed at three, U^{235} -Al at two and Pu^{239} -Al at all six of the positions used in the preceding activation. The second holder in this brick contained no foils. Six U^{238} foils, spaced about 1 in. apart, were attached to the outer face of the brick located at K-5 to detect any angular asymmetry caused by the nearby beam hole in the graphite reflector. Both holders were inserted in a second special brick placed at E-5, but only the one adjacent

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to the D-5 position contained foils. This location was chosen to make possible an interpretation of the results obtained radiochemically for bricks in the K-5 and E-5 locations.

A flat foil holder, shown in Figure 9, was loaded and placed between the bricks which occupied the E-5 and E-6 positions in order to obtain data at radial locations not provided for in the special bricks. Foils in the core and inner blanket were placed between uranium slugs in thimbles which replaced the rods. Sufficient slugs were not available for locating foils in each of the rings of inner blanket rods.

The depleted uranium foils did not differ dimensionally from the $1/8 \times 1/8 \times 0.003$ in. foils used in the fourth irradiation. The U^{235} was contained in a 3-mil thick, 4.6 % U^{235} -Al alloy as before, but the size was increased to $1/4$ in. diameter to simplify the marking, handling and inter-comparison of the uranium content by gamma-ray counting.

The plutonium foils were fabricated from an aluminum-clad sample of 5% plutonium-aluminum alloy fuel plate. The plate was first rolled down from 0.060 in. to 0.010 in. thickness, and $1/4$ in. diameter foils were then punched from it. Inasmuch as the latter operation exposed an edge of the fuel, the punchings were double wrapped in aluminum foils 1 mil thick. Aluminum foils (1 mil thick $\times$ 0.30 in. dia) were used as spacers between foils. The milled depressions in the uranium slugs of the holders used were enlarged to accommodate these larger foil sandwiches. The U^{235} foil was always placed in the outermost position, the Pu^{239} foil next, and the U^{238} foil (if any) on the core side at each position in these holders. At other locations containing a 3-foil sandwich, the Pu^{239} foil was also at the center.

Sixty-eight foils were irradiated for two hours at a power level of 50 kw. The cup was at maximum height and the uranium control rods in the E and K columns were fully inserted during this irradiation.

C. Counting Procedure

The irradiated U^{238} foils were returned to Argonne from the EBR site for measurement of the induced activity. The activity of each foil was observed through a 10 % energy window centered on the 100-kev peak of a U^{238} foil which had been irradiated in a thermal neutron flux.

Initially, each of the foils from the first and second irradiations was counted for one minute; however, errors due to either counting losses or statistical fluctuations were unavoidable because of the wide range of activities (about a factor of 50). In the modified procedure, the activated foils were separated into groups of low and high specific activity. The foil holder was then positioned so that the counting losses for the group of foils

being counted were insignificant. Either 10,000 counts or the counts over a ten-minute period were obtained in each measurement of activity as a compromise between statistical inaccuracies and excessive counting times.

During the counting of each group of foils, the activity of one foil was remeasured often to determine the proper decay correction and to detect any change in the counter characteristics. In the counting of the foils from the first three irradiations, the center foil from the bare EBR thermal column sandwich (termed the T foil) was used both as the reference foil and as the standard foil with which the location of the 100-kev peak was determined before each counting of a set of foils. A cup foil was used as the reference foil for the Run No. 4 data and the outermost inner blanket foil for Run No. 5. U^{238} foils were irradiated in a thermal neutron flux for use as standard foils for these latter runs. The counting routine also included a frequent measurement of the counter background and the activity of an unirradiated foil.

Values for the relative Np^{239} activities are derived from a minimum of two separate observations. The average number of activity measurements used per irradiated foil was approximately four. Some observations were discarded because of excessive counting losses (early counting of foils from Run No. 1) or because of large corrections compared with the net Np^{239} activity (late counting of all foils). Core and inner blanket data are based on two sets of observations for the Run No. 1 foils, five for both Runs No. 3 and 4 and six for Run No. 5. The outer blanket (cup) data are averages of four values for the Run No. 1 and Run No. 5 foils, and five for those from Runs No. 3 and 4.

D. Treatment of Data

The observed counting rates required the usual corrections for counter background, variations in weight among the foils, natural activity of the foils and radioactive decay of the Np^{239} . The activity observed in the energy window centered on the neptunium decay peak contained contributions from the decay of fission products and U^{237} . The fission product and U^{237} components contribute a minimum to the observed activity in the interval from two to six days after irradiation, but only the observations on the foils involved in the supplemental irradiations were made during this optimum time interval. The primary purpose of these supplemental irradiations was to provide information on the plutonium production in the outer blanket. In this case the degradation of the neutron spectrum in conjunction with counting during the optimum time interval made the correction for fission product and U^{237} activity insignificant; thus only the usual corrections for counter background foil weight variation, natural activity and radioactive decay were applied to the observed activities of the foils involved in Runs 4 and 5. For this reason the discussion of the application of corrections to the experimental observations is presented in terms of the foils involved in the initial irradiations.

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1. Normal Corrections

a. Counter Background

The normal background activity of about 10 counts per minute for the scintillation counter, as operated for the measurements of the plutonium production pattern, was augmented by a time-dependent contribution from the foils activated in this experiment. Because of the large number of foils stored nearby, it was necessary to measure the counter background often. The magnitude of this correction applied to the observed activities varied with time from a maximum value of about 50 counts per minute to an asymptotic value of 10.

b. Foil Weight Variation

The effect of foil weight variation was investigated by means of the ten pairs of foils activated in the third irradiation. Variations in both thickness and area contribute to the weight variation, but each in turn was considered to be the sole cause. Division of each observed activity by the weight of the foil ascribes the total variation to an area effect, while the assumption of a difference in thickness only requires a self-absorption type of correction. Slightly better agreement in the pairs of foil activities resulted from the weight correction of the observations; accordingly this type of correction has been made to all of the observations. The foils used in the first and second irradiations had an average weight of 69.7 mg, with an average deviation of 3.7 mg. In the third irradiation, the corresponding values were 45.9 and 3.2 mg, respectively. For each set the difference in the activities, when weight-corrected by the two methods, would amount to 1.1% for foils differing in weight by twice the average deviation, so that the possible error resulting from the choice of method is small. The sets of foils used in the fourth and fifth irradiations were prepared from foils matched in weight; this procedure led to an insignificant error in the correction for weight variations.

The correction for self-absorption of the foil activity required a knowledge of the mass absorption coefficient of uranium for radiation of the energy of the $K\alpha_1$ and $K\alpha_2$ X rays from plutonium. Although the type of weight correction finally chosen for application to the observations does not utilize this coefficient, its measurement is of interest because it demonstrates an effect of significance in the correction for fission product activity. In a supplemental experiment, a 1.3 in. diameter uranium foil, containing only 500 ppm of isotopes other than U^{238} , was covered with cadmium and irradiated in the moderator of a thermal reactor. The activity in a 10% energy window located at the 100-kev peak was observed with varying amounts of 1.3 in. diameter uranium foils interposed between the detector and the irradiated foil located 4 in. from the detector. The data, corrected for the activity contributed by the uranium absorbers, are plotted in Figure 10. The observed attenuation corresponds to an effective mass absorption coefficient

$\left(\frac{\mu}{\rho}\right)_{\text{eff}}$ of $1.36 \text{ cm}^2/\text{gm}$, or a half-value thickness of 10.7 mils. This value for the mass absorption coefficient is somewhat lower than the true value ($\sim 2 \text{ cm}^2/\text{gm}$) because of a contribution from the higher energy neptunium decay gamma rays. Some of these gamma rays which are not internally converted in the decay process interact photoelectrically with the uranium in the foil resulting in emission of uranium K X rays. The energies of these K_{α_1} and K_{α_2} lines of uranium are 98.4 and 94.6 kev, which are not appreciably different from the corresponding 103.7- and 99.5-kev X rays associated with the Np^{239} decay. Thus the measured attenuation results from a combination of the attenuation of the plutonium X rays and the production and subsequent attenuation of the uranium X rays. Only when these supplemental X rays originate from gamma rays not associated with the Np^{239} decay (e.g., fission product gamma rays) is this effect undesirable.

c. Natural Foil Activity

In order to account for the natural radioactivity of the uranium used as foil material, a correction as large as 7% of the observed activity was applied. In practice, this correction was determined by a measurement of the activity of an unirradiated foil when the irradiated foils were counted. The magnitude of this background activity and its spectral distribution serve to place a lower limit on the nvt for which this method of measurement of plutonium production will furnish accurate results. Accordingly the origin of this activity was investigated. U^{235} was also measured because of an interest in the possible use of less depleted uranium foils for such measurements.

Observations on the pulse height distribution for a depleted and enriched uranium sample are plotted as unnormalized curves in Figure 11. The depleted sample contained only 500 ppm of uranium isotopes other than U^{238} , and the enriched sample contained 93.7% of U^{235} by weight. Each of the samples was viewed through $1/8$ in. of aluminum to suppress the beta particle activity. The specific activity (disintegrations per second per gram) is appreciably greater for U^{235} , e.g., the $\text{U}^{235}/\text{U}^{238}$ specific activity ratio for the peaks near 90 kev (channel level ~ 40) is approximately 20. For purposes of scale calibration the 36.7- and 146-kev peaks associated with the decay of Ce^{141} are also shown in Figure 11.

The following decay pattern is observed for U^{238} :

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The alpha decay of U^{238} is often (23%) accompanied by a 48-keV gamma ray, and emission of a 93-keV gamma ray is observed in 20% of the disintegrations of its daughter, Th^{234} . The resulting Pa^{234} decays to U^{234} with the emission of a beta particle, either directly (>99%) with an accompanying gamma ray of 817 keV (13%), or indirectly (0.15%) to an isomeric state (394-keV γ) preceding beta emission which is accompanied (90%) by gamma rays of about 0.8 MeV. The principal low-energy peak observed at 95 keV results from a combination of the 93-keV gamma ray and K_{α} radiation following internal conversion and photoelectric interaction in the foil material of the gamma rays of higher energy. The bulge on the low energy side of this 93-keV peak is ascribable to the 48-keV gamma ray and to the escape of the K_{α} radiation of iodine which is produced by the photoelectric absorption of the gamma rays in the NaI crystal. The long-lived decay of U^{234} to its long-lived daughter Th^{230} is included in the above decay chain to show that the contribution of the U^{234} in the uranium samples scanned is negligible.

The structure observed for the enriched sample can be understood from a consideration of the U^{235} decay chain:

The decays of both U^{235} and Th^{231} are accompanied by a complex spectrum of gamma rays. Their yields are high, because only 20% of the U^{235} and none of the Th^{231} decay directly to the ground state. The energies, in keV, and relative yields (in parentheses) of these gamma rays are: 94 (0.9), 143 (0.2), 184 (1.0), 289 (0.1), and 386 (0.05) for U^{235} decay; and 22 (?), 39 and 63 (0.40), 85 (1.00), 107 (0.065), 122 (0.02), 167 (0.018), 208 (0.003) and 230 (0.001) for Th^{231} . The granddaughter, Pa^{231} , is sufficiently long-lived so that the contribution of it and the remaining constituents of the U^{235} decay chain are negligible. The observed low energy spectrum is interpretable on the basis of the reported yields almost wholly in terms of the 94-, 143- and 184-keV gamma rays associated with the U^{235} decay and those of 59-, 63- and 85-keV from Th^{231} .

d. Radioactive Decay

In each measurement of the activities of a set of foils, the proper channel level setting was determined by scanning the center foil (T-foil) of the bare thermal column sandwich. The activity of the T-foil was measured frequently during the counting interval. The values were corrected in the manner described previously and were plotted as a function of time. These experimental observations of the T-foil activity were fitted by a decay curve corresponding to the known 2.33-day half-life of Np^{239} . The consistently good fit of the experimental points by such a curve attested to the stability of the electronic circuitry. Each of the other activities, properly

corrected for counter and foil background and weight variations, was related to the decay curve value for the T-foil activity at the corresponding time, in order to eliminate the time dependence of the observations.

e. Summary of Normal Corrections

The stepwise application of normal corrections may be summarized as follows. The activity of a typical foil x is determined as a certain number of counts per minute at a time t_x corresponding to the mid-point of the time interval during which the foil was counted. The average of the values for the counter background determined before and after the counting of the set of foils is subtracted. The result is then divided by the foil weight to give the specific activity of foil x at time t_x . From this is subtracted the specific activity of an unirradiated foil counted under identical conditions to give the net specific activity induced by irradiation. Np^{239} , fission products and U^{237} contribute to this net specific activity. The time dependence of this value is eliminated through division by the net specific activity of the T-foil at the time t_x , as read from the decay curve obtained for this reference foil. Since the T-foil was located in the thermal column of the EBR, its specific activity has no component due to U^{237} and only a slight contribution of fission products from the small amount of U^{235} present in the highly depleted foils used. The application of these routine corrections furnishes the ratio:

$$\frac{A_x}{A_T} = \frac{(\text{Np} + \text{F.P.} + \text{U}^{237})_x}{(\text{Np} + \text{F.P.})_T}$$

The mathematical extraction of the neptunium component is discussed in the following sections.

2. Correction for Fission Product Activity

The multiplicity of fission products and the complex time dependence of their concentrations make impractical a detailed consideration of the origin of the fission product activity in the vicinity of 100 kev. This complexity is enhanced because a scintillation counter detects energy loss in the crystal; thus the possibility exists for counts at 100 kev resulting from a Compton interaction of gamma rays of higher energy. The magnitude of the correction for fission product activity was determined in a supplemental experiment involving a measurement of the relative fission activity pattern and a normalization by means of the observed activities of the chemically separated components of several foils.

The relative fission activity associated with each of the irradiated uranium foils was determined by detection of only those gamma-ray interactions in the crystal which resulted in an energy loss of at least 600 kev. No gamma rays of energy greater than 430 kev are observed in

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the decay of Np^{239} and U^{237} , so that the observation of events having a minimum energy loss of 600 kev provides a measure of the fission product activity.

Most of the measurements of the fission product activity associated with the depleted uranium foils involved in the initial irradiations (Runs 1 to 3) were made from two to six weeks after irradiation. With the exception of one set of data, the observations were based on 10,000 counts or 10-minute counting times, but the foils were not always counted in two groups as was done in the measurement of the neptunium activity. Consequently, the accuracy is limited for the low-intensity foils, in spite of the 10,000 or 10-minute counting criterion. The conditions of irradiation and counting were such that the corresponding range for the natural background activity was 0.6 to 1.8 % of the fission product count for the foil located at the center of the reactor (C-foil). The correction for the natural background activity is excessive for those foils not in the immediate vicinity of the core; at times the fission product activity in some of the foils was completely masked by this natural activity. This limited accuracy in the fission rates observed for position outside the core and inner blanket is not significant in the correction of observed neptunium activities for the fission product component, because of the extremely small magnitude of the correction for foils located in those positions.

