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FISSION YIELDS IN URANIUM-235 AND URANIUM-238

by

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INTRODUCTION

Objectives

The primary aim of the present study was to put fission yields from U^{235} on a quantitative basis. The absolute fission yield of a convenient reference nuclide, $12.8d Ba^{140}$, was measured in a more direct manner than had previously been done. Fission yields in U^{235} and in U^{238} were compared for a number of nuclides to determine whether or not the fission yields in natural uranium in a thermal neutron reactor might be influenced appreciably by fast fission of U^{238} . As a result of this last experiment it was noted that the fission yield curves in U^{235} and U^{238} have significantly different shapes.

General Concepts

In the nuclear fission of uranium¹ by thermal neutrons a U^{235} nucleus is divided into two large fragments and an average of two neutrons. The fission fragments separate with a total kinetic energy averaging approximately 160 Mev. The neutrons appear to be emitted isotropically from the moving fragments with velocities comparable to those of the fragments.² The masses observed for the fragments range from 72 to 158 mass units. The most probable mode of fission leads to two fragments with unequal masses. If the probability of formation of a fragment of a given mass is plotted versus the mass number, a curve with two maxima at about 94 and 140 and a deep minimum between them is

¹An excellent review of the earlier work on fission is given by L. A. Turner, Revs. Modern Phys., 12, 1 (1940).

²R. R. Wilson, Phys. Rev., 72, 189 (1947).

obtained. The fission yield curve for U^{235} is shown in Figure 1. The ordinate gives the probability of formation of a fragment of a given mass, usually expressed as the percentage fission yield. The solid curve represents radiochemical fission yields and is reproduced from the Plutonium Project report³ on fission yields. The other curve will be discussed later. At the present time no theory has been advanced which accounts satisfactorily for the marked preference for asymmetric fission.

Since U^{235} has a higher neutron to proton ratio than the stable nuclei with masses corresponding to those of the fission fragments, practically all of the initial fragments are unstable with respect to negative beta emission and undergo successive beta transformations until stability is reached. These beta decay chains average three members in length.

The determination of fission yields is important not only for the purpose of obtaining a better understanding of the fission process but also for practical reasons connected with pile operations. A knowledge of fission yields, particularly of specific nuclides, is useful for the calculation of radiation shielding, pile poisoning, and fission product isotope production. One method for the determination of the ratio of capture to fission in the pile,⁴ a quantity essential in the determination of pile economy, depends upon the use of a fission nuclide of known yield as a monitor of the number of fissions.

Survey of Absolute Fission Yield Determinations in U^{235}

Two general methods have been used for the determination of fission

³J. M. Siegel and others of the Plutonium Project, J. Am. Chem. Soc., 68, 2411 (1946).

⁴L. B. Borst, Plutonium Project Report CP-2024 (February 15, 1945).

FIG. 1. FISSION YIELDS IN U^{235} , CHEMICAL.

yields, a chemical and a physical method. In the physical method a thin foil of fissionable material placed between two parallel-plate ionization chambers is irradiated with neutrons, and the ionization produced by the oppositely directed fission fragment recoils is observed in each chamber. If the ionization produced by a fission fragment is proportional to its energy, it may be shown that the masses of the recoil fragments are in the inverse ratio of the ionization produced by each. Emission of neutrons from the moving fragments modifies this relationship slightly, as will be seen later. Since the sum of the masses is known, the individual masses of the fragments may be calculated. After observation of many fissions, the frequency of occurrence of a given mass may be determined. The double ionization chamber method for the study of the fission process has been carried out by Jentsche,⁵ Flammersfeld, Jensen, and Gentner,⁶ Brolley,⁷ and Deutsch and Ramsey.⁸ In the chemical method of fission yield determination a sample of fissionable material is irradiated for a period of time, and the total number of fissions is measured in some manner, preferably with a fission chamber. The sample is analyzed radiochemically for a number of elements. The different nuclear species of each element present in the sample are identified by observation of the decay periods of the sample and by analysis of its radiations. In many instances the nuclides found are known, thus enabling definite mass assignments to be made. The number of atoms of each nuclide formed is calculated from its disintegration rate. The fission yield of a nuclide is equal to the number of atoms formed divided by the total number of fissions. In the fission process a variation of the nuclear charge

⁵W. Jentsche, Z. Physik, 120, 165 (1943).

⁶A. Flammersfeld, P. Jensen, and W. Gentner, ibid., 450 (1943).

⁷J. E. Brolley, Plutonium Project Report CN-1840 (June 26, 1944).

⁸M. Deutsch and M. Ramsey, Los Alamos Scientific Laboratory Report MDDC-945 (January 31, 1946).

ratio occurs for a given mass ratio of the fission fragments. As a result the relative yields of the members of a beta decay chain of given mass will increase progressively as stability is approached. The yield of a chain member of atomic number Z equals the yield of the preceding member $Z-1$ plus the amount formed independently in fission. The yield of a chain member which is only one or two charge units removed from stability may be assumed to be equal to the total chain yield with a reasonable degree of certainty.

The first systematic absolute fission yield studies by the chemical method were carried out by Anderson, Fermi, and Grosse.⁹ Their irradiations were carried out with cyclotron neutrons slowed down in paraffin. The fission rate of the uranium was determined by replacing the uranium solution with a solution of $MnSO_4$ and measuring the activation of the manganese. The fission rate was then calculated from the ratio of the thermal fission cross section of uranium to the thermal capture cross section of manganese. A number of fission products were isolated from the irradiated uranium solution with the aid of carriers, and the absolute amount of each active nuclide was determined from its beta disintegration rate and half-life. A comparison of their results with those determined by the Plutonium Project³ is shown in Table 1.

The absolute fission yield work presented in this paper was carried out in an effort to eliminate some of the sources of error inherent in the experiments of Anderson, Fermi, and Grosse. In particular, it was felt that errors arising from the cross-section measurements of uranium and manganese and from possible neutron resonance effects could be eliminated by counting the fissions directly. A parallel-plate 50% geometry was decided upon, thereby necessitating the use of a very thin film of uranium in order to insure

⁹H. L. Anderson, E. Fermi, and V. Grosse, Phys. Rev., 59, 52 (1941).

TABLE 1

FISSION YIELDS IN U^{235}

Mass Number	Anderson, <u>et al.</u> ¹⁰		Canadian Investigators ^{12,13,14}		Plutonium Project ³ and Present Work	
	Nuclide Studied	% Yield	Nuclide Studied	% Yield	Nuclide Studied	% Yield*
97	17h Zr	6.1	--	--	--	--
127	93h Sb	0.18	--	--	93h Sb	0.093
129	4.2h Sb	0.34	--	--	--	--
131	8.0d I	1.6	8.0d I	2.23	8.0d I	2.9
131	--	--	Stable Xe ¹³¹	2.23	--	--
132	2.4h I	5.2	Stable Xe ¹³²	3.31	77h Te	3.6
133	22h I	7.6	--	--	22h I	4.7
134	54m I	12.	Stable Xe ¹³⁴	5.85	54m I	6.0
135	6.7h I	9.	--	--	6.7h I	6.2
136	--	--	Stable Xe ¹³⁶	4.85	--	--
139	85m Ba	6.4	85m Ba	6.1	85m Ba	6.6
140	12.8d Ba	8.4	12.8d Ba	5.6	12.8d Ba	6.4

*With the exception of Te^{132} , the yields presented in the Plutonium Project paper were based upon a yield for Ba^{140} of 6.1%. In tabulating the values here, the yields were increased slightly to conform with a yield of 6.4% for Ba^{140} . The yield of Te^{132} was not adjusted since it is based upon a direct fission yield measurement similar to that made on Ba^{140} .

quantitative counting of the fission fragments. Since irradiation of the thin uranium sample for a reasonable length of time would not have yielded sufficient fission product activity for convenient analysis, a heavier disk of uranium was irradiated in the same neutron flux at the same time. The number of fissions which occurred in the heavy sample was calculated from the number of fissions counted in the light sample and the ratio of the weights of the two samples. The heavy sample was dissolved after the end of the irradiation and analyzed for specific fission products.

The first fission yield measurements by this method were made by Engelkemeir, Novey, and Schover¹⁰ who measured the absolute yields of Ba¹⁴⁰ and Te¹³² in U²³⁵ fission. In their experiment it was not possible to count fissions accurately at a neutron flux high enough to give the desired fission product activity. The integrated neutron flux during the irradiation was monitored with gold foils attached to the fission chamber. The fission rate was computed from measurements of the ratio of gold activity to the fission counting rate carried out at a power level sufficiently low that the fission counting was reliable. The possibility that systematic errors of the order of five or ten per cent might have been introduced by this procedure prompted the present investigation. In the experiments reported here amplifier improvements permitted counting at high enough rates that the gold monitoring system could be eliminated.

Since the completion of this work in 1944 other investigators¹¹ have used the same general technique for the measurement of absolute fission yields.