The averages of observed U^{238} fission rates relative to that of the foil located at the reactor center are summarized for the initial irradiations in Table III and plotted in Figure 12. Also indicated in Figure 12 is the range of the relative magnitude of the associated background correction; this provides a guide to the reliability of the data associated with locations of low fission product activity. Observations wherein the net fission product activity is only a small fraction of the natural background activity of the foil have so much scatter that their inclusion in Figure 12 would result in confusion. Consequently, those values less than 0.004 (average background activity is ~ 0.01) are not plotted, but the curves derived from the omitted data points are included in this figure. Values from the smooth curves drawn through the experimental observations have been used in the application of the correction for fission product activity.

Detection of the fission product activity of the depleted uranium foils contained in the fourth and fifth sets of irradiated foils provided more reliable data on the U^{238} fission patterns in the outermost portion of the EBR. These observations are included in Tables IV and V. Each of the relative U^{238} fission rates reported in Table IV is an average of four determinations made during the second day after irradiation. These values have been corrected for the counter background, variations in the foil weight, radioactive decay and a natural background activity which averages 1.4% of the total activity of the foil at $R = 12.4$ in. in the special brick at G-5. The observations on the U^{238} fission product activity reported in Table V were

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also corrected in the same manner. Eight sets of measurements of these activities were made for the U^{238} cup foils and six for those located in the rods.

Some of the observations included in Table V, together with the rod No. 268 data from Table IV, have been used to plot the radial variation of the U^{238} fission rate on the reactor mid-plane (Figure 13). Also included in this figure is a radial pattern derived from the earlier results presented in Figure 12. The curves have been normalized in the core and inner blanket. Two factors contribute to the discrepancy between the curves in the outer blanket. Data from the E column of cup bricks have been used for the radial curve based on the more recent irradiation. This represents the direction of maximum reflector thickness, and its effect in increasing the U^{238} fission rate is shown in Figure 14. The U^{238} fission rate patterns in the outer portion of the cup are shown for directions in which there is a wide variation in reflector density (see Figure 4). In addition to a less favorable location in regard to reflector density, the original measurements of the U^{238} fission rate in the cup were inaccurate because of an excessively high correction for the natural background activity of the foils.

The reality of the increase in U^{238} fission rate at the outer edge of the cup, as observed in the fourth and fifth irradiations, is in doubt because of an observed time dependence of the relative activities of those foils located at the outer face. The values of the relative U^{238} activity for several of the Run 5 foils counted on the third and fourth day after irradiation did not fall within a range expected from statistical considerations, and so the entire set of U^{238} cup foils were recounted four additional times, on the seventh and eighth day. It was observed that the activities of those foils located on the outer face of the cup, relative to that of the reference foil, showed a consistent variation with time. This effect is illustrated in Figure 15, where the time dependence of the sum of the relative activities of the eight outermost foils is compared with that for the seven cup foils which were located at various distances from the outer edge. The 492 ± 6 ppm of U^{235} present in the depleted uranium foils is sufficient to account for the apparent rise in U^{238} fission rate and the time dependence of relative activities. Burn-out of a fission fragment which contributes significantly to the fission product activity may also be partly responsible for this observed time dependence.

To effect a normalization of the relative U^{238} fission rate patterns to the fission product component of the foil activities observed in the counting at 100 kev, several foils were irradiated at positions which duplicated those used in the original irradiations. As mentioned earlier in the description of Run 3, foils were irradiated in pairs at each of ten positions in the core and inner blanket to make possible a direct comparison of the physical and chemical determinations of fission product activity.

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The fission product fractions of the chemically-separated foil from each of the ten positions, together with that obtained from chemical treatment of one-half of the inner foil from the thermal column sandwich, were counted on the sixth and eighth day after their irradiation. Their activities were observed in the same energy window used for the measurement of neptunium activity, and the untreated half of the thermal column foil was used for reference in the manner described earlier. The activity of the neptunium component of the chemically-processed half of the thermal column foil was also related to the activity of the reference half-foil.

After application of the usual corrections for counter background activity, variations in weight, radioactive decay and detector efficiency (geometry), the observations were combined to furnish the specific fission product activity of the x foil when counted in the neptunium window relative to the specific fission product and neptunium components for a foil in the standard thermal column position. The observations, expressed in the form

$$\frac{(F.P.)_x}{(Np)_T + (F.P.)_T}$$

are directly applicable as a correction for the fission product component of the measured activities when the latter is expressed in the manner indicated earlier,

$$\frac{A_x}{A_T} = \frac{(Np + F.P. + U^{237})_x}{(Np + F.P.)_T}$$

To make such a correction to foils at positions other than the ten involved in the chemical determination of the fission product component, it is necessary that the observations be related to the patterns determined by counting techniques. To this end, the chemically determined values for

$$\frac{(F.P.)_x}{(Np)_T + (F.P.)_T}$$

were plotted as a function of the corresponding values of the fission product activity of the x foil relative to that for the foil located at the core center,

$$\frac{(F.P.)_x}{(F.P.)_c}$$

It should be noted that the chemical treatment results in the loss of the noble gas fission products. These data, plotted in Figure 16, exhibit a linear interrelation.

The slopes $F(t)$ of the straight lines which fit the data presented in Figure 16 are time dependent because of the difference in the radioactive decay rates of the neptunium and the fission product activity in the energy

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window at 100 kev. Unfortunately, the latter rate is not known; therefore it is necessary to supplement the observations made 6 and 8 days after the irradiation. Measurements made in connection with conversion ratio experiments on thermal reactors⁶ have established the contribution of U^{235} fission products to the activity observed at 100 kev in the interval from 2 to 14 days after irradiation. This curve was normalized to the measurements for U^{238} fission product activity at 6 and 8 days, as shown in Figure 17.

The gross fission product decay curves for U^{235} and U^{238} are known to differ somewhat. However, the moderate variation of the factor in the 2 to 8 day interval during which most of the observations were made, coupled with an inverse relationship between the magnitude of the fission product correction and the importance of the location to total plutonium production, serve to minimize the error introduced by the assumption of identical decay for the 100-kev activity from U^{235} and U^{238} fission products.

Probably a larger source of error in the magnitude of the fission product correction applied to the data results from an effect mentioned in connection with the measurement of the attenuation of 100-kev radiation by uranium (page 15). The action of uranium in degrading the energy of the gamma rays from neptunium and fission product decay results in a spectrum rich in 100-kev radiation. The chemically separated components used to determine the fission product contribution were free of uranium and so implicit in the application of this correction is the assumption that the ratio

$$\frac{(F.P.)_x}{(F.P.)_T + (Np)_T}$$

would be unchanged by the dispersal of the fission product and neptunium components in a thick uranium foil.

A rough estimate of the effect of such a dispersal on this ratio may be made from existing data. The average "amplification" of the 100-kev radiation from U^{235} fission products caused by their dispersal in a 0.010-in. thick uranium foil is about 1.7 for the two to eight-day interval after irradiation.⁷ Assuming equivalence of U^{235} and U^{238} fission products and a linear dependence of the amplification factor minus unity upon thickness, the numerator of the ratio

$$\frac{(F.P.)_x}{(Np)_T + (F.P.)_T}$$

would increase by 1.25 for a 3.6-mil thick foil (corresponding to the Run 1 average foil weight of 69.7 gm). The 100-kev attenuation data of Figure 10 provides the lower limit of an equivalent factor for neptunium activity, because the effect of reflection from layers above the emitter is not present in the attenuation experiment. For a 3.6-mil thickness, the attenuation

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factor is 0.80. $(F.P.)_T$ is negligible compared with $(N_p)_T$ and so an estimate of the factor by which the ratio would be increased by dispersal of the components in a typical foil is $1.25/0.80 = 1.56$.

No allowance for such an amplification effect was made in the application of the fission product correction to the observed activities, and there was no indication in the corrected data of the need for a larger (or smaller) correction. Many observations were made on the cup foils from Run 3, but no trend was observed in the corrected values for sets of data obtained at several different times after the irradiation. However, most of these observations were made from two to eight days after irradiation for which neither the magnitude of, nor the variation in, the fission product correction is large, so that a trend might be obscured by random fluctuations of statistical origin. Because of delayed counting, the Run 1 core and inner blanket data required a large correction for fission product and also U^{237} activity, but the corrected values show no significant deviations from the corresponding values of the Run 3 foils which were counted in the optimum time interval. It is possible that an under-correction for fission product activity is balanced by an over-correction for U^{237} activity in the more active Run 1 foils, but an explanation of comparable probability is that the curve based on U^{235} fission product activity exceeds the proper correction for U^{238} fission product activity by an amount which compensates for the omission of a uranium amplification factor for data obtained outside of the optimum (time) interval for counting.

The mathematics of the correction for the fission product activity present in the observations at the 100 kev neptunium activity peak may be summarized as follows:

- a. The appropriate smooth curve value for

$$\frac{(F.P.)_x}{(F.P.)_c}$$

is determined from Figure 12;

- b. the appropriate time-dependent slope factor, $F(t)$, is selected from the curve shown in Figure 17; and

- c. the product of $F(t)$ and

$$\frac{(F.P.)_x}{(F.P.)_c}$$

equivalent to

$$\frac{(F.P.)_x}{(Np)_T + (F.P.)_T}$$

is subtracted from

$$\left(\frac{A_x}{A_T} \right)_t = \frac{(Np + U^{237} + F.P.)_x}{(Np + F.P.)_T}$$

to yield

$$\frac{(Np + U^{237})_x}{(Np + F.P.)_T}.$$

The result of such a subtraction for the thermal column foil is actually

$$\frac{(Np)_T}{(Np + F.P.)_T},$$

since U^{237} production in the thermal column position is negligible. Division of

$$\frac{(Np + U^{237})_x}{(F.P. + Np)_T}$$

by

$$\frac{Np_T}{(Np + F.P.)_T}$$

puts each fission product corrected activity in the form

$$\frac{(Np + U^{237})_x}{(Np)_T}$$

which is convenient for the application of the correction for the U^{237} component.

3. Correction for U^{237} Activity

U^{237} is present in the irradiated uranium foils as a consequence of a 6 Mev threshold $(n, 2n)$ reaction on U^{238} . The gamma radiation which accompanies its 6.75-day decay contributes to the activity observed in an energy window centered on the 100-keV Np^{239} peak, as shown graphically in Figure 18. Figure 18 is a plot of the results of scans of chemically-separated uranium and neptunium components of a foil which was located in the core at $R = 0$, $h = +4.76$ cm during the first irradiation. These components were subsequently extracted for a comparison of the Np^{239} and U^{237} activities. Repeated scans confirmed the reported half-lives and revealed no extraneous activities. The plotted data were obtained three weeks after the irradiation, and the samples were counted in the same geometry.

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A recent investigation⁸ confirms the U^{237} decay structure observed here and provides an explanation for the origin of these peaks. A magnetic lens beta-ray spectrometer and scintillation spectrometers for betas and gammas singly and in coincidence were used to establish the complicated decay scheme of U^{237} . The predominant transition involves a 245-kev beta ray in cascade with gamma rays of 59 and 207 kev. The probability for internal conversion of the latter gamma ray is high, thereby accounting for the comparable intensities of the peaks at channel levels of 20 and 34. Other high-energy gamma rays of appreciably lower yield also contribute to the production of K_{α} radiation from the Np product atom, and there is indirect evidence for a 102-kev gamma ray which would add to the peak near 100 kev. The displacement of the U^{237} and Np^{239} peaks is due to the slight difference in the energies of the K_{α} radiation from Np and Pu, the daughter atoms.

The known half-lives for Np^{239} and U^{237} were utilized in the correction of the observed activities for the contribution of U^{237} . Initially, the activities of the separated U and Np components of several of the Run 3 foils were determined, but the observations indicated an incomplete separation of the components. Consequently, the actual correction is based on a comparison of the sum of the components, and their activities at eight and fifteen days after irradiation were used to deduce the relative contributions by U^{237} and Np^{239} .

Such observations were available only for a few of the foil positions used in the first irradiation; therefore the method used for the similar situation in the case of the fission product correction was employed. In this method the fraction of U^{237} activity present in the U^{237} and Np^{239} components,

$$\frac{(U^{237})_x}{(U^{237} + Np)_x}$$

was plotted as a function of the fission product activity at x relative to that at the core center,

$$\frac{(F.P.)_x}{(F.P.)_c}$$

A straight line was fitted to the points plotted and the slope determined. The ratio

$$\frac{(U^{237})_x}{(U^{237} + Np)_x}$$

is time dependent; thus several such curves were plotted to determine the time variation of the slope, $U(t)$. This factor varied smoothly from 0.042 to 0.115 in the interval from two to eight days after irradiation.

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Application of the correction for U^{237} activity to the ratio

$$\frac{(Np + U^{237})_x}{(Np)_T}$$

resulting from the correction for fission product activity was accomplished in the following manner:

a. The proper value of the slope factor was combined with the appropriate value of

$$\frac{(F.P.)_x}{(F.P.)_c}$$

to give

$$\frac{(U^{237})_x}{(Np + U^{237})_x} = U(t) \frac{(F.P.)_x}{(F.P.)_c} .$$

This may be written as:

$$\frac{(U^{237})_x}{(Np)_T} = \frac{(Np + U^{237})_x}{(Np)_T} \cdot U(t) \frac{(F.P.)_x}{(F.P.)_c} .$$

b. Now

$$\frac{(Np)_x}{(Np)_T} = \frac{(Np + U^{237})_x}{(Np)_T} - \frac{(U^{237})_x}{(Np)_T} ,$$

so the desired quantity is obtained from

$$\frac{(Np)_x}{(Np)_T} = \frac{(Np + U^{237})_x}{(Np)_T} \left[1 - U(t) \frac{(F.P.)_x}{(F.P.)_c} \right] .$$

This method of correction for the U^{237} activity is based on an assumption that the spectra of >1 and >6 Mev neutrons have the same spatial variation in the reactor. The two sets of data used to determine the relative contributions of U^{237} and Np^{239} to the activity observed in the window centered on the neptunium peak were obtained under different experimental conditions. The components were counted separately and the activities interrelated by means of a reference foil on the eighth day, while the components were superimposed in the observations made on the fifteenth day. Thus, the conditions of attenuation and uranium "amplification" are not identical. The effect of these sources of error is not considered serious because of the small magnitude of the correction for activity originating in the U^{237} decay.

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4. Counting Losses

Counting loss in differential counting is a complicated phenomenon. In Geiger counting, each beta particle or gamma ray which loses any of its energy in the active volume of the counter results in a pulse, and only if a second energy loss occurs before the counter recovers from the first event is the event undetected. In pulse and proportional counters only those events involving more than a selected energy release are detected; occurrence of two such events involving more than a selected energy release are detected, and occurrence of two such events within the resolving time of the counter and associated circuitry results in a counting loss. An additional effect, not present in Geiger counting, tends to offset this counting loss. This phenomenon, termed "piling up," results when two or more pulses, each below the minimum energy, occur sufficiently close together in time that they add up to produce a composite pulse of sufficient size to be detected. The relative importance of these two effects which cause a difference between the actual and observed number of events is dependent upon the number of events above the minimum energy and the number and distribution of those below the selected energy threshold.

When it is desired to detect only those events in a definite energy range, the mechanism for counting loss is even more involved. In addition to losses due to the occurrence of two pulses in the energy range of interest within the resolving time and gains through pile-up of pulses to achieve a composite pulse of the proper range of energies, the near-coincidence of a pulse within the proper energy range with any pulse such that the composite is sufficiently energetic that it falls above the upper limit of the range of energies also causes a counting loss. Thus the counting losses encountered in the detection of the Np^{239} activity depend upon the energy spectrum of events below, in and above the energy window.

A further effect, resulting from the design of the particular differential pulse-height analyzer used for these measurements, influenced the counting losses. A single-channel analyzer determines whether or not a pulse has crossed the lower boundary of the energy window and also whether or not the pulse has crossed the upper boundary. The signals indicating a lower- or upper-level crossing are obtained from two voltage discriminators. A lower-level crossing generates an output signal which is suppressed if the upper level is also crossed. In the circuit used the duration of the suppression of signals from the low level unit was dependent upon the amount by which a pulse exceeded the upper boundary.

The strong dependence of counting losses upon the energy spectrum of pulses from the crystal and photomultiplier combination and marked time variation of the spectrum because of the mixture of half-lives present, made the avoidance of counting losses a more practical approach than the correction for them. To establish a criterion for negligible counting losses, a supplemental measurement was performed. Two foils, whose

100-kev activities differed by an appreciable factor, were counted successively at each of several distances between the foil holder and detector. The observed ratios were plotted as a function of the counting rate of the more active foil, and an estimate of the rate at which losses became significant was deduced from the deviation of the ratio from its asymptotic value. Because the loss is strongly dependent upon the fraction of events outside the energy window, the foil located at the reactor center was compared with one for which the fraction of the fission product and U^{237} components was appreciably smaller. Two representative sets of data are plotted in Figure 19 for the C- and T-foil ratio twelve days after irradiation and for another pair of foils seven days after exposure. The error limits shown are those associated with statistical inaccuracies. From such observations it was decided that a maximum window counting rate of 6000 per minute was desirable. For some of the data reported, the counting rates were slightly higher for the most active foil in the group counted, but the average counting rate was much lower.

E. Summary and Evaluation of Data

The average value of the net Np^{239} activity for each of the depleted uranium foils irradiated in the EBR as a part of the conversion ratio measurements is included in Tables III, IV or V. Measurements made on foils involved in the first three irradiations are reported in Table III. The coordinate location is given for each foil, together with its U^{238} fission product activity relative to that of the foil located at the core center and the net Np^{239} activity resulting from the application of the corrections discussed above. The U^{238} fission rate data were considered previously (see page 17) in connection with the correction of the observations of Np^{239} activity for a fission product component.

The average Np^{239} activities given in Table III are related to the Pu^{239} production rate at the normalization point in the thermal column. These values have all been corrected in the manner outlined above, and they have been normalized to the U^{235} fission rate data by means of a factor whose derivation is given in a subsequent section. The number of observations on which these averages are based varied from two to five. Core and inner blanket data are based on two sets of observations for the Run 1 foils and five for the Run 3 foils. The outer blanket (cup) data are averages of four values for the Run 1 foils and five for those from Run 3.

The individual values of the corrected activities differed from the average for each foil by less than 2% in 82% of the observations. In general, the spread in the individual values decreases with increasing radius, indicating that the errors associated with the application of the corrections for U^{237} and fission products are larger than those resulting from reproducibility of counting conditions and statistics. Approximately two-thirds of the plutonium production in the EBR occurs in the cup (outer

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blanket). Those foils which were located in the cup were counted more frequently, and their reproducibility was better than average. Consequently, an estimate of plutonium production based on the data reported here will be appreciably less in error than implied by the $>2\%$ deviation of 18% of the individual observations.

The plutonium production patterns derived from the measurements reported in Table III are shown in Figure 20 for the core and inner blanket, in Figure 21 for the radial portion of the outer blanket (cup), and in Figure 22 for the base of the outer blanket. The curves were plotted in a manner consistent with experimental observations; wherever repeated measurements (third irradiation) were made they were weighted more heavily in fitting the experimental data. The scatter in the inner blanket data is, in part, due to the omission of any provision for centering of the foils placed between the 0.9-in. diameter slugs in this region of a strong flux gradient in the radial direction. A cross-plotting procedure was utilized in the construction of the curves followed in the integration of these patterns, so that the curves plotted in Figure 22 differ somewhat from those actually used in the evaluation of the total plutonium production.

The results of those irradiations undertaken to provide more detailed information on the production and fission patterns in the outer portion of the cup are summarized in Tables IV and V. The observed Np^{239} and U^{238} fission product activities from the foils of Runs 4 and 5 have been normalized to the results given in Table III through the common inner blanket activities. The reported activities of the copper and U^{235} foils are considered later as a part of the determination of the U^{235} fission patterns. Data on the relative Pu^{239} fission product activities have been included in Table V only to indicate which of the U^{238} foils were partially screened from the true flux because of the proximity of Pu^{239} (and U^{235}) foils. Values of the Pu^{239} fission rate are given in terms of an arbitrary rate of 100 at the core center.

The data in Table IV reveal a definite variation of the radial patterns with angular location for Pu^{239} production, U^{238} fission, and U^{235} fission. In each case the effect of a solid graphite reflector (C-2 data) is to enhance the production and fission for a depth of at least 1 in. The very sharp rise in plutonium production, however, is confined to the outermost $1/4$ in. These results served to explain the discrepancies between the physical and chemical determinations of the fission and capture rates in the outer blanket (cup) and also provided better physical data on the conversion ratio in the outer blanket.

No explanation is available for the pronounced disagreement in the run 4 data for the outer foils of the two holders in brick K-5. For foils in holders No. 2 at K-5 and No. 1 at G-5, a sharp rise in U^{238} capture rate was observed in the outermost $1/4$ in. of the cup brick, while none was observed in holder No. 1 at K-5. The U^{238} fission rate behaves in a similar

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fashion. The U^{235} fission rate does show some rise near the outer edge of the brick for holder No. 1 at K-5 but levels off in the outer $1/4$ in. The fission and capture rates are higher in brick G-5, which is opposite fairly solid graphite, than in brick K-5, which is nearly in line with a hole. Reference to Figures 3 and 4 shows that holder No. 2 at K-5 is more directly in line with the hole than holder No. 1, yet foils in the latter position fail to show the rise. Some of the measurements in holder No. 1 at K-5 were repeated in the second irradiation and additional foils were placed on the circumference of brick K-5. These new observations, included in Table V, did not confirm this anomalous behavior.

The importance of the graphite reflector to Pu^{239} production in the outer portion of the blanket is revealed by Figure 23. The maximum rates are observed for foils located in the E-5 brick which faces the thermal column. The foils in the G-5 brick, which is located near fairly solid graphite, were only slightly less active. The effect of the beam hole near the K-5 brick in reducing the observed rates is shown to be appreciable. Reference to Figure 4 reveals that even the slight differences observed at the two locations within a brick can be correlated with the structure of the graphite reflector near the brick. The activities of the foils located in the outermost position of holder No. 1 at K-5 in the fifth irradiation are more consistent with the other data than those obtained in the fourth irradiation. An average of the Np^{239} activities observed for the foils located on the outer face of the K-5 brick was used to correct the Np^{239} activities of the outermost U^{238} foils in the E-5 and K-5 bricks for the effect of screening by the U^{235} -Al and Pu^{235} -Al foils.

Some of the observations included in Table V have been used, together with the rod No. 268 data from Table IV, to construct a curve showing the radial variation of Pu^{239} production rate on the reactor mid-plane (Figure 24). Data from the E column of cup bricks have been used; therefore the curve shows the maximum radial rates existing in the EBR. A second curve derived from the results obtained in the first irradiations is included in Figure 24. The curves have been normalized in the vicinity of the inner face of the cup. The deviation of these curves in and near the core is the result of the omission of a correction of the Np^{239} activities from Runs 4 and 5 for the U^{237} and fission product activities. The better definition of the outer blanket production pattern, made possible by the subsequent measurements, is illustrated by these curves. The effect of neutron streaming between the cup bricks makes the effective radial location of the outermost column of foils in the original measurements greater than the actual distance involved, and the attenuation of the reflected plutonium-producing flux is more rapid than originally assumed.

The determination of the integrated plutonium production in the EBR from the data reported in this section is subject to errors in addition to those associated with the measurement of the net Np^{239} activity of the

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irradiated foils. During the initial irradiations, the outer blanket was located below the position of maximum effectiveness, so that a significant fraction of the neutrons produced were lost by leakage over the top of the outer blanket. The results of the subsequent measurements demonstrate that an assumption of symmetry for the plutonium production in the cup is unrealistic. However, the data do not provide sufficient information to allow an accurate correction for the effect of voids in the graphite reflector, because measurements were made at only one height and a few angular locations. These data also show that the initial measurement of the distribution of plutonium-producing flux near the outer edge of the cup was in error because of neutron streaming, but they make possible an accurate correction of the original results only at a single height.

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III. MEASUREMENT OF U^{235} FISSION PATTERNS

A U^{235} fission chamber of the gamma-ray compensated type was used to establish the relative distribution of U^{235} fission-producing flux in the core and inner blanket of the EBR. Measurements made with this chamber and copper and U^{235} foils have been combined to provide this same information for the outer blanket.

A. Experimental Observations

For the initial measurement of the U^{235} fission patterns in the EBR, a choice of methods was available. Because of anticipated difficulties due to the high background of gamma radiation if counters were used and a lack of knowledge of the dependence of the decay rate of fission product activity induced in foils upon the energy of the incident neutrons, it was decided that the use of a compensated current chamber was the most reliable method.

A cross section of the chamber used is shown in Figure 25. Three parallel aluminum plates define the two active volumes. A coating of 0.15 mg/cm^2 of 93% enriched uranium oxide is plated on the facing sides of two of these electrodes to provide a chamber which is sensitive to both neutrons and gamma radiation. Ionization in the other volume is produced only by gamma-rays. The use of a hydrogen-free insulator (Teflon) serves to reduce the degradation of neutron energy by the chamber. The chamber is filled with air at atmospheric pressure.

In operation, 300 v is supplied to the central electrode by dry cells, and the currents from the two collector electrodes are measured separately with an electronic meter. One hundred per cent negative feedback is used to enhance the stability of the linear amplifier. The meter sensitivity allows current measurements over a range from 10^{-11} to 10^{-6} amp. Multiplying factors among the different scales and the linearity of chamber response were determined in the Argonne Heavy Water Reactor (CP-3¹) and rechecked roughly during the measurements in the EBR.

Fission rate traverses were made along axial lines through the core and inner blanket by passing the chamber through empty thimbles. No more than two thimbles were placed in the reactor at one time, and these were widely separated. Stainless steel thimbles passing through the core and normal uranium sections above and below the core had an ID of 0.404 in. Similar thimbles, except for an ID of 7/8 in., passed through the inner blanket surrounding the core. A single axial traverse was made in the outer blanket or cup by placing the chamber on a dummy aluminum control rod which was moved in the usual manner.

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Radial fission rate traverses were obtained for a given horizontal plane by taking values from the axial traverses at a common height. Rod positions were selected along two radial directions in the core, one along a diagonal of the hexagon and one perpendicular to one face. The inner blanket positions were an approximate extension of the latter direction.

All of the fission rate pattern measurements in the core and blanket and the normalization measurement in the thermal column were made at the same pile power of approximately 5 kw. The power level was monitored by a boron current chamber placed in the reactor shield. It was not compensated for gamma backgrounds. This background reading is independent of the previous power at which the pile was operated. After a few hours operation at full power it can be equivalent to a neutron signal corresponding to a level of 20 watts. This value can be neglected at the operating power for this experiment. Furthermore, all the fission pattern measurements were made after at least a two-day shut-down period. For this work the chart reading on the vibrating reed electrometer was kept between 96 and 97 on the 100 scale with a 10-megohm resistor in the circuit. Since the maximum chart reading was 100, the extremes of power variation were within approximately 1%.

The current from the fission chamber registered on a meter scale with 100 divisions. It was read approximately to the nearest tenth of these divisions. With the chamber working properly, it was, in general, possible to reproduce a gamma-compensated fission current when repositioning the chamber to within 1%. Some difficulty was experienced with the electrical contacts between chamber electrodes and the lead wires. Nearly all of the currents from points throughout the core and blanket and in the thermal column were read on the linear scale measuring up to 10^{-7} amp.

Figures 1 and 2 show rod locations in the core and inner blanket and the structure of the outer blanket or cup. Fission rate pattern data taken in the core and blanket appear in Table VI. The readings from both sides of the chamber are given. The difference, giving the current due only to fission fragment ionization, is the most reliable. The electronic meter was frequently adjusted with the voltage electrode grounded, so that the reading from the uncoated portion of the chamber gives the signal due to the background and operating gamma radiation. There should be a very small contribution from recoil atoms produced by the fast neutron flux, equal on both sides of the chamber. The gamma correction is relatively large at the center of the core, amounting to about 35% of the total reading from the neutron sensitive portion of the chamber and decreasing away from the core center. Distances given are measured from the reactor mid-plane. The last column ($I_{\text{norm}}^{U^{235}}$) for each rod position gives fission rate values normalized to 100 at the center of the core after correction for the fission of the U^{238} contained in the enriched material. This correction, based on earlier

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measurements⁹ of the relative fission rates of U^{238} and U^{235} at the center of EBR, had a maximum of approximately 1% at the center of the core. Representative axial distributions of the U^{235} fission-producing flux are plotted in Figure 26.

The structure of the outer blanket (cup) precluded a detailed survey of the U^{235} fission pattern with the compensated fission chamber used for the measurements in the core and inner blanket. The single axial distribution measured with the chamber in a control rod hole in the cup was supplemented by foil activations. Initially copper foils were irradiated in those positions throughout the cup which were inaccessible to the chamber. In subsequent measurements, U^{235} -Al foils were used to provide a direct measurement of the quantity of interest.