¹⁰D. W. Engelkemeir, T. B. Novey, and D. S. Schover, "Radiochemical Studies: The Fission Products," NNES, Div. IV, Vol. 9B, Book 3, Paper 205, The McGraw-Hill Book Co., New York, 1951.

¹¹E. P. Steinberg, Dissertation, Univ. of Chicago, Chemistry Department (August, 1947). See also "Radiochemical Studies: The Fission Products," NNES, Div. IV, Vol. 9B, Book 3, Papers 200, 201, 202, 203, 204, McGraw-Hill Book Co., New York, 1951.

Grummett, Guéron, Wilkinson, and Yaffe¹² have measured the absolute fission yields of Ba^{139} and Ba^{140} in the thermal neutron fission of uranium by comparison of the barium fission product activities with that of the U^{239} formed by neutron capture in natural uranium. The same objection may be raised to this experiment as to the experiments of Anderson, Fermi, and Grosse;¹⁰ namely, that it is necessary to know the ratio of two cross sections. In this experiment a value of $2/3$ was used for the ratio of the capture cross section to give U^{239} to the thermal fission cross section. Their experiment suffered somewhat from the low beta counting rates obtainable since their neutron source consisted of five grams of radium mixed with beryllium. However, their values agree reasonably well with the values determined by the Plutonium Project as may be seen by inspection of Table 1.

Relative Fission Yields in Uranium

The absolute methods of measuring fission yields which employ fission counting not only are time consuming but also suffer from intensity limitations since it is not feasible to count fissions for more than a few hours or to place the fission chamber in the high flux positions of a pile. Therefore, in the investigation of the yields of long-lived or low yield nuclides it is convenient to measure their yields relative to that of another nuclide of known fission yield. The activity of the nuclide of known fission yield is used as a monitor of the number of fissions which occurred in the uranium. Relative fission yields of a number of nuclides formed in the thermal neutron fission of U^{235} and the fast neutron fission of U^{238} are reported in this paper.

The relative fission yields in U^{235} of chains ending in stable isotopes

¹²W. E. Grummett, J. Gueron, G. Wilkinson, and L. Yaffe, Can. J. Research, B25, 364 (1947).

of krypton and xenon were determined by Thode and Graham¹³ by mass spectrometer analysis of the rare gases obtained from uranium which was irradiated with thermal neutrons. A measurement of the yield of $8d\ I^{131}$ by comparison with Ba^{140} by Yaffe and Mackintosh¹⁴ enabled them to calculate the absolute yields of the stable xenon isotopes by making the reasonable assumption that the yield of Xe^{131} equals the yield of I^{131} . The value taken for the absolute fission yield of Ba^{140} was that determined by Grummett, et al.¹² The fission yields for the stable xenon isotopes found by the Canadian investigators are shown in Table 1.

Application of the mass spectrometer method of determining fission yields to other elements would be very desirable as a check on the validity of the radiochemical method of obtaining fission yields and also for the evaluation of the yields of masses which are not readily measurable by radiochemical methods. It also appears that the precision attainable by the mass spectrometer method is much higher than obtained by radiochemical methods.

Comparison of Physical and Chemical Methods of Fission Yield Measurements

It should be noted that in the ionization chamber fission yield measurements the masses determined are those of the primary fission fragments before the emission of the prompt neutrons. For U^{235} fission, therefore, the sum of the two fragment masses should equal 236. In the chemical method the yields are measured after emission of the prompt neutrons so that the sum of the masses of the fragment pairs should, on the average, be less than 236.

The results of the fission yield measurements by the double ionization chamber technique are plotted in Figure 2. Since more refined experimental

¹³H. G. Thode and R. L. Graham, Can. J. Research, A25, 1 (1947).

¹⁴L. Yaffe and C. E. Mackintosh, Can. J. Research, B25, 371 (1947).

FIG. 2. FISSION YIELDS IN U^{235} , PHYSICAL.

techniques were employed by Deutsch than by the other investigators, Deutsch's results were used for a comparison of the physical and chemical measurements. In Figure 1 the results obtained by Deutsch and the results of chemical determinations³ are shown on the same graph. In order to facilitate comparison, the results by Deutsch have been normalized to give the same peak yields as were obtained chemically. It was also necessary to recalculate Deutsch's results on the basis of a total mass of 236 since, in his original calculations, the masses were summed to 234.

It may be observed that the two light peaks are centered over nearly the same mass value, 95. The heavy peak determined chemically is shifted to a mass value lower by about two mass units than that obtained by Deutsch. This shift, if real, implies that most of the prompt neutrons are emitted from the heavy fragment. A similar shift has recently been noted for Pu^{239} fission by Brunton and Thompson¹⁵ who also conclude that the effect is probably due to favored neutron emission from the heavy fragment.

Other prominent differences between the curves of Figure 1 are that the widths of the peaks and the height of the minimum between them are greater in Deutsch's curve than in the radiochemical curve. On an absolute scale the peak values obtained by Deutsch are also about 20 per cent lower than those determined radiochemically. The remainder of this section will be devoted to discussing possible reasons for these differences.

In the double ionization chamber measurements, the quantity of primary interest is the ratio of the energies of the two fission fragments. The quantity measured experimentally is the ratio of the pulse heights of each fragment of a pair in the two halves of the ionization chamber. The broadening and lowering of the fission yield curves can be explained qualitatively if the

¹⁵D. C. Brunton and W. B. Thompson, Phys. Rev., 76, 848 (1949).

ratio of pulse heights corresponding to a given mass ratio is not a unique value but shows a distribution of values over a considerable range. This is a mass resolution error which leads to the result that pairs of fragments with mass ratios in the peak of the fission yield curve give pulse height ratios corresponding to mass ratios appearing in the sides of the curve and therefore cause the sides to be raised. This type of error could be caused by:

1. Background "hash" due to α and β ionization and to amplifier noise.
2. Energy straggling due to finite thicknesses of fissionable material and supporting foil.
3. Neutron emission from moving recoil fragments.
4. Electron capture by impurities in the argon filling gas.
5. Ionization straggling of fission fragments of the same initial energy.

The experiment by Deutsch appears to be the best on the basis of easily recognizable sources of error such as foil thickness, degree of collimation, and background ionization level. In addition, the chamber used by Deutsch had a "Frisch" grid to eliminate the effect of the positive ions on the negative pulse from electron collection. Jentschke used a long chamber and a small collecting electrode to minimize the effect of the positive ions. Flammersfeld used a time constant longer than the collection time of the positive ions. The use of a short time constant is advantageous in reducing the fluctuations due to stray ionization in the chamber and to reduce microphonic effects.

The fact that the results by Jentschke and Deutsch are in good agreement in spite of the refinements present in Deutsch's experiment suggests that the difference between their results and the chemical results may be due to

errors inherent in the ionization chamber method. Examples of such errors are numbers 3 and 5 above.

The energy spread introduced by neutron emission was calculated on the assumption that one neutron is emitted isotropically from each moving fragment before the fragment has lost an appreciable amount of its initial kinetic energy. The distribution of recoil energy given to the fission fragment was calculated as a function of the energy and angle of emission of the neutron, and a numerical integration was made over the neutron energy spectrum for U^{235} fission neutrons. A neutron energy distribution curve in the moving fragment coordinate system of the form

$$N(E) = Ee^{-E}$$

was assumed. It has been shown by Bonner, De Benedetti, Francis, and Preston¹⁶ that this relationship gives very nearly the neutron energy distribution curve observed in the laboratory coordinate system.

The energy broadening of initially monoenergetic fission fragments introduced by neutron emission produces an energy distribution curve which approximates a Gaussian distribution curve in shape. The maximum is at 94 Mev, and the width at half-height is 4.1 Mev for a fragment of mass 95 and initial energy 95 Mev. The maximum is at 63.5 Mev, and the width at half-height is 2.8 Mev for a fragment of mass 140 and initial energy 64 Mev. These calculations were based on the assumption that one neutron is emitted from each fragment. If more than one neutron is emitted from some of the fragments, the energy broadening will be modified slightly.

In fission chambers employing electron collection, electron capture by impurities in the argon filling gas will cause a reduction and spread in pulse

¹⁶T. W. Bonner, S. De Benedetti, J. E. Francis, and W. W. Preston, Plutonium Project Report MonP-368 (September 22, 1947).

height for monoenergetic particles since the negative ions are not collected quickly enough to be registered. In the experiment by Flammersfeld in which positive ions were collected, electron capture could still cause trouble by increasing the probability of recombination of the ions, thus resulting in a loss of pulse height. Direct recombination of electrons and positive ions is believed to be insignificant.¹⁷

The uncertainty introduced into the energy measurements by ionization straggling is the factor about which least is known. By ionization straggling is meant the variation in the amount of ionization produced by fission fragments of the same initial energy. For alpha particles the ionization straggling is known to be quite small and gives rise to a distribution curve having a width at half-height of less than 2 per cent. If ionization straggling is to be important for fission fragments, the straggling must be introduced by events which are so infrequent that the statistical variation in the number of such events per fission fragment path is appreciable. It is evident that the statistical fluctuations in the total number of ions produced (ca. 2×10^6), treated as random, independent events, would be inappreciable. Close nuclear encounters, as evidenced in cloud chamber pictures by the abrupt changes in direction of the fission fragment or the production of short branches by the recoil atoms, are rather infrequent. If the recoiling nucleus of the atom encountered expends a different amount of energy per ion pair than does the fission fragment, ionization straggling will be introduced. Knipp, et al.¹⁸ estimate that the average light fragment loses 5 Mev and the average heavy fragment 8 Mev in nuclear collisions and that the amount of energy which is

¹⁷D. H. Wilkinson, "Ionization Chambers and Counters," Cambridge University Press, Cambridge, England, 1950, p. 57.

¹⁸J. K. Knipp, R. B. Leachman, and R. C. Ling, Phys. Rev., 80, 478 (1950).

not recorded as ionization energy is about 2.5 Mev for the light fragment and 4.2 Mev for the heavy fragment.

The energy dispersion introduced by each of the factors discussed above is listed in Table 2 for the experiment by Deutsch. The quantity listed is the root-mean-square value or standard deviation. The dispersion due to nuclear collisions was arbitrarily assumed to be equal to the energy not appearing as ionization energy. The total energy dispersion leads to a mass dispersion of 4.6 mass units at the peaks of the mass distribution curve. This means that fissions leading to masses 95 and 141 will be recorded not as peaks one mass unit wide but will be spread out to give Gaussian-like distributions having a standard deviation of 4.6 mass units or a total width at half-height of about 11 mass units. This dispersion is probably sufficient to account for the observed differences between the fission yield curves obtained by the physical and the chemical methods.

A point which must be considered in evaluating the results of fission yield measurements by the double ionization chamber method is its statistical accuracy. Examination of the data shows that for a one per cent fission yield only 16 events would have been recorded in the experiment by Deutsch. The shape of the curves below 0.5 per cent fission yield has little significance. It is in the measurement of low fission yields that the chemical method is most useful; yields as low as 10^{-5} per cent have been measured. The chemical method also has the advantage that discrete mass and nuclide resolution is possible, whereas in the physical method, the results to date represent averages over several mass units.

In discussing the difference between the fission yield curve obtained by chemical isolation of radioactive fission products and those obtained by double ionization chamber measurements, the limitations of the chemical method

TABLE 2

RESOLUTION ERRORS IN IONIZATION CHAMBER FISSION YIELDS

	Light Fragment	Heavy Fragment
Energy dispersion from neutron emission, Mev	1.8	1.3
Energy dispersion from nuclear collisions, Mev	2.5	4.2
Energy dispersion from sample thickness,* Mev	0.6	0.5
Energy dispersion from background ionization, Mev	1.6	1.6
Total dispersion, Mev	3.5	4.7
Mean energy of fragments, Mev	95	64
Most probable mass ratio	1.48	
Standard deviation in most probable mass ratio	± 0.12	
Mass dispersion introduced by energy dispersion	± 4.6 mass units	

*Calculated losses for fragments of masses 95 and 141 passing through foil normal to surface; 159 Mev total kinetic energy and mean range¹⁹ of 2.52 and 1.92 cm. used in calculations; assumption made that the energy loss per unit path length is twice as great at beginning of path as the average over the entire path.²⁰

¹⁹S. Katcoff, J. A. Miskel, and C. W. Stanley, Phys. Rev., 74, 631 (1948).

²⁰N. O. Lassen, Phys. Rev., 70, 577 (1946).

must be appreciated. Absolute errors in the chemical fission yields may be introduced by errors in the measurement of the fission rate, by errors in the radiochemical separations, or by errors in the evaluation of the beta disintegration rates from the observed counting rates. The last error is usually the most serious one because of the difficulty in beta counting of evaluating correctly the counter efficiencies and scattering and absorption corrections. The absolute errors in the chemical fission yield curve reproduced in Figure 1 must be quite small, fortuitously perhaps, since the area under the yield curve adds up to 96 per cent as compared with the expected 100 per cent. Another source of error in the chemical method which could affect the shape of the yield curve is that of direct formation of the stable members of the chains. A study of the variation of fission yield along the chain has been made by Glendenin,²¹ who has compared the experimental data with several theories of the charge distribution of the primary fission products. His studies indicate that the probability of direct formation of a stable chain member is quite low. It should be pointed out that in the worst possible case, that in which one stable nuclide is formed in each fission, the composite fission yield curve obtained by superposition of the light and the heavy groups would be low by a factor of two. Since the yield curves obtained by chemical and physical means differ by factors of ten or more for masses formed in low yield, no significant part of this difference can be attributed to formation of stable chain members which are missed by radiochemical analysis.

²¹L. E. Glendenin, "Radiochemical Studies: The Fission Products," NNES, Div. IV, Vol. 9B, Book 1, Paper 52, McGraw-Hill Book Co., New York, 1951.

at +450 volts, and the collecting electrode connected directly to the grid of a 959 tube placed in the cylindrical case which housed the ionization chamber. The 959 tube was connected through a long cable to a three-stage amplifier which led to a pulse height selector, pulse limiter, differentiator, and scale of 64. A diagram of the fission chamber showing the details of sample placement is shown in Figure 3. In Figure 4 is given the circuit diagram of the first stage of the amplifier.

The Geiger-Müller counter used for beta counting was of the thin mica, end-window type. The window was 1-1/8 in. in diameter and about 3.5 mg/cm² thick. The cathode was a brass cylinder 2-1/2 in. long with 1/16 in. walls. Counting was done on the shelf nearest the tube window. This placed the sample about 3 mm. from the window which, in turn, was about 3 mm. from the end of the central wire. The counter was filled to a pressure of 1 cm. of mercury with ethanol and 10 cm. of mercury with argon and was mounted in a lead shield with 2 in. walls.

The alpha counter which was used for the measurement of the weight of the thin uranium foil was of the parallel-plate, 50 per cent geometry, air-filled type.

Preparation of Samples

The thin sample of uranium was prepared by electrodeposition of $\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in absolute ethanol solution on a 1 mil polished platinum foil. The method of deposition was similar to that of Cohen and Hull²² except that large, parallel, stationary electrodes rather than a rotating anode were used to insure a uniform deposit. The deposit was removed from all parts of the foil except for a circular, central area 1.2 cm. in diameter by means of dilute

²²B. Cohen and D. E. Hull, Columbia Project Report A-1235 (August 28, 1944).

DETAILED VIEW OF SAMPLE MOUNTING

FIG. 3. FISSION CHAMBER.
(Drawn to Scale)

hydrochloric acid applied with a brush. The remaining central area oxidized rapidly to give a hard, shiny surface (probably UO_3) which was very uniform as judged by its interference colors. The weight of uranium in the sample, 82.5 micrograms, was determined by comparison of its alpha counting rate with those of three weighed uranium samples supplied by A. Jaffey of the Metallurgical Laboratory of Chicago. The weight was also calculated by employing the data of Scott²³ on the variation of specific activity of U_3O_8 with sample thickness. The observed counting rate of the sample was 63.0 ± 0.2 counts per minute, corresponding to a surface density of 86 micrograms per cm^2 . For a sample of U_3O_8 of this thickness, Scott found a specific activity of 775 c/m per mg. of uranium. Using this value for the specific activity, the weight of uranium was calculated to be 81.3 micrograms, in good agreement with the value 82.5 micrograms determined by direct comparison with samples of uranium of known weight. The number of fission fragments which were stopped in this thin foil was neglected in computing the fission rate. It was calculated that only 0.7 per cent of the fragments would be stopped in the sample or would enter the chamber with a residual range of less than one-third the total mean range.

The heavy samples of uranium were cut from a sheet of uranium metal 20 mils thick and had a diameter of 1.2 cm. and a weight of approximately one gram. Calculation of the loss of fission fragments from the heavy sample by fission recoil indicates a loss of less than 0.5 per cent. This loss was neglected since it was almost exactly compensated by the counting loss of 0.7 per cent in the thin sample. The shadowing of the light sample by neutron absorption in the heavy uranium sample and the platinum sheet was small. For thermal neutrons incident normally upon the surface, the absorption would be 0.25 per cent for the one mil platinum and 2 per cent for the 20 mil uranium

²³B. F. Scott, Plutonium Project Report CN-1764 (July 1, 1944).

sheet. No correction was applied for this shadowing effect.