Copper foils were included with each of the U^{238} foils placed in the outer blanket during the first and third foil irradiations performed as a part of the conversion ratio measurements. These runs were described in detail in Section II-B. The foils were approximately 1/4 in. in diameter and 0.003 in. thick. The relative copper foil activities were determined with an RCL end-window counter. During the period of counting, one of the foils was remeasured at intervals to check on the decay rate. Table VII gives the locations of the copper foils and their relative activities normalized to the U^{235} fission chamber measurements made in the cup. The outer blanket chamber data are also included. The axial distributions derived from these results are plotted in Figure 27.

A radial plot of the U^{235} fission rate on the mid-plane of the EBR, constructed by cross-plotting of the axial fission chamber and copper foil data, is shown in Figure 28. An asymmetry of geometrical origin in the core is clearly shown by these data. The radial U^{235} fission-producing flux drops most rapidly in the direction of the corners of the hexagonal core. The extension of the radial plot through the outer blanket was made with the normalized copper foil data.

Inspection of the distributions observed with copper and U^{235} in the cup (Figure 27) reveals that the response of these detectors is not identical. Only 6% of the U^{235} destruction occurs in the outer blanket of the EBR, consequently no large error would result in the conversion ratio derived from an assumed equivalence of the neutron response of U^{235} and copper. Nevertheless, the relative sensitivity of these materials to a varying neutron energy spectrum was compared in a subsequent irradiation in the EBR.

Pairs of copper and U^{235} -Al foils were inserted at each of six locations along a radius near the outer face of the cup. The details of the size, location and irradiation of the foils were presented in Section II-B as a part of the description of Run 4. The observed activities are included in Table IV. The given copper foil activities are averages of two sets of

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observations made with a scintillation counter on the first and second days after irradiation. These copper foil activities have been normalized to the U^{235} chamber data in the outer blanket, as was done with the original copper data. Because of the low activity of these foils, all events above the circuit noise level of approximately 20 kev were detected. Each value was corrected for the scintillation counter background, 12.8-hour radioactive decay and foil weight.

The U^{235} fission product activity was determined in a manner identical with that described previously for U^{238} . Only those interactions of fission product gamma-rays in the crystal resulting in a minimum energy loss of approximately 500 kev were detected. Each of the values of U^{235} fission product activity reported in Table IV is an average of four determinations made during the second day after irradiation. The activities reported are normalized to the current chamber measurements in the inner blanket. All observations were corrected for counter background, variations in foil weight and radioactive decay. The activities of the paired copper and U^{235} foils, are plotted in Figure 29. These results do not substantiate the original assumption of the equivalence of copper and U^{235} as neutron detectors.

In the course of the measurement of the angular asymmetry of plutonium production in the outer blanket, similar data were obtained for the fission of U^{235} . U^{235} -Al alloy foils were used for these cup measurements, and foils were also activated simultaneously at a few positions in the core and inner blanket, in order to normalize these results to the current chamber measurements. These measurements formed a part of Runs 4 and 5 which were discussed previously. Foil coordinates and observed U^{235} fission product activities, normalized to the current chamber data in the inner blanket, are given in Tables IV and V. The results for Run 4 foils are averages of four determinations. Each of the activities from Run 5 is based on a minimum of two observations. The rod foil data used were obtained following decay of an Na^{24} activity resulting from a 2.4-Mev threshold (n,α) reaction of the aluminum in the alloy foils. Data from these irradiations (Figure 30) show the effect of reflector solidarity on the U^{235} fission rate in the outer blanket. As was observed for the plutonium production, the rates can be correlated with the density and thickness of the graphite reflector. The pronounced increase in U^{235} fission, due to reflected neutrons, extends deeper into the outer blanket than was observed for Pu^{239} production.

Some of the observations included in Table V have been used, together with the value of rod No. 268 from Table IV, to construct a curve, Figure 31, showing the radial variation of the U^{235} fission rate on the reactor mid-plane. Data from the E column of cup bricks have been used; therefore the curve shows the maximum rate existing in the outer blanket of the EBR. Also included in Figure 31 are values based on the U^{235} fission rate as determined with the compensated current chamber. The single core foil activity

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given is uncertain because of a discrepancy in weight (see below), but the value plotted, although it falls significantly above the current chamber curve, is believed to be a lower limit. The U^{235} foil data show an effect due to neutron streaming in the gap between the inner tank and the cup, whereas the single current chamber measurement in the cup is ostensibly uninfluenced by the void.

The "weight" correction applied to each of the observed activities for the U^{235} -Al alloy foils actually utilizes the natural activity of the foil because of the inhomogeneity of the alloy. The foil located at the core center in Run 5 appeared to experience a weight decrease from 6.6 to 6.45 mg between shipment to the EBR and subsequent counting. If the initial weighing was not in error, an allowance for the loss of material would increase the reported value of 3.32 to 3.40.

The distribution observed with U^{235} -Al foils along the central axis is compared in Figure 32 with similar axial U^{235} fission rate curves obtained in this conversion ratio measurement with a current chamber and as a part of some shielding studies¹⁰ with a U^{235} -coated fission pulse counter. The chamber and counter data are normalized at the core center, and their agreement is excellent. All axial foil data plotted, although previously normalized to the chamber measurements in the inner blanket, had to be multiplied by an additional factor of 0.82 to produce the indicated agreement with the chamber and counter results.

B. Random and Systematic Errors

The magnitude of many of the errors associated with the determination of the U^{235} fission pattern in the EBR is difficult to assign. In several cases these errors are of only minor importance because they are associated primarily with data for a region of low contribution to the total U^{235} destruction.

The routine difficulties of power-level monitoring, chamber and circuit linearity, accuracy of meter reading and reproducibility of observations in measurements made with compensated chambers have already been considered. The effective volumes of the chambers were identical to within 2%, as determined by measurements made with uranium lining both regions. This results in an error of less than 1%, because the gamma-radiation signal never exceeded 35% of the current due to neutrons and gamma radiation. The fact that signals of comparable magnitude must be subtracted in order to determine the neutron component also serves to limit the accuracy obtainable in the current chamber measurements of the U^{235} fission rate. Another error associated with the chamber measurements is of a geometrical nature. The chamber used fitted snugly in the thimbles which were inserted for measurements in the core, but there was room for appreciable radial motion in the inner blanket and cup measurements. The

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instrument was suspended in the empty thimbles, and the strong radial flux gradient, especially in the inner blanket, made possible a large effect due to lateral motion. Nevertheless, the error introduced by such an effect is slight because the U^{235} isotopic content of the blanket uranium is far less than that of the core.

Several effects other than counting statistics and errors associated with weight corrections serve to limit the accuracy of the foil measurements of the U^{235} fission rate patterns. Data were presented in Figure 29 to show the extent to which copper deviates from U^{235} in neutron response at several locations in the outer blanket. The copper foils were positioned with the U^{238} foils in Run 1 and, consequently, the outermost column of foils, at $R = 38.6$ cm, is subject to the same errors due to neutron streaming between the cup bricks that were mentioned as a weakness in the initial irradiation of the U^{238} foils. The U^{235} -Al foils involved in Runs 4 and 5 were shielded in part by adjacent foils of dissimilar materials which would modify both the flux intensity and neutron spectrum at the point of measurement. No special device was used to insure that the rod foils in these irradiations were centered in the slug-filled thimbles, so that there exists the possibility of an error in the coordinate location assigned to the rod activities.

Two other potential sources of systematic errors exist, one a neutron spectrum effect, and the other a consequence of neutron streaming. The dependence of the neutron response on the neutron spectrum has been considered analytically for the U^{235} fission current chamber and investigated experimentally for the U^{235} foils. Evidence for the existence of an effect due to neutron streaming along the empty thimble in which chamber measurements were made is contradictory.

If the ionization current produced in the chamber by a fast fission differs from that produced by a thermal fission, then fission rate comparisons made with a current chamber as a part of the conversion gain measurements would be in error. The air gap between the electrodes of the fission chamber was 1.5 mm, which is a very short gap compared to the range of fission fragments. The range of the heavy fragment is 19 mm of air, while the light fragment has a range of 25 mm. The thickness of the fissionable coating on the chamber electrode was only 0.15 mg/cm^2 , which is thin compared to the range of fragments in uranium. Thus, the majority of those fission fragments which traverse the air gap expend most of their energy in the metal of the opposite plate.

Under these conditions, the ionization produced in the air gap by a fission fragment is related to the rate of energy loss at the start of the fission track. Measurements¹¹ have been made which indicate that the initial ionization density varies approximately as the square root of the fission product energy. More accurate expressions, derived from the referenced measurements, are as follows:

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Light fragments: Initial ionization density = $2.38 (\sqrt{E} + 0.63)$
 Heavy fragments: Initial ionization density = $2.17 (\sqrt{E} + 0.69)$

The energy distribution of fission fragments from U^{235} has been measured as follows:

	Thermal	~0.7 mev	2.5 mev	14 mev
By Fowler and Rosen ¹²	X	X		
By Davis and Friedland ¹³	X		X	X

These data were integrated to obtain the average initial ion density produced by a fission product. The results were then normalized to the ionization produced by a fragment from thermal fission. A portion of a curve by Davis and Friedland for 2.4-mev fission was redrawn to better fit the experimental points and to indicate a maximum energy consistent with observations at thermal and 14 mev. These integrations resulted in the following values:

<u>Neutron Energy</u>	<u>Initial Ionization</u>
Thermal	1.000
About 0.7 mev	0.987
2.5 mev	0.999 (Would be 1.014 if based on the original curve)
14 mev	0.988

From these results it is apparent that the ionization current produced in the chamber by a fission in the core of the EBR will not differ appreciably from the current produced by a thermal fission. Thus, an appreciable error due to variation in current per fission due to neutron spectrum would not occur in the comparison at the core center and thermal column location necessary for a normalization of fission and production patterns.

To provide information on a possible dependence of fission product decay rate on the energy of the neutrons causing fission, sandwiches of Al, U^{235} -Al, and natural uranium foils were irradiated simultaneously in the converter thimble and goat hole of the Argonne Heavy Water Reactor (CP-3'). The converter thimble is a facility which provides a neutron spectrum rich in high-energy neutrons. This is achieved by a sleeve of a 7.5% enriched uranium-aluminum alloy (1.07 in. ID x 1.50 in. OD) into which a sample may be inserted for irradiation. Because the U^{235} -Al sleeve is not opaque to thermal neutrons, the spectrum incident on the foil sandwich was further hardened by 8.7 gm of B_4C which surrounded the foils. The goat hole is a graphite column provided for sample irradiations in a flux of thermal neutrons. Each foil was separated by aluminum sufficiently thick to prevent the interchange of recoil fission fragments.

A scintillation counter was used to observe the activity induced in these foils. Only those disintegrations which resulted in a minimum energy loss of $1/2$ Mev in the NaI crystal were detected. Unirradiated foils were used to provide the proper background corrections, and the decay rates up to six days after the irradiation were interrelated.

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The observed decay of the enriched uranium sample located in the converter thimble is shown in Figure 33. The contribution of the aluminum with which the uranium was alloyed has been subtracted. From the activity observed for the natural uranium foil similarly located, it is known that the contribution from fission of the 6% of U^{238} present in the alloy foil is negligible, so that the curve shown represents the decay of fission products formed only by the fast fission of U^{235} . Also included in Figure 33 are the observations on the U^{235} sample from the thermal flux location. These data have been normalized in the time interval from 40 to 80 hr. The deviation of these sets of results for shorter times after irradiation is qualitative evidence of a slight dependence of the U^{235} fission fragment distribution on the energy of the neutron causing fission. However, the deviation over the interval normally used in observations of activities is not sufficiently large so as to be a cause for concern in the use of foils for U^{235} fission pattern measurements.

With one exception, the U^{235} fission rate measurements made with the compensated-type of current chamber were performed in empty thimbles which replaced rods in the EBR lattice. Because of the possibility of an effect due to neutron streaming, U^{235} slugs were placed below the chamber and steel sleeves around the cable above the chamber in the normalization measurements made at the core center. This procedure increased the observed fission rate by approximately 2%. Contradictory evidence on the effect of neutron streaming was revealed in the comparison of the foil and chamber U^{235} fission rate distributions. Significantly different normalization factors were needed to yield the agreement shown in Figures 31 and 32 for the radial and axial directions. The foils were positioned between fuel slugs, and consequently the possibility for neutron streaming is present only in the chamber data. The higher value for the ratio of chamber current to foil activity in the radial direction is not in accordance with the suspicion that neutron streaming in the hole left by the removal of a rod influences the axial distributions measured with the current chamber. Such streaming would lower the peak value of an axial distribution relative to the values removed from the region of maximum intensity. No evaluation of the error in the U^{235} fission rate measurements due to neutron streaming is possible until the cause of this apparent contradiction is understood.

IV. NORMALIZATION OF THE U^{238} CAPTURE AND U^{235} FISSION PATTERNS

The conversion ratio (CR) for the Experimental Breeder Reactor (CP-4) is defined as the ratio of Pu^{239} production to U^{235} destruction. This may be expressed as the product of two ratios, as follows:

$$CR = \frac{Pu^{239} \text{ production}}{U^{235} \text{ fissioned}} \cdot \frac{U^{235} \text{ fissioned}}{U^{235} \text{ fissioned} + U^{236} \text{ production}}$$

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The latter ratio has been established by a mass spectroscopic measurement of U^{236}/U^{235} combined with a radiochemical determination of the U^{235} fissioned, for several locations in the EBR.¹⁴ The physical measurement of the Pu^{239} production and U^{235} fission patterns has been reported in the preceding sections. The interrelation of these patterns necessary for a determination of the EBR conversion ratio is discussed below.

In order to correlate the plutonium production rate with the U^{235} fission rate, it is necessary to compare the sensitivities of the detectors used for these measurements. Such a comparison was made in a thermal flux in which the cross sections of the detector materials are known. To this end the fission current chamber and a depleted uranium foil were irradiated in the same reproducible position in the thermal column of the EBR. This current chamber reading was compared with the chamber response at the core center, to which all other fission rate measurements had been related, as discussed in Section III. All plutonium production rates were referred to the activity of the thermal column foil, as described in Section II. The response of these detectors when encased in cadmium was also determined so as to make possible a correction for the effect of epithermal neutrons.

A. Experimental Procedure

For the purpose of locating a normalization point in the thermal column at which the fission rate was comparable with that at the core center, a traverse was made from the edge of the graphite reflector outward through an approximately 1/2-in. square channel. The results are shown in Figure 34. Although this measurement was made quickly without regard for great accuracy, it is of interest to compare the chamber response with that of gold foils irradiated by Persiani and Ringo.¹⁵ In the present measurement, the thermal flux peaks farther out in the graphite. This may be due to leakage of fast neutrons farther into the graphite in the present arrangement. After equilibrium has been established, the flux is attenuated exponentially with approximately the same rate of a factor of 10 in 63 cm in both measurements.