Irradiation Procedure

The fission chamber was placed about six feet into the lattice of the Argonne graphite pile CP-2 near the center of the pile face. The pile was then run up to 2 kilowatts and held at that level for 30 minutes. This level gave a fission counting rate of about 13,000 c/m. The pile was then stopped, the chamber removed, and the heavy sample withdrawn. The fission counter was turned on before the beginning of the irradiation and was left on for a few minutes after the pile was stopped in order to allow the delayed neutron level to fall to a low value. The same light sample was used for each of six heavy uranium samples. A check of the alpha activity of the light sample after the end of the irradiations showed that no loss in weight had occurred. The fission background of the chamber was checked and found to be less than 0.1 per cent of the counting rate with the light sample in place.

At a counting rate of 13,000 c/m, the rather high ionization in the chamber due to pile radiations and induced radioactivity raised the background "hash" level to the point where rather careful discrimination was necessary in order to count all of the fissions without counting any of the "hash". Consequently, curves of counting rate (at a given pile level) vs. both pulse height selection and amplifier gain were run. Plateaus on each were observed (Figure 5). At the operating point chosen, it was estimated that the fissions were counted with an accuracy of one per cent. Since positive ion collection was employed, it was necessary to determine if any resolution losses occurred at 13,000 c/m. This was done by means of weighed gold monitors placed reproducibly in the pile. The monitors were inserted into the pile operating at a constant level as the fission counter was turned on and withdrawn as the counter was turned off. Fissions from the light sample were counted at several

FIG. 5. FISSION COUNTER PLATEAU CURVES.

power levels, counting the same number of fissions at each level so as to give approximately the same monitor activity. Several gold samples were run at each level. The ratio of the number of fissions to the monitor activity is plotted vs. the fission rate in Figure 6. This curve gives the relative efficiency as a function of counting rate. By making a short extrapolation to zero counting rate, the resolution loss at 13,000 c/m was estimated to be 1.7 per cent.

Chemical Procedure

The chemical separation of barium was carried out on the heavy uranium samples two weeks after the irradiations. At this time, only 12.8d Ba^{140} was present in the barium fraction in measurable amounts. The samples were dissolved in 2 ml. of 6N HCl and oxidized to the uranyl state with 1 ml. of concentrated HNO_3 , and 1.977 ml. of Ba^{+2} carrier was added (19.8 mg. $\text{BaCrO}_4/\text{ml.}$). The barium was precipitated as the chloride by the addition of 25 ml. of concentrated HCl, centrifuged, dissolved in 1.5 ml. of water, and precipitated again with 10 ml. of concentrated HCl. Two more chloride precipitations were carried out in the same way. The last BaCl_2 precipitate was dissolved in 10 ml. of water, 10 mg. of La^{+3} added, and $\text{La}(\text{OH})_3$ precipitated with a slight excess of NH_4OH . The supernatant liquid was neutralized with dilute acetic acid and buffered with 2.5 ml. of 6N acetic acid and 10 ml. of 3M ammonium acetate. The solution was diluted to 30 ml. and heated to boiling, and BaCrO_4 was precipitated by the dropwise addition of 2.5 ml. of 1.5F Na_2CrO_4 to the boiling solution. The BaCrO_4 was filtered onto a weighed filter paper 1.6 cm. in diameter, washed with hot water, dried at 105°C, weighed, and mounted on a cardboard card with a 2.9 mg/cm² cellophane covering. Counting was done as soon as possible in order to minimize the growth of the 40h La daughter.

FIG. 6. RESOLUTION LOSS CURVE OF FISSION COUNTER.

Beta Counting

The counting was done on the top shelf position of an end window counter with a mica window 3.8 mg/cm^2 thick. The counting rates averaged about 500 c/m. A total of about 25,000 counts was recorded for each sample, thus giving a statistical standard deviation of 0.6 per cent for each sample.

Correction must be made for growth of the lanthanum daughter. The time of lanthanum separation was considered to be the time of the $\text{La}(\text{OH})_3$ precipitation. Since precipitation of BaCrO_4 took place within ten minutes of this time, uncertainty as to which precipitation should be regarded as the separation time of the lanthanum will introduce a negligible error. The initial theoretical rate of increase of activity in the samples, the difference between the rate of growth of lanthanum and the rate of decay of barium, 1.5 per cent per hour, was used to correct each observed counting rate to that of the barium at the time of lanthanum separation. Since four counts were made on each sample, only the average counting rate of barium, corrected for lanthanum growth, is given in Table 3. The correction for lanthanum growth averaged about 3 per cent and was 5 per cent at the largest.

The aluminum absorption curves of a thin sample of Ba^{140} and of a sample of Ba^{140} somewhat thicker than those used in these experiments are shown in Figure 7. The two curves are superposable and were analyzed into two components with half-thicknesses of 7.9 mg/cm^2 and 38.5 mg/cm^2 . The curves are represented well by the equation:

$$A = A_0(0.784e^{-0.0180T} + 0.216e^{-0.088T})$$

where A is the activity through an absorber of thickness $T \text{ mg/cm}^2$ and A_0 is the sum of the two components extrapolated to zero absorber. Absorption corrections were made by extrapolation of the counting rate to zero absorber

TABLE 3

ABSOLUTE FISSION YIELD OF 12.8d Ba¹⁴⁰ IN FISSION OF U²³⁵

Sample	1	2	3	4	5	6
Observed Fission Counts, c/m x 10 ⁻⁵	2.905	2.919	3.213	2.915	2.923	2.913
Fission Counting Loss Correction	1.017	1.017	1.017	1.017	1.017	1.017
Weight of Light Sample, g x 10 ⁶	82.5	82.5	82.5	82.5	82.5	82.5
Fissions/g U x 10 ⁻⁹	3.582	3.599	3.962	3.594	3.605	3.592
c/m of 12.8d Ba Corrected for La Growth	554	459	450	426	395	357
Chemical Yield	0.626	0.482	0.492	0.456	0.410	0.387
Hours Decay	326	327	328	329	330	332
Decay Factor	0.480	0.479	0.478	0.477	0.476	0.474
Total Absorber, mg/cm ²	13.1	11.7	11.8	11.5	11.0	10.8
Absorption Factor	0.688	0.712	0.711	0.716	0.726	0.729
Geometry Factor	0.286	0.286	0.286	0.290	0.290	0.290
Weight of Uranium in Heavy Sample, grams	1.038	1.130	1.013	1.099	1.120	1.112
Dis/min per gram Uranium	9027	8640	9289	8582	8583	8278
Ba atoms/g Uranium x 10 ⁻⁸	2.407	2.304	2.477	2.288	2.289	2.207
Fission Yield of Ba ¹⁴⁰	0.0672	0.0640	0.0625	0.0637	0.0635	0.0614

Average = 0.0637 ± 0.0018 (RMS deviation)

FIG. 7. ALUMINUM ABSORPTION CURVE OF Ba¹⁴⁰.

by means of this equation. The total absorption for the sample was computed as the sum of the window, air, and cellophane thicknesses plus one-half the sample thickness in mg/cm^2 . The procedure of using one-half the sample thickness as the effective sample absorption is not strictly correct since the counting rate is modified considerably by back scattering and sample scattering effects which often outweigh the true absorption effect, especially with high-energy betas and relatively thin samples. The error introduced by making the correction in this way is partially compensated by similar scattering effects which occur in the UX_1 - UX_2 sample which is used for determination of the counter efficiency. Some preliminary empirical experiments²⁴ on the combined backscattering, sample scattering, and sample absorption effects have been carried out by comparing the activity of samples mounted in the usual fashion, with carrier, with the activity of essentially weightless samples mounted on thin collodion films to minimize these effects. However, the results of these experiments are not sufficiently precise nor are they sufficiently well understood to justify their use at this time.

The efficiency of the counter after correction for absorption of the betas and counting rate losses is termed the geometrical efficiency or the geometry factor. The geometry factor was determined by calibration with the beta rays of UX_2 in equilibrium with its parent, UX_1 . In order to reduce the large scattering effects introduced by the uranium, the 24.5d UX_1 was separated from a weighed amount of U_3O_8 with which it was in equilibrium by coprecipitation with 1 mg. of La as LaF_3 . The LaF_3 precipitate was quantitatively transferred to a thin sheet of mica which was mounted on a cardboard card and

²⁴D. W. Engelkemeir, J. A. Seiler, E. P. Steinberg, L. Winsberg, and T. B. Novey, "Radiochemical Studies: The Fission Products," NNS, Div. IV, Vol. 9B, Book 1, Papers 4 and 5, McGraw-Hill Book Co., New York, 1951.

covered with 18 mg/cm² of Scotch tape which, added to the 4 mg/cm² absorption of the tube window and air, served to filter out the beta rays of UX₁. The percentage of the UX₁ not mounted was determined by carrying out a second precipitation of LaF₃ from the supernatant liquid and by igniting and counting the Lustroid tube in which the precipitation was carried out. The radiochemical yield of the UX₁ averaged about 97 per cent and was taken into account in the calculations. Absorption of the radiations of UX₂ by the sample covering and window was corrected for by assuming exponential absorption with a half-thickness of 166 mg/cm². An aluminum absorption curve of one of the thin UX₁-UX₂ standards is shown in Figure 8.

For convenience in counting over extended periods of time, permanent reference standards of U₃O₈ were calibrated with the thin UX₁-UX₂ standards, and empirical factors deduced which related the counting rate of the reference standard and the geometry factor of the counter.

The counting rate losses for the beta counters were determined by the paired sample technique on the assumption that the percentage loss was a linear function of the counting rate. The counting rate loss amounted to 0.5 per cent per 1000 c/m. Counting loss corrections were applied to the standards (5000 c/m) but not to the Ba¹⁴⁰ samples since their counting rates were only about 500 c/m.

The data used in the fission yield calculations are given in Table 3. The fission yield of a nuclide equals its rate of formation divided by the fission rate.

If: Y = fission yield of nuclide

f = number of fissions occurring in a uniform irradiation
of length T

A_{∞} = disintegration rate of nuclide after an infinite

FIG. 8. ALUMINUM ABSORPTION CURVE OF THIN UX₁ - UX₂ STANDARD.

irradiation

A_t = disintegration rate after an irradiation of length T and
a period of decay of length t .

Then: $Y = A_{\infty} T/f = A_t T/f(1 - e^{-\lambda T})e^{-\lambda t}$.

An average value of 0.0637 ± 0.0018 was obtained for the fission yield of Ba^{140} . The precision of 0.0018 given above is the root mean square deviation of the six measurements and is not an estimate of the over-all accuracy of the result. This value may be compared with that of 0.0582 obtained by Engelkemeir, Novey, and Schover.¹⁰

Discussion of Errors

The errors which may affect the absolute fission yield of Ba^{140} may be divided into two classes: random errors and systematic errors. Random errors may be introduced by statistical fluctuations in counting, weighing errors, and variations in sample mounting. The effect of these errors may be estimated from the deviations observed in the six separate experiments. If the fluctuations follow the error law, the probable deviation of a single result equals 0.0012. This corresponds to a probable error in the mean of 0.0005 or 0.8 per cent. The precision of the experiments, therefore, is quite good. However, systematic errors may introduce a comparatively large inaccuracy into the results. Systematic errors could be introduced in the fission counting by improper pulse height selection, which may result in either the counting of spurious pulses or the missing of fission pulses. These errors are probably no greater than 1 per cent, as evidenced by the flatness of the plateaus obtained. Errors introduced by stopping of fragments in the thin foil, loss of fragments from the thick foil, and neutron shadowing by the thick foil have been considered previously, and together could not introduce an error greater than 1 per cent.

The half-life of Ba^{140} is probably known to within 1 per cent. Because of partial cancellation of errors, an error of 1 per cent in the half-life would introduce an error in the fission yield of only 0.3 per cent.

The largest possible source of systematic error lies in the evaluation of the disintegration rates of the Ba^{140} samples from their observed counting rates. The method of measuring the geometry factor by means of thin UX_1 - UX_2 standards was checked by comparison of the UX standards with a calibrated Ra DEF standard and a 40h La^{140} standard, the disintegration rate of which was determined by coincidence techniques. The three standards, UX, Ra DEF, and La^{140} , gave values of 0.320, 0.334, and 0.310, respectively, for the geometry factor of a certain counter. In view of the agreement obtained between these different standards, it seems likely that the geometry factor given by the UX standards is not in error by more than 5 per cent.

The correction for beta absorption is complicated by sample and mounting scattering effects which are not known very precisely. However, similar scattering effects in the standards cause partial cancellation of errors from this source. It is believed that the over-all error introduced in correcting for beta absorption is no greater than 10 per cent.

In conclusion, it is believed that the value of 0.064 obtained for the fission yield of Ba^{140} could not be in error by more than 20 per cent. Since it is unlikely that all of the errors would add in the same direction, the result is probably correct to within 10 per cent.

COMPARISON OF YIELDS IN U^{235} AND U^{238} FISSION

Introduction

Relative fission yield measurements were carried out to determine whether or not the shape of the mass-yield curve is different for U^{235} and U^{238} fission. It has been shown²⁵ that for Pu^{239} fission the maximum of the heavy group is nearly the same as for U^{235} fission, whereas the maximum of the light group is shifted toward heavier mass numbers by about four mass units. Also, the yields for symmetric and for extreme asymmetric fission are higher in Pu^{239} fission than in U^{235} fission. A similar effect was expected for U^{238} fission.

Much of the earlier U^{235} fission yield work was done under conditions which might have resulted in an appreciable amount of fission of U^{238} by fast neutrons. In order to determine whether or not the previous fission yields in U^{235} had been influenced appreciably by U^{238} fission, relative fission yields of a number of selected nuclides were measured using a sample of normal uranium irradiated in the thermal column of the Argonne heavy water pile, CP-3, at a position where the ratio of the fast to the thermal neutron fluxes was very low. The nuclides selected for study were on the wings and in the trough of the fission yield curve where the effect of U^{238} fission was expected to be most pronounced.

Relative yields for the fast neutron fission of U^{238} were obtained by

²⁵B. Finkle, E. J. Hoagland, S. Katcoff, and N. Sugarman, "Radiochemical Studies: The Fission Products," NNES, Div. IV, Vol. 9B, Book 3, Paper 216, McGraw-Hill Book Co., New York, 1951.

irradiation of uranium depleted in U^{235} in the interior of a thick, hollow cylinder of normal uranium placed in the lattice of the Oak Ridge pile. Fissions occurring in the uranium cylinder provided a high flux of neutrons with energies above the threshold for U^{238} fission. The depleted uranium sample was placed in a cadmium container to reduce the thermal neutron fission of the small amount of U^{235} present. In order to facilitate comparisons, the relative yields in U^{238} fission were normalized to give the same yield for Ba^{140} as was found in U^{235} fission.

Preparation and Irradiation of Samples

The irradiations for the thermal neutron U^{235} fission yields were carried out in the thermal column of the Argonne heavy water pile, CP-3, in a graphite stringer at a distance of 40 cm. from the face of the pile reflector. At this position the fission of U^{238} by fast neutrons from the pile should be negligible. In order to check this point, a special irradiation, A-50, was carried out using normal and depleted uranium. A piece of normal uranium foil 15 mils thick weighing 1.6722 g. and a sample of depleted U_3O_8 weighing 2.527 g. were sealed in quartz capsules and irradiated in holes in the graphite 2 in. apart and 40 cm. from the reflector. The samples received an irregular irradiation of 13 hours total duration. The depleted sample had a depletion ratio of 17.4 as determined by fission counting and was included to check the possibility of U^{238} fission. Two fission nuclides, 12.8d Ba^{140} and 7.5d Ag^{111} , were separated from the depleted and the normal uranium samples. If only U^{235} fission had occurred, the ratio of activity per gram of uranium in the normal uranium to that in the depleted uranium should equal the depletion ratio. A ratio of 21 was obtained from Ba^{140} and a ratio of 23 from Ag^{111} . A 2 per cent U^{238} fission contribution to the fissions in the normal uranium sample would have given a ratio of 13. The observation of ratios higher than

17.4 may have been caused by a local perturbation in the neutron flux. A thin sheet of normal uranium was used for the irradiation in order to reduce the amount of U^{238} fission from fast neutrons generated within the sample by U^{235} fission. By means of data given by Castle, et al.²⁶ it was calculated that the ratio of U^{238} to U^{235} fissions should be 0.004 from this source.

Another irradiation, A-40, was carried out for the determination of the yields of a number of other nuclides relative to Ba^{140} . For this irradiation five sheets of uranium 15 mils thick weighing 8.174 g. total were sealed separately into five quartz capsules and placed in five holes one inch apart drilled into a graphite stringer. The samples were placed 40 cm. from the reflector in the same position used for irradiation A-50. A steady irradiation of 13.25 hours duration was obtained.

The data from an experiment carried out by Winsberg,^{27,28} who has kindly allowed me to reproduce them here, are included for the sake of completeness. In this experiment, A-86, 10 g. of uranyl nitrate hexahydrate were irradiated for 12.8 hours in the thermal column of CP-3, and analyses performed for Ba^{140} , Sm^{153} , and I^{131} . Fission yields for Sm^{153} and I^{131} were obtained by comparison with Ba^{140} .

The irradiation for the fast neutron U^{238} yields was carried out in a hollow uranium cylinder placed in the lattice of the Oak Ridge pile, which served as a fast neutron source. The uranium cylinder was 24 in. long and 2 in. in outside diameter and had a hole 1 in. in diameter running through it.

²⁶H. Castle, H. Ibser, G. Sacher, and A. M. Weinberg, Plutonium Project Report, CP-644 (May 4, 1943).

²⁷L. Winsberg, Dissertation, Univ. of Chicago, Chemistry Department (August, 1947).

²⁸L. Winsberg, "Radiochemical Studies: The Fission Products," NNES, Div. IV, Vol. 9B, Book 2, Paper 195, McGraw-Hill Book Co., New York, 1951.