Both the chamber and the U^{238} foils were located in turn at the center of an approximately 3 in. x 4 in. x 6 in. cavity in a graphite stringer of the thermal column. This stringer had a 1/2-in. diameter hole leading outward for the chamber cable. This precaution was taken to minimize the flux perturbation by the chamber or the foil which was mounted in a holder duplicating the chamber in geometry and materials. The detector position was 53 cm from the inner edge of the graphite reflector.

1. Current Chamber Measurements

Although the fission rate traverses throughout the core and blanket were made in empty thimbles, it was desirable to reduce the neutron streaming in order to obtain an absolute reading. Consequently, U^{235} slugs

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were placed below the chamber and steel sleeves around the cable above. The chamber thus positioned at the core center indicated a fission rate approximately 2% higher than that observed in an empty central thimble.

The comparison of chamber response was based on successive measurements at the core center and the thermal column location. Observations at the first location were occasionally repeated immediately after the second series of readings. Several such sets of measurements were made prior to the fission rate traverses and a single set a few days later. Table VIII gives the result of each set of measurements. The root-mean-square deviation from the average of all results is 1.2%.

The measured factor indicates that there were $1/0.922$ U^{235} fissions in the thermal column location for each one at the core center. The thermal column reading was reduced by a factor of 82.6 when a cadmium can with a 30-mil wall thickness was slipped over the chamber. Thus the thermal fission rate at the normalization point was $\frac{(1-1/82.6)}{0.922} = 1.071 \pm 0.013$ times the fast fission rate at the center of the core.

2. Foil Measurements

A bare, depleted uranium foil sandwich was positioned in the thermal column location during the first irradiation on October 9, 1952, and a cadmium-covered sandwich was exposed shortly thereafter (Run 2). The first irradiation was at 25 kw from 0445 to 1245, and the second at 104 kw from 1520 to 1715. The weights of the central foil in each sandwich were 71.7 and 69.0 mg, respectively. Their activities were compared on twelve occasions during the foil counting on the seventh and eighth days after irradiation.

The average ratio of the cadmium-covered foil in the thermal column (CD) to the T-foil, corrected for counter and foil backgrounds, differences in weight and fission product activity, was 0.3211 with a root-mean-square deviation of 3.4%. An average ratio of 0.3219 deduced from plots of the decay curves for the CD- and T-foils is in excellent agreement with the value obtained from the individual comparisons.

The Np^{239} activity at a time t after an irradiation time τ at a flux level ϕ is proportional to:

$$\frac{\lambda_B}{\lambda_B - \lambda_A} \phi \left[e^{-\lambda_A t} (1 - e^{-\lambda_A \tau}) - \frac{\lambda_A}{\lambda_B} e^{-\lambda_B t} (1 - e^{-\lambda_B \tau}) \right],$$

where λ_B and λ_A are the respective disintegration constants of Np^{239} and its parent U^{239} . It is evident from this relationship that the ratio for CD/T given above requires correction for the difference in power level, irradiation time and decay time for the two foils.

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Because $\lambda_A \gg \lambda_B$, the contribution of the first term is insignificant in the observations made on the seventh and eighth day after irradiation. Consequently, the ratio of CD/T is corrected for the difference in power level and irradiation time through multiplication by:

$$\frac{\phi_T(1 - e^{-\lambda_B \tau_T})}{\phi_{CD}(1 - e^{-\lambda_B \tau_{CD}})} = 0.9655$$

Multiplication by $e^{-\lambda_B \Delta t_0} = 0.946$ corrects for the 4-1/2 hour shorter decay time for the CD foil. Performing the indicated operations yields a value of 0.2933 ± 0.0100 for the ratio of CD/T. This is not the true cadmium ratio because of the use of cover foils. Shielding by the cover foils minimized major surface absorption effects of resonances and thus reduced the resonance capture correction while depressing the thermal flux by only about 0.17%.

B. Calculation of the Normalization Factor

If a value of 100 is assigned to the U^{235} fission rate at the center of the core, then the thermal fission rate at the normalization point is 107.1. This is proportional to the product of the flux and the fission cross section for U^{235} , integrated over the energy range of the thermal flux. Then the U^{238} thermal absorption rate at the normalization point, relative to a U^{235} fission rate of 100 at the core center, may be expressed as:

$$107.1 \frac{\int_0^{E_{CD}} \phi(E) \sigma_a^{U^{238}}(E) dE}{\int_0^{E_{CD}} \phi(E) \sigma_f^{U^{235}}(E) dE}$$

For simplicity the integrals will be replaced by the cross sections at 2200 meters per second. A recent compilation¹⁶ gives the present best values as $2.77 \pm .05$ for $\sigma_a^{U^{238}}$ and 575 ± 9 for $\sigma_f^{U^{235}}$. A 2.7% higher ratio results when these cross sections are averaged over a neutron spectrum composed of a Maxwellian distribution for a kT of 0.025 ev plus a $1/E$ tail joined so that the measured ratio of resonance to total capture for U^{238} is predicted. For this integration the energy dependence for the U^{238} capture cross section was represented by a single-level Breit-Wigner formula, adjusted to give the present best value for 0.025 ev. The U^{235} fission cross section curve used was that of BNL-170-B¹⁶ renormalized to agree with the recommended thermal value.

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The normalized plutonium production rate at any location X may be expressed in a form convenient for application to the measurements reported in Section II as follows:

$$\text{Normalized } U^{238} \text{ absorption rate at X} = \frac{\text{Normalized thermal absorption rate at T}}{\left(\frac{\text{Observed thermal absorption rate at T}}{\text{Observed absorption rate at T}} \right) \cdot \left(\frac{\text{Observed absorption rate at X}}{\text{Observed absorption rate at T}} \right)}$$

The values reported in this section may be used to evaluate the normalizing factor represented by the first ratio. The second ratio is identical with the values of $(Np)_X / (Np)_T$ resulting from the treatment discussed in Section II. Thus, relative to a U^{235} fission rate of 100 at the center of the EBR core, the U^{238} absorption rate at x equals

$$\frac{1.071}{1 - 0.2933} \left(\frac{2.77}{575} \right) 1.027 \frac{(Np)_X}{(Np)_T} = 0.750 \frac{(Np)_X}{(Np)_T}$$

C. Estimate of Error

From the spread in the measured ratios of the response of the U^{235} fission chamber at the center of the core and at the normalization point in the thermal column a probable error of 0.8% is calculated. As shown in Table VIII, the fuel and coolant temperatures were not identical in these sets of measurements. However, Figure 35, a plot of the normalization factor as a function of the fuel temperature, shows little, if any, evidence of a correlation between these quantities. The fission current chamber used for these measurements was not sealed, but the variation in the barometric pressure throughout this series of comparisons was insignificant.

The probable error of 2.3% in the average ratio of the cadmium-covered to the bare thermal column U^{238} foils is an index of the inaccuracies introduced by counting statistics, geometrical effects, circuit instabilities and application of corrections to the observed foil activities. Additional errors in the knowledge of this ratio are introduced because the foils involved were irradiated at different times. It is felt that the only error of possible importance added by this procedure is that associated with the correction of the two activities for a difference in power level of irradiation. Because no monitor foils were employed, the power levels of 25 and 104 kw, as determined by the magnitude of the signals developed by the operating instruments, must be taken with no check available on the linearity of the control circuits over this range.

Errors of $\pm 1.6\%$ and $\pm 1.8\%$ are presently assigned by the Cross-section Advisory Group to the thermal energy neutron cross-sections for U^{235} fission and U^{238} capture, respectively. To these errors is added some unassessable uncertainty in the normalization because of limited knowledge of the energy dependence of these cross-sections and of the neutron energy spectrum at the thermal column normalization point.

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The probable errors of 0.8% for the fission rate comparison, 1.8% for $\sigma_a^{U^{238}}$, 1.6% for $\sigma_f^{U^{235}}$ and 2.3% for the U^{238} thermal absorption rate foil data combine to give a probable error of 3.4% in the value of 0.75 for the normalization factor. This value of 3.4% is a minimum probable error, because it does not include certain effects mentioned above for which no precise error could be estimated. This error in the normalizing factor combines with those associated with the accuracy of the measurements of U^{235} fission patterns, Pu^{239} production patterns, the ratio of captures to fissions for U^{235} and total fissions, and with those resulting from the assumptions made in the integration of the data to limit the precision of the value of conversion ratio for the EBR, as determined by physical methods of measurement.

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V. INTEGRATION OF NORMALIZED DATA

The computation of the EBR conversion ratio from the experimental observations was divided into three parts: (1) the determination of total fissions in U^{235} ; (2) total captures in U^{235} ; and (3) total production in U^{238} . The data obtained in Runs 1 and 3 were used for these integrations, except as specifically indicated.

A. Fissions in U^{235}

The U^{235} fissions occur primarily in the enriched material of the core; therefore the most effort was placed in the calculation of the fissions in this region.

The axial fission data at various radii in the core and inner blanket were plotted and smooth curves drawn through the data as objectively as possible. Cross plots, i.e., plots of fission rate against radius at constant axial position, were then made and the original axial curves adjusted until the radial distribution varied in a smooth manner through the core. The axial curves were then integrated over appropriate intervals to obtain average fission rates. Typical curves of axial fission rate together with the original data are shown in Figure 36. Typical radial cross plots are shown in Figure 37. It is apparent in Figure 37 that two distinct curves appear at each axial position. The higher of these two curves corresponds to core measurements across a flat of the hexagon, the lower curve to measurements across a corner. The distinction appeared to be real, although unexplained.

Since the enriched material of the core was contained in rods of two lengths (7-1/2 in. and 10 in.), it was found convenient to divide the core and inner blanket into several axial sections for which average fission rates were obtained. In Figure 38 the average fission rate in the central 7-1/2 in. of the reactor is given as a function of the radial location of the rod, while in Figure 39 the average fission rate over two other representative regions of the core and inner blanket are presented.

The distribution of U^{235} and U^{238} in the core, inner blanket and cup is given in Table IX. By reference to this information, the curves of average fission rate in the various regions and the total number of fissions in each region was obtained. The results are listed in Table X on an arbitrary scale of mole-fissions, where the U^{235} fission rate at the center is taken as 100.

The remaining U^{235} fissions to be accounted for occurred in the outer blanket bricks, the 12 safety rods and the lower part of the cup. The first was measured with copper foils during a run in which the cup was 2.4 in. down from the uppermost position; the second is available from these foil measurements or a fission chamber measurement in one of the safety rod

holes, and the third was measured with copper foils when the cup was 0.95 in. down. The production measurements in the cup were made simultaneously with the fission rate measurements and have this same discrepancy in cup position between brick measurements and lower cup measurements. Since most of the production is in the bricks, a cup position of -2.4 in. is taken as the standard and other measurements are corrected accordingly.

Typical curves of axial fission rate in the bricks together with the associated experimental data are given in Figure 40. These curves were integrated to obtain the average fission rate in the bricks, which is plotted as a function of radius in Figure 41. The curve of Figure 41 was then integrated radially to obtain the average fission rate and thus the total number of U^{235} fissions in the bricks.

The position of the twelve 26-in. long safety rods during the irradiation of foils in the bricks was as follows: the upper ends of eight rods were 14.06 cm above the mid-plane of the core, that is, at $z = 14.06$ cm; the top edges of the remaining four rods were at $z = -0.97$, -4.01 , -7.06 and -12.14 cm, respectively. The average fission rate in these rods was determined by integrating over the axial distribution of fission rate with appropriate limits. From this result the total number of U^{235} fissions in the safety rods was obtained.

The relatively meager data on U^{235} fission in the lower part of the cup was analyzed in the following manner. The average fission rate at $z = 36.24$ cm was found by performing a radial integration. The average over the cup was then set with the aid of axial integrations at $R = 14.3$ and 19.0 cm. A $\frac{1}{R}$ correction was then imposed on the result to adjust for the relative displacement of the cup with respect to the brick measurements, i.e., the result was lowered by the ratio

$$36.24/36.24 + 2.54 (2.4 - 0.95) = 36.24/39.92$$

The results of the computations on U^{235} fission in the outer blanket are given in Table IX.

B. Captures in U^{235}

The only available data on alpha, the capture to fission rate in U^{235} , comes from mass-spectrographic measurements¹⁴ on samples representative of the average in three different enriched fuel rods.

Rod Hole No.	Radial Rod Location, cm	Rod Length, in.	Alpha = $\frac{\sigma_c U^{235}}{\sigma_f U^{235}}$
1	0	7-1/2	0.11
61	5.019	7-1/2	0.123
170	9.473	10	0.172

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To supplement these data, alpha was assumed to be 0.20 everywhere outside the 7-1/2-in. high, hexagonal core proper. This includes the enriched extensions in the heavy, 10-in. long core rods. Furthermore, to make possible the construction of a curve of alpha versus radius for 7-1/2-in. long rods, a value for the portion of rod No. 170 in the core proper was estimated on the following basis. Approximately 20% of the total fissions in rod No. 170 occur in the extensions. Thus if α_{standard} represents the value for the 7-1/2-in. central section,

$$0.2(0.2) + 0.8(\alpha_{\text{standard}}) = 0.172$$

$$\alpha_{\text{standard}} = 0.165 \text{ at } R = 9.473 \text{ cm}$$

Curves of alpha as a function of core radius, $\alpha(r)$, were then drawn, as shown in Fig. 42. If $(MF)_{\text{rod}}$ designates the mole-fissions of U^{235} in any rod, then the total captures in enriched material is given by

$$\text{Captures} = \sum_{\text{all rods}} (MF)_{\text{rod}} \cdot \alpha(r)$$

and the average alpha for the enriched material is given by

$$\bar{\alpha} = \frac{\sum_{\text{all rods}} (MF)_{\text{rod}} \cdot \alpha(r)}{\sum_{\text{all rods}} (MF)_{\text{rod}}}$$

The value obtained in this manner was $\bar{\alpha} = 0.138$ in the enriched material.

C. Production by U^{238} Capture

The integration of the production data was performed in a manner similar to that used for the fission data. However, the regions of greatest importance to production differ from the situation for fission. First, the axial production data at various radii in the core and inner blanket were plotted, and the curves were so drawn as to obtain smooth radial cross plots. The available production data are rather meager for the region immediately below the core. Although an attempt was made to anchor these curves by fitting them to the data in the lower cup, considerable leeway was still available in drawing the axial curves. Typical axial curves and radial cross plots are presented in Figures 43 and 44, respectively. The latter curves have been extended partly into the cup bricks to show the match obtained with cross plots therein. The former curves were integrated to obtain average production rates over regions of interest to the calculation. The results are plotted as a function of radial position in Figure 45.

The disposition of U^{235} and U^{238} in the core, inner blanket and cup is given in Table IX. By reference to this information and to the curves of average fission rate in the various regions, the total number of captures in these rods was obtained. The results are listed in Table X.