The U_3O_8 used had a depletion ratio of 17.4 as determined by comparison of its fission counting rate in the thermal column of CP-2 with that of normal uranium. The U_3O_8 was packed in a cadmium cylinder as shown in Figure 9. Six normal uranium disks were spaced uniformly along the length of the cylinder in order to correct for the small amount of U^{235} fission which occurred in the depleted U_3O_8 . These disks weighed 450 mg/cm^2 and were covered on each side with 9 mg/cm^2 of Scotch tape to prevent penetration of fission fragments from the normal uranium into the depleted U_3O_8 . The cylinder contained 10.498 g. of U_3O_8 packed to a density of 2.8. The sample was irradiated practically continuously for 117 hours.

Radiochemical Analysis

The normal uranium foil and the depleted U_3O_8 samples were dissolved separately in concentrated nitric acid and diluted to volume. In the U^{238} fission yield experiment the Scotch tape attached to the normal uranium foils failed to go into solution and appeared as a scum on the top of the solution soon after the addition of the nitric acid. The dissolution of the metal was stopped, and the Scotch tape and solution were discarded; the remaining metal was washed and dissolved in a fresh portion of nitric acid. Of the initial 1.713 g. of metal foil, 0.482 g. was discarded. It is not believed that a serious fractionation of the fission products from the metal could have occurred in this operation. A slight fractionation would not be serious since the normal metal foil was used only to correct for the small amount of U^{235} fission which occurred in the depleted U_3O_8 . In general, the radiochemical procedure consists of the addition of a known weight of inactive carrier element followed by the appropriate chemical treatment, where necessary, to insure radiochemical exchange. The carrier element is then separated from other fission products and uranium by characteristic precipitation reactions,

CROSS SECTION

FIG. 9. IRRADIATION CAPSULE FOR U²³⁸ FISSION YIELDS.

solvent extractions, or distillation. Interfering fission products are eliminated by precipitation, extraction, or distillation away from the desired element. After radiochemical purity has been attained, the remaining carrier is precipitated in a suitable form, and the chemical yield determined by weighing. The sample is then mounted on a cardboard card, covered with thin cellophane, and counted. If several active isotopes of the element are present, the amount of each is determined by an analysis of the decay and absorption curves. A brief outline of the analytical method employed for each element follows.

Germanium and Arsenic

The method used for germanium and arsenic was that developed by Winsberg.²⁹ Germanium and arsenic were separated from the uranium solution by precipitation with H_2S from a 6N HCl solution. The sulfides were dissolved in NH_4OH , and the germanium and arsenic distilled from a concentrated hydrochloric acid solution. $GeCl_4$ was distilled first in a stream of Cl_2 which served to retain the arsenic in the nonvolatile pentavalent state. After sweeping out the Cl_2 with air, arsenic was reduced to the trivalent state with cuprous chloride and distilled as the trichloride in a stream of air. Tin, antimony, and tellurium holdback carriers were present during the distillation. The distillation was repeated on both the germanium and the arsenic fractions in order to obtain a clean separation. The germanium and arsenic were precipitated as the sulfides, filtered on weighed filter disks, and weighed.

Strontium

The strontium procedure employed was a modification of the barium-

²⁹L. Winsberg, Ibid., Book 3, Paper 228.

strontium procedure reported by Glendenin.³⁰ Three precipitations of strontium nitrate with fuming nitric acid were carried out, followed by a ferric hydroxide scavenging precipitation. Barium carrier was then added and separated from the strontium by precipitation of barium chromate in a buffered acetic acid solution (pH = 5) in which the strontium is soluble. The strontium was precipitated as the carbonate, collected on a weighed filter disk, and weighed.

Zirconium

Zirconium was determined by the barium fluozirconate method reported by Hume.³¹ Stable, soluble complexes of zirconium and columbium which lead to rapid and complete exchange between the tracer and the carrier are formed in the presence of hydrofluoric acid. After addition of zirconium carrier, the solution was treated with hydrofluoric acid, and lanthanum fluoride was precipitated by addition of lanthanum carrier. The precipitation of lanthanum fluoride removes rare earth and alkaline earth activities. Zirconium was then separated from columbium and other elements by the addition of $\text{Ba}(\text{NO}_3)_2$, which causes precipitation of insoluble BaZrF_6 . Further purification was effected by dissolving the precipitate in boric acid and concentrated nitric acid and reprecipitating the barium fluozirconate twice. The barium was removed as barium sulfate, and the zirconium separated by precipitation with cupferron and ignited to ZrO_2 . The ZrO_2 was then weighed and mounted.

Molybdenum

The procedure developed by Ballou³² was used. Molybdenum was precipi-

³⁰L. E. Glendenin, Ibid., Book 3, Paper 236.

³¹D. N. Hume, Ibid., Book 3, Paper 245.

³²N. E. Ballou, Ibid., Book 3, Paper 257.

pitated from an oxalic acid solution by the addition of α -benzoinoxime. The oxalic acid was present in order to complex columbium and prevent its co-separation with the molybdenum. The precipitate was dissolved with a mixture of potassium chlorate and concentrated nitric acid, diluted, and made slightly alkaline with ammonium hydroxide, and lanthanum hydroxide was precipitated by the addition of lanthanum carrier. The cycle was repeated, and molybdenum precipitated as Ag_2MoO_4 from an acetic acid-sodium acetate buffered solution of pH 5-6. The silver molybdate was collected on a filter disk and weighed.

Ruthenium

Ruthenium was separated as volatile RuO_4 from boiling perchloric acid solution according to the method of Glendenin.³³ Volatilization of the halogens was prevented by the presence of sodium bismuthate, which oxidizes the halogens to their nonvolatile oxyacids. Volatilization of molybdenum was prevented by the addition of phosphoric acid. The ruthenium tetroxide was caught in a sodium hydroxide solution, and the ruthenium precipitated as a mixture of Ru_2O_3 and RuO_2 by reduction with ethanol. The ruthenium oxides were dissolved in hydrochloric acid, the solution was diluted, and ruthenium metal precipitated by reduction with magnesium metal. The metal was then dried, weighed, and mounted.

Palladium

Palladium was separated by the procedure developed by Seiler.³⁴ Palladium was precipitated with dimethylglyoxime in slightly acid solution, the precipitate dissolved in aqua regia, and scavenging precipitations of

³³L. E. Glendenin, Ibid., Book 3, Paper 260.

³⁴J. A. Seiler, Ibid., Book 3, Paper 264.

silver chloride and lanthanum hydroxide were carried out. The cycle was repeated, and palladium precipitated as PdI_2 in one instance and as the dimethylglyoxime in two other samples. The precipitates were filtered on weighed filter paper, dried, weighed, and mounted. The only interfering contaminant not removed by this procedure is selenium. Since the longest-lived selenium found in fission has a half-life of about one hour, no difficulty was encountered from this source.

Silver

The silver procedure used followed that given by Novey.³⁵ Silver was isolated by precipitation as the chloride and was purified by precipitation of the sulfide from ammoniacal solution. The silver sulfide was dissolved in boiling concentrated nitric acid, and the cycle repeated. The silver was finally precipitated as the chloride for weighing and mounting.

Cadmium

The procedure used was a slight modification of that developed by Metcalf.³⁶ A hydrogen sulfide scavenging precipitation of $1N$ HCl was carried out on the active solution to which had been added cadmium, tin, and antimony carriers. The tin and antimony sulfides were discarded, and cadmium sulfide was precipitated by making the solution slightly basic with ammonium hydroxide and passing in hydrogen sulfide. The cadmium sulfide was dissolved in hydrochloric acid, and a basic ferric acetate scavenging precipitation made in a neutral, buffered solution. This was followed by a scavenging precipitation of lanthanum hydroxide with ammonium hydroxide. The cycle was repeated, and cadmium precipitated as CdNH_4PO_4 from an ammonium chloride solution by addition

³⁵T. B. Novey, Ibid., Book 3, Paper 266.

³⁶R. P. Metcalf, Ibid., Book 3, Paper 268.

of ammonium monohydrogen phosphate. The precipitate was ignited to $\text{Cd}_2\text{P}_2\text{O}_7$, weighed, and mounted.

Antimony

Antimony was separated according to the procedure of Seiler.³⁷ Antimony was separated as Sb_2O_5 by precipitation from boiling, fuming nitric acid solution. The antimonite oxide was dissolved by fuming with sulfuric acid, tellurium and arsenic carriers were added, and the solution was transferred to a distilling flask. Cuprous chloride and concentrated hydrochloric acid were added, and AsCl_3 was distilled in a stream of hydrochloric acid gas at a temperature of 105–110°C and discarded. The temperature was then raised to 155°C, and SbCl_3 distilled out. The antimony was purified further by two As_2S_3 scavenging precipitations in concentrated hydrochloric acid solution, in which the antimony is soluble. The entire cycle was repeated, and the antimony precipitated and weighed as Sb_2S_3 .

Iodine

The most important single factor involved in the quantitative radiochemical determination of iodine is that of exchange. In the procedure of Glendenin and Metcalf³⁸ which was used here, exchange was effected by the oxidation of iodide carrier to periodate with sodium hypochlorite in alkaline solution. Sodium carbonate was used as the alkaline reagent in order to complex the uranium and prevent its precipitation. The solution was then acidified, the periodate reduced to iodine with hydroxylamine hydrochloride, and the iodine extracted with carbon tetrachloride. The iodine was removed from the carbon tetrachloride layer by extraction with a dilute sodium bisulfite

³⁷ J. A. Seiler, Ibid., Book 3, Paper 270.

³⁸ L. E. Glendenin and R. P. Metcalf, Ibid., Book 3, Paper 278.

solution which causes reduction to iodide. The extraction cycle was repeated three times, using sodium nitrite for oxidation and sodium bisulfite for reduction. The iodine was precipitated as PdI_2 for weighing and mounting.

Cesium

Cesium was separated by the procedure of Glendenin and Nelson.³⁹ The separation of cesium was accomplished by precipitation of cesium perchlorate from perchloric acid solution with absolute ethanol. A scavenging precipitation of ferric hydroxide was then carried out, and the cycle repeated. Cesium was precipitated as the perchlorate and filtered onto a weighed filter disk for weighing and mounting.

Barium

The procedure used for barium was one reported by Glendenin.³⁰ Barium was precipitated three times as barium chloride from concentrated hydrochloric acid solution, a scavenging precipitation of lanthanum hydroxide carried out, and barium precipitated as barium chromate for weighing and mounting.

Samarium

Samarium was separated by a procedure similar to that given by Winsberg.⁴⁰ A preliminary separation of the rare earths from other fission products was made by precipitation of SmF_3 . Neptunium was separated at the same time by oxidation to a fluoride-soluble state with divalent silver plus persulfate. Samarium was then separated from the other rare earths by extraction of the samarium with sodium amalgam and removal from the amalgam with 2N hydro-

³⁹L. E. Glendenin and C. M. Nelson, Ibid., Book 3, Paper 283.

⁴⁰L. Winsberg, Ibid., Book 3, Paper 303.

chloric acid. Four extractions were made. The samarium was then precipitated as the oxalate and ignited to Sm_2O_3 for weighing and mounting.

Europium

Europium was separated by a procedure developed by Winsberg.⁴¹ Europium, along with other rare earths, was separated from other fission products by precipitation of EuF_3 . The EuF_3 was dissolved with boric and hydrochloric acids, and europium precipitated as $\text{Eu}(\text{OH})_3$ in the presence of barium and strontium holdback carriers. The precipitate of $\text{Eu}(\text{OH})_3$ was dissolved, cerium carrier added, and amalgamated zinc added to reduce Eu^{+3} to Eu^{+2} . After reduction was complete, the cerium was precipitated as $\text{Ce}(\text{OH})_3$ with ammonium hydroxide in order to carry down all rare earths except Eu^{+2} , which is soluble. The reduction separation was repeated, Eu^{+2} oxidized to Eu^{+3} with ozone, and europium precipitated as the oxalate. The oxalate precipitate was ignited to Eu_2O_3 for weighing and mounting.

Calculations

The U^{235} fission yields were calculated by comparison of the saturation disintegration rate of each nuclide with that of Ba^{140} , whose fission yield is known. Since no absolute fission yields from U^{238} fission have been determined, only relative yields were calculable. However, for convenience in making comparisons between U^{235} and U^{238} fission yields, the U^{238} relative fission yields were normalized to give a fission yield of 0.0637 for Ba^{140} , the value found for U^{235} fission.

If the fission rate is constant during the irradiation, the fission yield of nuclide (a) is given by the following expression:

$$Y_a = A_a^\infty \times Y_{\text{Ba}} / A_{\text{Ba}}^\infty, \quad (1)$$

⁴¹L. Winsberg, Ibid., Book 3, Paper 302.

where Y_a and Y_{Ba} are the fission yields of nuclide (a) and Ba^{140} , respectively, and A_a^∞ and A_{Ba}^∞ are the saturation activities of nuclides (a) and Ba^{140} . If the nuclide (a) is a primary fission product or if its ancestors have much shorter lifetimes than (a), the saturation activity may be calculated from the observed counting rate of (a) at time (t) by means of the expression

$$A_a^\infty = A_a^t / (1 - e^{-\lambda T}) e^{-\lambda t}, \quad (2)$$

where A_a^t is the counting rate at time (t) after the end of a uniform irradiation of length (T) and λ is the decay constant of nuclide (a). The relationship between the observed activity and the saturation activity of a nuclide whose parent is a primary fission product is

$$A_2^t = A_2^\infty \left[\lambda_2 (1 - e^{-\lambda_1 T}) e^{-\lambda_1 t} - \lambda_1 (1 - e^{-\lambda_2 T}) e^{-\lambda_2 t} \right] (\lambda_2 - \lambda_1), \quad (3)$$

where the symbols have the same meaning as in (2) and the subscripts (1) and (2) refer to the parent and the daughter, respectively. Equation (2) was used for the calculation of the saturation activities of all of the nuclides studied except As^{77} and Eu^{156} , for which equation (3) was required. Eu^{156} has a samarium parent of 10h half-life; As^{77} is formed in part by beta decay of 12h Ge^{77} . Evidence for an apparent independent yield of As^{77} was found by Steinberg and Engelkemeir⁴² and studied more thoroughly by Steinberg⁴³, who found an apparent independent yield of approximately 60 per cent. Arnold and Sugarman⁴⁴ discovered a 59s beta activity of germanium by neutron irradiation of germanium. By means of arsenic extractions from neutron-irradiated germanium, they were able to show that approximately 50 per cent of the As^{77} formed grew from a germanium parent of less than 3m half-life which is probably

⁴²E. P. Steinberg and D. W. Engelkemeir, Ibid., Book 2, Paper 54.

⁴³E. P. Steinberg, Dissertation, Univ. of Chicago, Chemistry Department (August, 1947).

⁴⁴J. F. Arnold and N. Sugarman, J. Chem. Phys., 15, 703 (1947).

identical with the 59s germanium and that the remainder grew from the 12h Ge^{77} . This is a strong indication that the apparent independent yield of As^{77} in fission is due to its formation by beta decay of 59s Ge^{77} . In the fission yield calculations presented here, it was assumed that 50 per cent of the As^{77} is formed by beta decay of 12h Ge^{77} and that the remainder is formed either independently or by decay of a very short-lived germanium parent.

In the instances in which the nuclide isolated was not the last active member of the chain, special treatment of the data was required. The individual cases are discussed below.

Zr^{95} decays mainly to 35d Cb^{95} with approximately 2 per cent branching to the isomeric 90h Cb^{95} . The particle radiations from the columbium isomers consist of 0.15 Mev beta particles from the 35d and 0.22 Mev conversion electrons from the 90h Cb^{95} and are counted with a much lower efficiency than the particle radiations of Zr^{95} , which consist of 98 per cent of a 0.39 Mev beta and 2 per cent of a 1.0 Mev beta. The Zr^{95} was counted soon enough after the last columbium separation that no appreciable growth occurred.

In the beta decay of 67h Mo^{99} branching occurs to give 90 per cent of the long-lived Tc^{99} and 10 per cent of the isomeric 5.9h Tc^{99} . The activity of the long-lived Tc^{99} was completely negligible, and the radiations of the 5.9h Tc^{99} are so weak that no appreciable contribution to the counting rate of the Mo^{99} was made through the thickness of absorber used.

In the case of the 42d Ru^{103} and in 13.4h Pd^{109} beta decay leads to a short-lived, low-energy isomeric state of the stable daughter nucleus. Sufficient absorber was used in each case to filter out the conversion electrons from the isomeric state.

The 21h Pd^{112} decays by emission of a 0.2 Mev beta to 3.2h Ag^{112} , which decays by emission of a 3.6 Mev beta to stable Cd^{112} . The silver daughter

was allowed to come to transient equilibrium with the palladium before counting was begun. In order to facilitate the analysis of the decay curve of the 13.4h and the 21h palladium activities, the palladium was counted through two thicknesses of aluminum absorber, one of 23.6 mg/cm² and another of 405 mg/cm². Only the beta radiations of the 13.4h Pd (1.1 Mev) and the beta radiations of the 3.2h Ag¹¹² are counted through 23.6 mg/cm² and only the beta radiations of the 3.2h Ag through 405 mg/cm². The decay curve through 405 mg/cm² of absorber gave a half-life of 21h, that of Pd¹¹². By means of a beta absorption curve taken on 3.2h Ag¹¹² alone it was possible to calculate what the counting rate of the Ag¹¹² would have been through zero absorber and through 23.6 mg/cm² of added aluminum absorber. The contribution of the Ag¹¹² was then subtracted from each point of the decay curve through 23.6 mg/cm² to give the decay curve of the 13.4h Pd¹⁰⁹. The saturation activity of the 21h Pd¹¹² was calculated by means of equation (4),

$$A_1^{\infty} = A_2^t(\lambda_2 - \lambda_1)/e^{-\lambda_1 t}(1 - e^{-\lambda_1 T})\lambda_2 \quad (4)$$

where A_1^{∞} is the saturation activity of the parent and A_2^t is the observed activity of the daughter in transient equilibrium with its longer-lived parent at time (t) after the end of an irradiation of length (T).