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Production data in the bricks were obtained at five radial positions, with many axial points at each radius. The data were internally consistent to the extent that it took little effort to obtain axial curves through the data giving smooth radial cross plots. Typical axial curves and radial cross plots are presented in Figures 46 and 47. The former were integrated to obtain average production rates for the five radii, but it can be seen from Figures 23 and 24 that the value obtained for the outermost radius cannot be considered representative of that position. As shown in Figure 23, the rise in U^{238} capture is confined mostly to the outer 1/4-in. section of the bricks; hence, the value at $R = 38.58$ cm was shifted outward and the curve drawn with the rise so confined. The results are given in Figure 48. The dotted curve would apply if the outermost foil measurements had not been shifted in position. The curve in Figure 48 was then integrated radially with specific allowance for the cooling and control rod holes to give the average production rate and hence the total production in the bricks. The results are given in Table X.

To find the production in the safety rods at $R = 26.67$ cm, the average for each rod was found as if the rod were in the axial location previously specified in the computation of fissions, but at a radius of 27.146 cm, at which value an axial production curve was available. These axial averages were then adjusted to their proper values in proportion to the ratio of average production rates as read at the respective radii from Figure 48.

The production in the lower part of the cup was found in identical fashion to the fissions therein. The results for this region and for the safety rods are included in Table X.

It should be noted that the data used on production in the cup are not in full agreement with data obtained from subsequent irradiations. A comparison of the $z = 0$ curve in Figure 47 with the results given in Figure 23 indicates that the curve of Figure 47 is probably optimistic, and that a lower rate of production actually exists in the central and outer sections of the bricks. However, data were obtained in Runs 4 and 5 only at $z = 0$, and a sufficient basis for correcting the data at all axial positions does not exist. Hence, the only correction made on the production data of Runs 1 and 3 is that which has already been discussed, concerning the rate of increase in production near the outer face of the cup.

D. Results of Integration

The conversion ratio is calculated to be 0.98 with the cup down 2.4 in. from its uppermost position. The distribution of fissions and captures in U^{235} and of captures in U^{238} is summarized in Table XI, where all numbers are given as the fractional events per atom of U^{235} destroyed in the reactor.

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Since there is a disproportionate amount of U^{238} available to capture neutrons in the lower half of the reactor (even when the cup is all the way up), the conversion ratio has not been obtained under the most favorable condition. It is possible to estimate the increase in the conversion ratio which would be attained by raising the cup 2.4 in.

The average production rate in the bricks, as a function of axial position (Fig. 49), is obtained by integrating radial cross plots such as those of Figure 47. Integrating the curve of Figure 49 over the proper range in z provides a means of obtaining the production in the bricks both when the cup is 2.4 in. down or in its uppermost position, assuming that the flux as a function of z and R remains essentially unchanged as a consequence of this minor perturbation.

On this basis it is found that raising the cup 2.4 in. would increase the production in the bricks and safety rods by 4%, with a corresponding increase in conversion ratio of 0.026. Of course, the lower part of the cup is raised simultaneously to a region of higher flux. Therefore, a $1/R$ correction to the production in this region was applied, resulting in an increase in conversion ratio of 0.008. Hence, the total increase would be 0.034, resulting in a conversion ratio of 1.01 with the cup in its uppermost position.

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VI. DISCUSSION OF RESULTS

The results of the integration of the physical data are compared with the radiochemical results² in the Table XII. All values are on the basis of one atom of U^{235} destroyed in the reactor. The conversion ratio of about unity for the EBR is lower than was originally anticipated. The agreement is better than the probable error of $\pm 5\%$ assigned to the physical measurement. The radiochemical determination was made from samples taken after a long period of irradiation for which an average cup position of 2 in. below the reactor mid-plane would be representative, again indicating better agreement than the rather optimistic probable error.

The somewhat higher production in the outer blanket bricks as determined by physical measurements may be due to radial asymmetries in the EBR. The graphite reflector surrounding the outer blanket has large beam holes, while the radiochemical samples came from a column of bricks in the least favorable position, from the point of view of reflector albedo.

There is rather strong, circumstantial evidence that a considerable number of neutrons are leaking out the blanket of EBR and that a more efficient blanket would make possible a conversion ratio of approximately 1.3.

Multigroup calculations both on EBR and on larger fast reactors indicate that even an 18-in. thick blanket containing 70% uranium by volume allows a significant leakage if not externally reflected. However, if the EBR blanket material were placed symmetrically around the core, the resulting blanket, half of which contains 50% uranium by volume, the other half 75% uranium, would be less than 1 ft thick. In the EBR there is an external graphite reflector around the cup bricks, but 1/7 of the cup bricks face beam holes rather than the graphite reflector.

Furthermore, measurements in the thermal column, where the 2-ft thick graphite reflector is reinforced by several additional feet of graphite, indicate the leakage rate is sufficiently high even in this direction, so that even if the reactor had a 1-ft thick blanket and extra thick graphite reflector in all directions, 2 to 3% of the neutrons would still leak from the blanket.

Insufficient data are available to calculate the leakage through the top and bottom portions of the blanket. However, the contour map of the U^{238} capture rate shown in Figure 50 indicates a high production rate and steep production gradient present at the upper and lower edges of the blanket. No flow of neutrons across the horizontal center line is apparent. The same general characteristics are true of a contour map of the U^{235} fission rate, shown in Figure 51. Thus, while the destruction of U^{235} (over 90% in the core) is very nearly equally divided by the horizontal center line, the production (almost exclusively in the blanket) is not so distributed. It is found that the conversion ratio for the lower half of the reactor is about 1.2 while that for the upper half is roughly 0.8.

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Since there is a considerable amount of leakage even out of the lower half of the reactor, this suggests that an adequate blanket surrounding the entire reactor would achieve a conversion ratio higher than 1.2.

The neutron balance substantiates this hypothesis. The conversion ratio may be expressed as

$$CR = \frac{\nu - 1 - \alpha - A - L + F(\nu - 1)}{1 + \alpha},$$

where

$$\nu = 2.5 \text{ neutrons per fission}$$

$$\alpha = \frac{\sigma_c^{U^{235}}}{\sigma_f^{U^{235}}} = 0.143$$

$$A = \begin{aligned} &= \text{neutrons absorbed in structure and coolant per } U^{235} \text{ fission} \\ &= 0.08, \text{ assuming an effective capture cross section of 40 mb for iron} \end{aligned}$$

$$L = \text{neutrons leaking from blanket per } U^{235} \text{ fission}$$

$$F = \begin{aligned} &= U^{238} \text{ fissions per } U^{235} \text{ fission} = 0.174 \text{ from integration of} \\ &U^{238} \text{ fission rate data (slightly higher number is obtained radiochemically)} \end{aligned}$$

$$CR = 1.01.$$

Solving for the leakage yields, $L = 0.36$ neutrons per U^{235} fission. If 90% of these leaking neutrons could be captured in U^{238} , the breeding ratio would become approximately 1.3.

FIG. 1
HORIZONTAL SECTION OF EBR

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FIG. 2
EBR ROD AND BRICK
IDENTIFICATION

J.W.BUTLER:E.S., 1-27-53

FIG. 3
VERTICAL SECTION
OF THE EBR

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RE-6-13301-B
W.C. REDMAN C.C., 7-26-54

FIG. 4
PLAN VIEW OF THE EBR

RE-6-13301-B

RE-6-13300-A

W.C. REDMAN: C.C., 7-27-54'

60

RE-6-13300-A

RE-6-13298-A

W.C. REDMAN: C.C., 7-27-54

61

PLAN VIEW

ELEVATION

FOIL HOLDER ASSEMBLY

FIG. 8
CUP BRICK-FOIL HOLDERS USED
FOR IRRADIATION RUNS NO. 4 AND 5

RE-6-13298-A

- A FOIL POCKET,
.045 DEEP
B COOLING HOLE
C CONTROL ROD HOLE

EB-6-12109-A

FIG. 9
FLAT PLATE FOIL HOLDER

EB-6-12109-A
W. REDMAN:V.C., 12-23-53

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RE-7-12160-A

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FIG. 12
 U^{238} FISSION PATTERNS IN THE EBR
 IRRADIATIONS NO. 1 AND 3

RE-7-13292-A

RE-7-13292-A

W.C. REDMAN: J.F.L., 7-28-54

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FIG. 13
RADIAL VARIATION OF U^{238} FISSION
RATE ON THE MIDPLANE OF THE EBR

RE-7-13296-A
W.C. REDMAN: C.C., 7.27.54

RE-7-13296-A

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RE-7-13291-A
W.C. REDMAN: C.C., 7-27-54

RE-7-13291-A

3295-A
EDMAN:V.C.C., 6-18-54

FIG. 15
TIME DEPENDENCE OF RELATIVE U^{238} FISSION
RATES FOR FOILS IN THE OUTER BLANKET

RE-7-13295-A

FIG. 16
DETERMINATION OF SLOPE FACTOR FOR
FISSION PRODUCT ACTIVITY CORRECTION

FIG. 17
TIME DEPENDENCE OF SLOPE FACTOR FOR
FISSION PRODUCT ACTIVITY CORRECTION

RE-7-13293-A

RE-7-13293-A

W.C. REDMAN: E.F., 7.27.54

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RE-7-13297-A

W.C. REDMAN: C.C., 7-26-54

FIG. 18
DIFFERENTIAL PULSE HEIGHT DISTRIBUTION FOR URANIUM
AND NEPTUNIUM COMPONENTS OF DEPLETED URANIUM FOIL

RE-7-13297-A

RE-7-13294-A

W.C. REDMAN: J.F.L., 6-15-54

FIG. 19
COUNTING LOSS ESTIMATE BY
METHOD OF ACTIVITY RATIOS

RE-7-13294-A

RE-7-13303-A

W.C. REDMAN: E.F., 7-27-54

FIG. 20
PLUTONIUM PRODUCTION PATTERNS
IN CORE AND INNER BLANKET

RE-7-13303-A
ANL-FWT-13303

RE-7-13306-A

W.C. REDMAN: C.C., 7-27-54

FIG. 21
PLUTONIUM PRODUCTION PATTERNS
IN OUTER BLANKET

RE-7-13306-A
ANL-FWT-13306

RE-7-13302-A

W.C.REDMAN:C.C.,7-27-54

FIG. 22
PLUTONIUM PRODUCTION PATTERNS
IN THE OUTER BLANKET

RE-7-13302-A
ANL-FWT-13302

RE-7-13307-A

RE-7-13307-A
W.C. REDMAN: E.F., 7.27.54

FIG. 23
EFFECT OF REFLECTOR ON Pu^{239} PRODUCTION
RATE IN OUTER BLANKET OF THE EBR

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FIG. 24
RADIAL VARIATION OF Pu^{239} PRODUCTION
ON THE MID-PLANE OF THE EBR

FIG. 25
AIR-FILLED DUAL FISSION CHAMBER

77

RE-7-13395-C
W. REDMAN: 7-21-54

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50

FIG. 29
COMPARISON OF RESPONSE OF Cu^{63} AND
 U^{235} TO THE NEUTRON SPECTRUM IN THE
OUTER BLANKET OF THE EBR

RE-7-13305-A
W.C. REDMAN: C.C., 7-27-54

RE-7-13305-A

097026030

RE-7-13308-A

FIG. 30
EFFECT OF REFLECTOR ON U^{235} FISSION
RATE IN THE OUTER BLANKET OF THE EBR

RE-7-13308-A
W.C. REDMAN: E.F., 7.26.54

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RE-7-13309-A

W.C. REDMAN: L.B., 7-28-54

FIG. 31
RADIAL VARIATION OF U^{235} FISSION
RATE ON MID-PLANE OF THE EBR

RE-7-13309-A
ANL-FWT-13309

FIG. 32
COMPARISON OF U^{235} FISSION RATE MEASUREMENTS
ON THE CENTRAL AXIS OF THE EBR

RE-7-13310-A
W.C. REDMAN: L.B., 7-28-54

RE-7-13310-A

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RE-7-13311-A

W.C. REDMAN:L.B., 7-28-54

FIG. 33
DECAY OF U²³⁵ FISSION PRODUCT ACTIVITY

RE-7-13311-A

FIG. 34
 U^{235} FISSION CHAMBER RESPONSE IN
THE THERMAL COLUMN OF THE EBR

RE-7-13499-A
W.C. REDMAN: L.B., 7-28-54

RE-7-13499-A

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FIG. 35
TEMPERATURE DEPENDENCE OF
NORMALIZATION FACTOR

RE-7-13506-A

RE-7-13542-A

D. OKRENT: V. CC, 7-30-54

FIG. 36
AXIAL U^{235} FISSION RATE VS ROD LOCATION
IN CORE AND INNER BLANKET

ANL-FWT-13542
RE-7-13542-A

FIG. 37
CALCULATED U^{235} FISSION RATE VS
RADIAL POSITION FOR CONSTANT Z

RE-7-13541-A

RE-7-13541-A
D. OKRENTLV.C.C., 6-18-54

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RE-7-13538-A

D.OKRENT:V.COLLI NS,7.30.54

FIG. 38
AVERAGE U^{235} FISSION RATE IN CENTRAL $7\frac{1}{2}$ in.
OF CORE VS RADIAL LOCATION OF ROD

RE-7-13538-A
ANL-FWT-13538

RE-7-13539-A

RE-7-13539-A
D. OKRENT · V. C. C., 6-18-54

FIG. 39
AVERAGE U^{235} FISSION RATE IN ENRICHED
FUEL ROD EXTENSION AND IN NATURAL
URANIUM RODS (BELOW CORE)

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RE-7-13543-A
D.OKRENT:L.R.D., 7-30-54

FIG. 40
AXIAL VARIATION IN U^{235} FISSION RATE FOR THREE
RADIAL POSITIONS IN OUTER BLANKET BRICKS

RE-7-13543-A

RE-7-13537-A

RE-7-13537-A
D. OKRENT: VCC, 6-18-54

FIG. 41
AVERAGE U^{235} FISSION RATE IN OUTER
BLANKET BRICKS VS RADIUS

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FIG. 42
AVERAGE U^{235} CAPTURE TO FISSION RATIO IN
STANDARD AND HEAVY FUEL RODS VS RADIUS

ANL-FWT-13540
RE-7-13540-A

RE-7-13540-A
D. OKRENT: V.C.C., 7-30-54

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RE-7-13545-A
D. OKRENT: L.R.D., 7-30-54

FIG 43
AXIAL U^{238} CAPTURE RATE FOR VARIOUS ROD
LOCATIONS IN CORE AND INNER BLANKET

TRE-7-13545-A
ANL-FWT-13545

RE-7-13544-A

D. OKRENT:L.B., 7-30-54

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FIG. 44
TYPICAL PLOTS OF U^{238} CAPTURE RATE
VS RADIAL POSITION FOR CONSTANT Z

RE-7-13544-A

RE-7-13536-A

RE-7-13536-A
D. OKRENT: CC, 6-18-54

FIG. 45
 U^{238} CAPTURE RATE AVERAGED OVER VARIOUS
AXIAL INTERVALS IN CORE AND
INNER BLANKET VS RADIUS

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75

FIG. 46
AXIAL VARIATION IN U^{238} CAPTURE
RATE FOR FIVE RADIAL POSITIONS
IN OUTER BLANKET BRICKS

RE-7-13546-A

RE-7-13547-A

RE-7-13547-A
D. OKRENT: V. C. C., 6.18.54

FIG. 47
TYPICAL PLOTS OF U^{238} CAPTURE RATE VS
RADIAL POSITION IN OUTER BLANKET
BRICKS FOR CONSTANT Z

0379229.030

RE-7-13548-A

D.OKRENT:L.R.D., 7-30-54

FIG. 48
 AVERAGE U^{238} CAPTURE RATE IN
 OUTER BLANKET BRICKS

RE-7-13548-A

RE-7-13535-A

D.OKRENT:L.R.D.,6-11-54

FIG. 49
AVERAGE U^{238} CAPTURE RATE IN
BRICKS VS AXIAL POSITION

RE-7-13535-A

Figure 50

CONTOUR MAP OF U^{238} CAPTURE RATE

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Figure 51

CONTOUR MAP OF U^{235} FISSION RATE

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Table I

SUMMARY OF INITIAL U²³⁸ FOIL IRRADIATIONS

	<u>Irradiation No. 1</u>	<u>Irradiation No. 2</u>	<u>Irradiation No. 3</u>
Date	10-9-52	10-9-52	11-5-52
Time	0445 - 1245	1520 - 1715	1120 - 1458
Power Level, kw	25	104	55.1
Cup Position, in.	-2.40	-2.40	-0.95
Foil Locations			
Core	9	0	10
Inner Blanket	31	0	10
Cup	45	0	15
Thermal Column	3	3	3
Total Uranium Foils	88	3	38
Fuel Rod Temperature, C	50	73	51
NaK Temperature, C	37	52	27

Table II

SUMMARY OF SUPPLEMENTAL FOIL IRRADIATIONS

	<u>Irradiation No. 4</u>				<u>Irradiation No. 5</u>	
Date	9-9-53				9-29-53	
Time	1135 - 1214				0830 - 1030	
Average Power Level, kw	150				50	
Average Cup Position, in.	-0.065				0.0	
Foil Locations	<u>U²³⁸</u>	<u>U²³⁵-Al</u>	<u>Cu</u>	<u>U²³⁸</u>	<u>U²³⁵-Al</u>	<u>Pu²³⁹-Al</u>
Core Rods	0	0	0	1	6	6
Inner Blanket Rods	1	1	1	2	4	4
Cup	18	24	6	15	13	17
Total Foils	19	25	7	18	23	27
Fuel Rod Temperature, C	180				105	
NaK Temperature, C	140				98	

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Table III

RELATIVE U^{238} FISSION AND Pu^{239} PRODUCTION IN THE EBR

Irradiation Number	Rod Number	Radius, cm	Distance From Core Mid-Plane, cm			Irradiation Number	Rod Number	Radius, cm	Distance From Core Mid-Plane, cm		
			(F.P.) _x (F.P.) _c	(Np) _x (Np) _T	(F.P.) _x (F.P.) _c				(F.P.) _x (F.P.) _c	(Np) _x (Np) _T	
Core and Inner Blanket											
1	1	0				1		24.61	-32.35	0.0026	1.103
									-50.13	Neg.	0.425
			+14.61	0.146	5.67				+14.96	0.0063	1.460
			+12.07	0.264	6.56				+ 1.95	0.011	2.029
			+ 9.53	0.541	8.05				- 3.14	0.013	2.067
			+ 4.76	(a)	(a)				- 8.22	0.0098	1.907
			0	1.000	8.15	1		27.15	-13.30	0.0068	1.696
			- 4.76	(b)	(b)				-18.38	0.0051	1.434
			- 9.53	0.457	7.46				-23.46	0.0033	1.203
			-11.43	0.255	6.48				-32.35	0.0011	0.875
3	1	0	-16.51	0.086	4.61				-50.13	Neg	0.399
			+14.61	0.081	4.55				+14.96	0.0031	1.245
			+12.07	0.239	6.72				+ 1.95	0.0045	1.596
			+ 9.53	0.425	7.71				- 3.14	0.0058	1.660
			+ 4.76	0.892	10.17				- 8.22	0.0047	1.515
			0	1.000	10.26	1		30.32	-13.30	0.0041	1.376
			+20.47	0.025	2.58				-18.38	0.0017	1.148
			+10.19	0.141	5.27				-23.46	0.0022	1.010
			+ 5.14	0.247	6.48				-32.35	Neg.	0.742
			+ 3.09	(b)	(b)				-50.13	Neg.	0.391
1	235	11.07	+ 1.03	0.280	6.89				+14.96	Neg.	1.079
			- 1.03	(a)	(a)				+ 1.95	Neg.	1.220
			- 3.09	0.262	6.77				- 3.14	0.0039	1.253
			- 5.14	0.249	6.66				- 8.22	0.0029	1.160
			-10.03	0.180	5.83	1		34.13	-13.30	0.0027	1.086
			+20.47	0.025	2.59				-18.38	0.0011	0.940
			+10.19	0.111	5.02				-23.46	0.0011	0.829
			+ 5.14	0.163	5.90				-32.35	Neg.	0.668
			+ 2.57	0.155	5.75				-50.13	Neg.	0.415
			0	0.180	6.19				+14.96	0.0012	2.327
1	268	13.20	- 2.57	0.142	5.68				+ 1.95	0.0021	2.408
			- 5.14	0.129	5.50				- 3.14	0.0027	2.477
			-10.03	0.086	5.01				- 8.22	0.0018	2.169
			0	0.148	6.15	1		38.58	-13.30	0.0017	2.183
			- 2.57	0.145	6.00				-18.38	0.0022	2.053
			- 5.14	0.137	5.84				-23.46	0.0011	1.956
			-10.03	0.085	4.72				-32.35	0.0018	1.836
			-20.3	0.025	2.54				-50.13	Neg.	1.843
			+20.47	0.017	2.05	3		0	-36.24	0.0019	1.337
			+10.19	0.052	3.69						
1	308	15.45	+ 5.14	0.079	4.57	3		5.08	-36.24	0.0019	1.318
			+ 1.72	0.104	5.23					0.0018	1.303
			- 1.72	0.107	5.21						
			- 5.14	0.082	4.67	3		10.16	-36.24	0.0018	1.279
			-10.03	0.062	4.31					0.0017	1.286
			+20.47	0.0087	1.67				-37.18	0.0015	1.141
			+10.19	0.037	3.17				-42.89	0.0009	0.748
			+ 5.14	0.055	3.89				-47.97	0.0004	0.545
			+ 1.72	0.058	4.04						
			- 1.72	0.051	3.85	3		15.24	-36.24	0.0016	1.191
1	343	17.60	- 5.14	0.069	4.44					0.0016	1.171
			-10.03	0.043	3.73				-37.18	0.0013	1.027
			+20.47	0.0087	1.67				-42.89	0.0008	0.658
			+10.19	0.037	3.17				-47.97	0.0004	0.490
			+ 5.14	0.055	3.89						
			+ 1.72	0.058	4.04						
			- 1.72	0.051	3.85						
			- 5.14	0.069	4.44						
			-10.03	0.043	3.73						
			+20.47	0.0087	1.67						
Outer Blanket (Cup)											
1		24.61	+14.96	0.0083	1.791	3		19.05	-37.18	0.0013	1.027
			+ 1.95	0.017	2.634				-42.89	0.0008	0.658
			- 3.14	0.016	2.581	1		20.32	-47.97	0.0004	0.490
			- 8.22	0.015	2.412				-36.24	0.0013	1.046
			-13.30	0.013	2.156					0.0009	1.007
			-18.38	0.0067	1.755	1,3	Thermal Column (c)	Bare Foil		0.0011	1.000
			-23.46	0.0044	1.438	2		Cadmium-covered Foil	Neg.	0.293	

(a) Foils lost between irradiation and counting.

(b) Foils separated chemically into components.

(c) Normalization location (See Section IV).

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Table IV

SUMMARY OF PRODUCTION AND FISSION
PATTERNS - IRRADIATION NO. 4

Outer Blanket Foils

Radial Location of Foil, in.:			15.4	15.15	14.9	14.4	13.4	12.4
<u>Brick</u>	<u>Holder</u>	<u>Source</u>						
K-5	1	Np ²³⁹	0.686	0.671	0.649	0.677	0.821	1.059
		U ²³⁵ F.P.	23.8	24.1	18.8	13.85	11.2	12.95
		U ²³⁸ F.P. (x10 ³)	3.38	3.42	3.42	3.70	4.85	7.00
	2	Np ²³⁹	1.916	0.647	0.611	0.654	0.821	1.050
		U ²³⁵ F.P.	33.7	23.4	18.3	13.0	11.1	12.95
		U ²³⁸ F.P. (x10 ³)	7.76	3.20	3.26	3.60	4.78	7.25
G-5	1	Np ²³⁹	2.372	0.779	0.750	0.733	0.843	1.063
		U ²³⁵ F.P.	46.5	32.8	25.0	16.8	12.25	13.15
		U ²³⁸ F.P. (x10 ³)	9.51	4.16	4.11	4.26	5.12	7.46
	2	U ²³⁵ F.P.	49.0	32.2	25.7	17.35	12.4	13.85
		Cu ⁶⁴	28.1	22.2	18.2	14.65	12.9	13.35

Rod Foils

Rod No. 268 (R = 5.20 in.; z = 0)

Np ²³⁹	4.65
U ²³⁵ F.P.	61.7
U ²³⁸ F.P.	0.1595
Cu ⁶⁴	43.1

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Table V

SUMMARY OF PRODUCTION AND FISSION PATTERNS -
IRRADIATION NO. 5

Radial Location, in.:			Outer Blanket Foils										
			15.4	15.5	14.9	14.4	14.0	13.4	13.0	12.4	12.0	10.5	9.8
Brick	Holder	Source											
K-5	1	Np ²³⁹	1.763	0.672						1.015			
		U ²³⁵ F.P.	34.4	24.1									
		U ²³⁸ F.P. (x10 ³)	4.44	3.43						6.90			
		Pu ²³⁹ F.P.	38.4	27.5	21.4	14.05		9.13		8.70			
E-5	2	Np ²³⁹	2.180	0.821		0.757				1.053			
		U ²³⁵ F.P.	53.8	38.4	29.6	18.25		13.9		13.4			
		U ²³⁸ F.P. (x10 ³)	6.95	4.53		4.55				7.56			
		Pu ²³⁹ F.P.	59.0	43.4	31.8	19.8		11.5		9.74			
E-6	Plate*	Np ²³⁹									1.221		1.978
E-5		U ²³⁵ F.P.					14.2		13.0		14.55	18.8	22.2
U ²³⁸ F.P. (x10 ³)										9.26		22.6	
Pu ²³⁹ F.P.						14.05		10.4		10.2	12.4	14.55	
K-5	Face**	Np ²³⁹ - U ²³⁸ F.P.	2.105 - 4.72 x 10 ⁻³										
2.075 - 4.86													
2.120 - 4.97													
2.150 - 4.78													
2.165 - 4.56													
2.265 - 4.69													

Rod Foils

Rod No.	Radius, in.	Distance from Core Mid-plane, in.	Np ²³⁹	U ²³⁵ F.P.	U ²³⁸ F.P.	Pu ²³⁹ F.P.
1	0	0	9.00	109.0	0.985	100.0
		1-7/8		111.0		98.0
		3-3/4		84.0		69.7
		5-3/4		51.1		39.6
		7-5/8		34.8		24.6
		10-1/8		22.1		14.1
235	4.36	0	5.51	63.3	0.288	53.5
		13/16		61.6		49.2
308	6.08	-		41.6		31.3
343	6.93	0	3.03	32.8	0.061	25.2

*Flat plate holder (Figure 9) inserted between outer blanket bricks located at E-5 and E-6, 1.35 in. above plane of special brick holders.

**Six foils spaced approximately one in. apart on the outer face of the brick at K-5.

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Table VI

FISSION RATE - CORE AND INNER BLANKET

Distance from Core Mid-plane, cm	Neutron + Gamma	Gamma Only	U^{235} I_{norm}	Distance from Core Mid-plane, cm	Neutron + Gamma	Gamma Only	U^{235} I_{norm}
Rod No. 1; R = 0 cm				Rod No. 14; R = 2.174 cm			
- 18.4	17.0	3.7	26.8	- 18.4	16.5	1.2	28.8
- 12.3	37.9	8.6	55.1	- 11.9	33.6	5.0	53.8
- 7.2	66.0	22.0	82.3	- 6.8	60.3	15.9	83.0
- 4.6	74.2	25.3	91.3	- 4.3	69.5	19.5	93.6
- 2.1	78.2	26.8	96.0	- 1.8	73.2	21.1	97.5
+ 0.2	80.9	27.4	100.0	+ 0.8	74.6	21.8	98.6
+ 2.8	76.9	24.8	97.4	+ 3.3	79.8	30.0	93.0
+ 5.3	68.4	20.0	90.4	+ 6.0	71.1	25.2	85.9
+ 7.8	58.6	15.0	81.5	+ 8.4	60.6	19.7	75.4
+ 10.6	41.7	8.0	63.0	+ 10.9	44.9	11.0	61.8
+ 13.2	25.8	4.0	41.0	+ 13.5	33.5	7.7	48.5
+ 15.9	22.6	2.6	37.6	+ 18.6	20.8	4.6	30.5
+ 21.1	14.0	1.2	24.2	+ 23.6	12.1	1.5	20.0
+ 26.5	9.2	0.8	15.9	+ 28.7	8.4	1.1	13.8
+ 30.2	7.5	0.5	13.2	+ 33.8	7.3	1.0	11.9
+ 43.6	5.9	0.1	10.9	+ 38.9	6.6	0.4	11.7
Rod No. 19; * R = 2.510 cm				Rod No. 61; * R = 5.019 cm			
- 18.4	16.5	2.0	27.4	- 18.4	16.2	1.8	27.2
- 11.9	35.8	7.8	52.7	- 11.9	35.7	8.8	50.6
- 6.8	62.5	18.9	81.5	- 6.8	60.6	20.0	74.5
- 4.3	71.4	22.2	92.1	- 4.3	68.0	22.7	84.9
- 1.8	75.0	23.7	95.9	- 1.8	71.0	24.7	86.6
+ 0.8	76.2	23.4	98.6	+ 0.8	72.0	25.0	87.5
+ 3.3	73.7	22.0	96.7	+ 3.3	68.8	24.0	83.8
+ 6.0	66.1	19.4	87.4	+ 6.0	62.2	21.5	79.7
+ 8.4	59.6	18.6	76.7	+ 8.4	51.4	13.3	71.5
+ 10.9	42.9	10.9	59.9	+ 10.9	36.7	6.5	56.7
+ 13.5	33.0	7.0	48.9	+ 13.5	26.2	3.0	43.6
+ 18.6	24.0	5.7	34.4	+ 18.6	15.8	1.0	27.8
+ 23.6	18.1	6.1	22.6	+ 23.6	10.3	0.3	18.9
+ 28.7	15.1	6.3	16.6	+ 28.7	8.0	0.7	13.8
+ 33.8	11.7	5.0	12.6	+ 33.8	6.9	0.5	12.1
+ 38.9	6.4	0.3	11.5	+ 38.9	6.6	0.4	11.7
Rod No. 79; R = 5.469 cm				Rod No. 127; * R = 7.529 cm			
- 18.4	15.8	1.8	26.5	- 18.4	16.4	4.1	23.0
- 10.9	25.8	6.7	35.8	- 11.9	29.2	5.4	44.7
- 5.7	61.0	17.1	82.3	- 6.8	47.2	12.1	65.9
- 3.9	65.5	19.4	86.3	- 4.3	52.1	14.0	71.5
- 0.6	68.4	20.5	89.6	- 1.8	54.8	15.0	74.5
+ 2.2	67.8	20.1	89.3	+ 0.8	54.7	14.8	75.3
+ 5.2	62.8	18.5	83.0	+ 3.3	54.0	14.2	74.1
+ 8.5	51.1	14.0	69.5	+ 6.0	49.6	12.8	69.1
+ 11.5	35.8	6.9	54.3	+ 8.4	42.1	9.9	62.4
+ 14.4	25.5	3.7	41.0	+ 10.9	32.3	5.5	50.4
+ 17.4	19.2	2.3	31.8	+ 13.5	25.2	3.7	40.4
+ 22.1	12.8	1.2	21.9	+ 18.6	16.4	2.8	25.7
+ 26.6	9.0	0.2	16.6	+ 23.6	12.2	3.4	16.6
+ 31.1	7.2	0.7	12.5	+ 28.7	10.9	3.9	13.2
+ 36.2	7.0	0.6	12.1	+ 33.8	10.2	5.0	9.8
+ 40.9	6.1	0.4	10.8	+ 38.9	8.6	2.6	11.3

*Lies on a line across corner of hexagon.

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Table VI (Contd.)

Distance from Core Mid-plane, cm	Neutron + Gamma	Gamma Only	U^{235} I norm	Distance from Core Mid-plane, cm	Neutron + Gamma	Gamma Only	U^{235} I norm
Rod No. 152; R = 7.633 cm				Rod No. 170; * R = 9.47 cm			
- 18.4	14.7	1.6	24.6	- 18.4	14.1	1.2	24.33
- 10.9	32.6	6.5	49.05	- 10.9	27.8	5.0	42.8
- 5.7	51.4	14.2	69.8	- 5.7	39.7	8.3	58.9
- 3.9	56.1	15.7	75.7	- 3.9	42.4	9.2	62.2
- 0.6	58.2	16.1	78.9	- 0.6	44.3	9.8	64.7
+ 2.2	57.9	15.9	78.7	+ 2.2	44.1	9.7	64.5
+ 5.2	54.0	15.0	73.2	+ 5.2	41.3	9.0	60.6
+ 8.5	45.7	11.8	63.6	+ 8.5	35.1	7.0	52.8
+ 11.5	32.9	6.6	49.5	+ 11.5	27.9	4.7	43.6
+ 14.4	23.7	3.4	38.15	+ 14.4	20.2	2.0	34.2
+ 17.4	17.5	2.0	29.2	+ 17.4	15.4	0.7	27.67
+ 22.1	11.7	1.0	20.2	+ 22.0	10.4	0.3	19.07
+ 26.6	8.4	0.8	14.3	+ 26.6	7.3	0.3	13.2
+ 31.1	6.9	0.5	12.1	+ 31.1	6.6	0.5	11.5
+ 36.2	6.5	0.4	11.5	+ 36.2	6.3	0.4	11.1
+ 40.9	6.1	0.3	10.9	+ 40.9	6.0	0.3	10.76
Rod No. 235; R = 11.072 cm				Rod No. 268; R = 13.198 cm			
- 18.4	16.9	5.0	22.4	- 18.4	16.2	3.6	23.8
- 10.1	32.2	9.2	43.3	- 10.1	21.8	2.9	35.4
- 4.0	45.1	13.2	60.0	- 9.1	24.2	3.4	39.2
- 1.5	46.9	13.8	62.2	- 4.0	29.2	5.0	45.5
+ 1.0	46.9	13.9	62.1	+ 1.0	31.8	5.3	49.3
+ 3.6	46.2	13.8	60.9	+ 6.1	28.5	5.1	44.0
+ 6.1	43.1	13.1	56.5	+ 11.2	22.4	4.0	34.6
+ 8.8	38.4	11.7	50.2	+ 16.3	16.2	3.0	24.9
+ 11.2	32.8	10.0	43.1	+ 21.4	11.7	2.2	17.95
+ 13.7	25.6	7.2	34.8	+ 26.4	8.9	1.9	13.2
+ 16.3	20.0	5.6	27.2	+ 31.5	8.7	2.7	11.3
+ 21.4	14.0	4.4	18.1	+ 36.6	6.7	0.4	11.9
+ 26.4	10.3	3.9	12.1	+ 41.7	6.2	0.3	11.1
+ 31.5	8.8	3.0	11.1				
+ 36.6	8.3	3.0	10.0				
+ 41.7	8.0	3.2	9.06				
Rod No. 308; R = 15.45 cm				Rod No. 343; R = 17.6 cm			
- 18.4	13.8	1.7	22.8	- 18.4	13.1	2.9	19.3
- 9.1	20.9	2.9	33.9	- 10.1	19.1	5.2	26.2
- 4.0	24.4	3.4	39.5	- 4.0	20.9	4.0	32.4
+ 1.0	25.5	3.8	40.8	+ 1.0	21.8	4.5	32.9
+ 6.1	23.2	3.2	37.6	+ 6.1	20.4	4.2	30.5
+ 11.2	18.7	2.3	30.9	+ 11.2	17.7	3.6	26.6
+ 16.3	14.8	2.4	23.4	+ 16.3	15.2	4.3	20.6
+ 21.4	10.7	1.7	17.0	+ 21.4	12.7	4.0	16.4
+ 26.4	7.7	0.9	12.8	+ 26.4	11.2	3.9	13.8
+ 31.5	6.8	0.4	12.1	+ 31.5	10.2	3.8	12.1
+ 36.6	6.6	0.0	12.5	+ 36.6	10.1	3.7	12.1
+ 41.6	6.0	0.0	11.5	+ 41.6	10.0	3.7	11.9

*Lies on a line across corner of hexagon.

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Table VII

CUP DATA NORMALIZED

Fission Chamber in Control Rod Hole (R=26.76 cm)		Copper Foils in Bricks (Run 1)						
$I_{\text{norm}}^{U^{235}}$	Distance From Core Mid-Plane, cm	Radius, cm:						
		Distance From Core Mid-Plane, cm						
		24.61	27.15	30.32	34.13	38.58		
6.30	-57.61	+14.93	13.02	11.56	11.12	10.94	20.04	
5.18	-52.53	+ 1.95	16.41	13.84	11.07	11.14	22.53	
4.01	-47.45	- 3.14	16.06	13.39	11.32	10.82	22.59	
3.56	-42.32	- 8.22	15.27	13.07	10.71	10.07	22.71	
4.34	-37.36	-13.30	13.45	11.37	9.68	9.94	22.21	
5.58	-32.21	-18.38	12.01	9.80	9.19	8.65	21.29	
6.86	-27.05	-23.46	9.61	8.19	7.63	7.71	20.91	
8.27	-22.12	-32.35	7.19	6.15	5.34	6.89	19.51	
9.95	-16.76	-50.13	3.69	3.85	3.70	4.92	14.23	
11.87	-11.86							
13.57	- 6.83							
13.90	- 4.27	Copper Foils in Lower Part of Cup (Run 3)						
14.18	- 1.73	Radius, cm:	14.29	19.05	20.16	15.12	10.80	5.04
14.33	+ 0.74	Distance From Core Mid-Plane, cm						
14.24	+ 3.38							
14.08	+ 5.89							
13.65	+ 8.38							
12.32	+13.39	-34.24	---	---	5.90	6.90	7.20	7.85
10.26	+18.57	-37.18	6.64	5.52	---	---	---	---
		-42.89	4.47	4.04	---	---	---	---
		-47.97	3.25	2.98	---	---	---	---

Table VIII

COMPARISON OF FISSION CHAMBER RESPONSE

<u>Date</u>	<u>Core</u>	<u>Thermal Column</u>	<u>Core</u>	<u>Fuel Temp, C</u>	<u>NaK Temp, C</u>
			<u>Thermal Column</u>		
10-1-52	54.59	58.97	0.9257	55	43
	54.85	58.87	0.9317	58	45
	55.70		0.9462	60	47
10-2-52	54.33	58.9	0.9224	51	43
	53.53		0.9088	51	43
	53.34	59.2	0.9010	50	38
	53.66	58.0	0.9252	48	37
10-6-52	54.05	59.0	0.9161	34	24

Avg. 0.9221 $\pm$ 1.2%

Thermal Column Temp: $\sim$ 26C

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Table IX
DISTRIBUTION OF U^{235} AND U^{238} IN EBR
(In Moles)

Components	U^{235}	U^{238}	Component	Radius, cm	No. of rods
Standard Enriched Core Rod (7-1/2 in.)	0.9431	0.0657,	Heavy Enriched Fuel Rod	7.836	4
Heavy Enriched Core Rod (10 in.)	1.4231	0.1011		8.228	12
Thermocouple Rod (7-1/2 in.)	0.8997	0.0637		8.693	6
Uranium above Standard Enriched Rod (8 in.)	0.00773	1.065		8.783	18
Uranium below Standard Enriched Rod (4-3/4 in.)	0.00459	0.6324		9.048	12
Uranium above Heavy Enriched Rod (6-3/4 in.)	0.00694	0.9558		9.473	11
Uranium below Heavy Enriched Rod (3-1/2 in.)	0.00360	0.4956		Total	63
Uranium in Inner Blanket Rod (20-1/4 in.)	0.1135	15.64	Thermocouple Rod	2.174	1
Uranium in Outer Blanket Brick	1.1719	161.5	Inner Blanket Rod	11.072	12
Uranium in Lower Part of Cup	9.4242	1298.		11.640	12
Uranium in Safety Rod (26 in.)	0.4696	64.71		12.700	6
				13.198	6
				13.440	12
				14.142	12
				15.240	6
				15.450	12
				15.862	12
				16.656	12
				17.599	6
				17.780	18
				18.316	12
				Total	138
Standard Enriched Core Rod	0	1			
	1.255	6			
	2.174	5			
	2.510	6	Safety Rod	26.67	12
	3.320	12			
	3.764	6			
	4.346	6			
	4.524	12			
	5.019	6			
	5.469	12			
	5.750	12			
	6.274	6			
	6.520	6			
	6.640	12			
	6.986	12			
	7.529	6			
	7.633	12			
	7.836	8			
	9.473	1			
	10.038	3			
	Total	150			

There are 84 bricks in the outer blanket (cup) forming a cylinder (ID = 45.50 cm; OD = 78.32 cm). When the cup is 2.4 in. down, the top of the bricks is at $z = + 17.55$ cm; the bottom of the bricks is at $z = - 51.25$ cm; and the top of the lower part of the cup is at $z = - 39.92$ cm (where $z = 0$ is the mid-plane of the core).

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Table X

DETAILED DISTRIBUTION OF FISSIONS AND CAPTURES IN THE EBR
(In moles)

Fissions of U²³⁵

<u>Component</u>	<u>Fissions</u>	<u>Average</u>
Fuel (Enriched uranium)	16,682	71.9
Uranium above core	46	28.8
Uranium below core	32	35.0
Inner blanket rods	451	28.8
Cup bricks	1,064	10.8
Safety rods	68	12.0
Lower cup	40	4.2
Total	18,383	

Captures in U²³⁵

<u>Component</u>	<u>Captures</u>	<u>$\bar{\alpha}$</u>
Fuel (Enriched uranium)	2,295	0.138
Fuel (Natural uranium)	340	0.2
Total	2,635	

$\bar{\alpha}$ for entire reactor: 0.143

Captures in U²³⁸

<u>Component</u>	<u>Captures</u>	<u>Average</u>
U ²³⁸ in fuel	92	5.652
Uranium above core	680	3.074
Uranium below core	456	3.600
Inner blanket rods	5,811	2.693
Cup bricks	11,854	0.874
Safety rods	697	0.898
Lower cup	911	0.702
Total	20,501	

$$\text{Conversion Ratio} = \frac{20,501}{18,383 + 2,635} = 0.98$$

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Table XI

DISTRIBUTION OF FISSIONS AND CAPTURES
(On Basis of 1 Atom of U^{235} Destroyed in Reactor)

	<u>U^{235} Fission</u>	<u>U^{235} Capture</u>	<u>U^{238} Capture</u>
Enriched Material	0.794	0.1092	0.004
Uranium Above Core	0.002	0.0004	0.032
Uranium Below Core	0.002	0.0004	0.022
Inner Blanket Rods	0.021	0.0042	0.277
Cup Bricks	0.051	0.0102	0.564
Safety Rods	0.003	0.0006	0.033
Lower Part of Cup	0.002	0.0004	0.043
	<u>0.875</u>	<u>0.125</u>	<u>0.975</u>

Table XII

COMPARISON BETWEEN PHYSICAL AND RADIOCHEMICAL
DETERMINATION OF CONVERSION RATIO

	<u>U^{235} Atoms Destroyed</u>		<u>Pu^{239} Atoms Produced</u>	
	<u>Physical</u>	<u>Radiochem.</u>	<u>Physical</u>	<u>Radiochem.</u>
Enriched Uranium	0.908	0.909	0.004	0.004
Upper and Lower Blanket	0.005	0.001	0.054	0.054
Inner Blanket	0.024	0.037	0.277	0.300
Outer Blanket Bricks	0.058	0.047	0.588	0.549
Control Rods	0.003	0.003	0.035	0.042
Lower Part of Cup	0.002	0.003	0.051	0.046
Total	<u>1.00</u>	<u>1.00</u>	<u>1.01</u>	<u>1.00</u>

$\bar{\alpha}_{\text{Core}} = 0.138$
 $\bar{\alpha}_{\text{Reactor}} = 0.143$
 Physical CR = 0.98 with cup 2.4 in. down

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