The 2.33d Cd¹¹⁵ decays by beta emission to an isomeric state of stable In¹¹⁵ which transforms to the ground state of In¹¹⁵ with a half-life of 4.53h by emission of a 0.34 Mev gamma which is approximately 50 per cent internally converted. The beta radiations of Cd¹¹⁵ are complex and consist of a 0.6 Mev beta (60 per cent) and a 1.1 Mev beta (40 per cent). The In¹¹⁵ was allowed to come to transient equilibrium before the counting was begun, and the counting rate of the parent in equilibrium with its daughter was extrapolated back to the time of indium separation. The ratio of the initial

counting rate of Cd^{115} to the equilibrium counting rate of Cd^{115} plus In^{115} extrapolated back to the time of indium separation was found to be 0.572 in a separate experiment in which the Cd^{115} was mounted and counted rapidly after indium separation. In the actual fission yield experiments the time required for accurate chemical yield determinations made it impossible to determine the initial counting rate of Cd^{115} . By making use of this empirical factor it was possible to avoid the estimation of the counting efficiency of In^{115} .

The 93h Sb^{127} was counted in equilibrium with its 9.3h Te daughter. The activity of the Sb^{127} , A_1 , was calculated from the observed activity, $A_1 + A_2$, by means of the theoretical ratio

$$(A_1 + A_2)/A_1 = 1 + \lambda_2/(\lambda_2 - \lambda_1) = 2.11. \quad (5)$$

The half-life of 33 ± 3 years⁴⁵ reported for Cs^{137} was determined by observation of the disintegration rate of a sample of cesium in which the number of atoms of Cs^{137} was known. The number of atoms of Cs^{137} in the sample was estimated by isolating Ba^{140} and Cs^{137} from a sample of neutron-irradiated uranium and measuring their activities. The assumption was made that the yield of the mass 137 chain lies on a smooth curve drawn through neighboring points. The ratio of the yield of the 140 chain to the 137 chain was assumed to be 1.02. Until the half-life of Cs^{137} is measured by other means, the fission yield of Cs^{137} cannot be measured directly. However, changes in the yield of Cs^{137} relative to Ba^{140} can be measured for the fission of different nuclides or for fission by agents other than thermal neutrons.

The method of counting Ba^{140} and correcting for La^{140} growth was the same as in the absolute fission yield determinations.

⁴⁵L. E. Glendenin and R. P. Metcalf, "Radiochemical Studies: The Fission Products," NNES, Div. IV, Vol. 9B, Book 2, Paper 152, McGraw-Hill Book Co., New York, 1951.

In relative fission yield work it is not necessary to know the geometrical efficiency of the counter provided the nuclide of known fission yield is also measured on the same counter. Since measurements were carried out over a period of weeks on different counters, a geometry standard was used to correct for variations in the counter efficiencies. The counting efficiency was expressed in terms of a geometry factor, and all counting rates corrected to 100 per cent geometry.

Absorption of the beta rays was corrected for by assuming exponential absorption by the counter window, air, cellophane covering and the sample. As in the absolute fission yield work on Ba^{140} , the effective sample thickness for absorption was assumed to be equal to one-half the sample thickness per unit area. In the instances in which the radiations appeared to be complex, the absorption curve was expressed as the sum of two exponentials, and the correction made by extrapolating each component to zero absorber and summing them. No correction was applied for the contribution of gamma or X-rays to the beta counting rates. In no case would this introduce an error greater than 2 per cent.

In the determination of the relative fission yields in U^{238} it was necessary to correct for the amount of U^{235} fission which occurred in the depleted U_3O_8 . This was done by separating fission products from the normal uranium sample which was irradiated along with the depleted sample and calculating the contribution that thermal fission would make to the observed activity in the depleted oxide. The activity of a nuclide arising from U^{238} fission, A_{28} , was calculated from the observed activity of the nuclide in the depleted sample, A_d , and in the normal sample, A_n , by means of the expression

$$A_{28} = (17.4A_d - A_n)/16.4 \quad (6)$$

where 17.4 is the depletion ratio. About 95 per cent of the activity observed

in the U^{238} sample was due to U^{238} fission.

Discussion of Results

A comparison of the mass-yield curves for U^{235} and U^{238} fission is given in Figure 10. The curve for U^{235} was plotted from data presented in the Plutonium Project Report³ on fission yields and is identical with the solid curve of Figure 1 except that the fission yields are plotted on a logarithmic scale. Except for a few isolated points, the U^{235} curve represents fission yields obtained from pile irradiations of normal uranium under conditions which would have led to a small amount of fast fission of U^{238} . The open circles represent the U^{235} thermal fission yields reported in this paper. The points scatter rather badly, but there is no evidence that the shape of the U^{235} pile fission yield curve has been influenced appreciably by U^{238} fission. In particular, it should be noted that the non-zero minimum in the U^{235} curve is real and is not caused by a small amount of U^{238} fission.

The dotted curve in Figure 10 gives the fission yields for U^{238} fission. In drawing this curve the light and heavy groups were first superimposed, and the best smooth curve was drawn through them. The curve was then unfolded and plotted as is shown in Figure 10. The U^{238} curve was made symmetrical about a mass value of $118\frac{1}{2}$, corresponding to the emission of an average of two neutrons per fission. Although the shape of the U^{238} curve is not defined very well by the experimental points, several differences between it and the U^{235} curve should be noted; one is a general shift of the curve toward higher mass values; another is the increase in yield for symmetrical fission. The shift of the U^{238} curve toward higher mass numbers is to be expected because of the higher mass of the compound nucleus and has been observed for Pu^{239} fission also.¹¹ In Pu^{239} fission it was observed that the position of the heavy peak remained practically unchanged and that most of the shift

FIG. 10. FISSION YIELDS IN U^{235} AND U^{238} .

occurred in the light group. In addition, the wings of the fission yield curve were broadened, leading to increased yields for the wing elements of the heavy group. The same effects appear to be present in U^{238} fission. However, further study is needed to verify these last two effects.

TABLE 4

THERMAL FISSION YIELDS IN U^{235} 12.8d Ba^{140} - Irradiation A-40

Sample	1	2	3
Counts/min Corrected for La Growth	3782	3515	3614
Hours Decay	184	184	184
Decay Factor	0.661	0.661	0.661
Weight of Sample, mg	16.8	15.0	16.2
Chemical Yield	0.680	0.607	0.656
Total Absorber, mg/cm^2	12.1	11.7	12.0
Beta Absorption Factor*	0.704	0.713	0.706
Geometry Factor	0.278	0.278	0.278
Weight of Uranium Taken, $g \times 10^3$	1.635	1.635	1.635
Dis/min per g Uranium at End of Irradiation $\times 10^{-7}$	2.63	2.71	2.60
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	8.97	9.24	8.87

Average = 9.04×10^8 atoms/min per g Uranium

Fission Yield = 0.0637 (used as standard yield)

*Calculated assuming exponential absorption of the following components:

$$T_{1/2} = 7.9 \text{ mg/cm}^2 - 22 \text{ per cent,}$$

$$T_{1/2} = 38.5 \text{ mg/cm}^2 - 78 \text{ per cent.}$$

TABLE 5

THERMAL FISSION YIELDS IN U^{235} 13.4h Pd^{109} - Irradiation A-40

Sample	1	2	3
Counts/min through 23.6 mg/cm ² of Al	3500	4800	4200
Hours Decay	36.5	36.5	36.5
Decay Factor	0.152	0.152	0.152
Weight of Sample, mg	10.6	38.5	34.6
Chemical Yield	0.194	0.753	0.675
Total Absorber, mg/cm ²	33.7	40.7	38.7
Beta Absorption Factor*	0.602	0.542	0.558
Geometry Factor	0.283	0.0975	0.0975
Weight of Uranium Taken, g	0.4087	0.4087	0.4087
Dis/min per g Uranium at end of Irradiation x 10 ⁻⁶	1.703	1.944	1.843
Rate of Formation, atoms/min per g of Uranium x 10 ⁻⁶	3.38	3.86	3.66

Average = 3.63×10^6 atoms/min per g Uranium

Fission Yield = 0.000256

*Half-thickness = 46 mg/cm².

TABLE 6

THERMAL FISSION YIELDS IN U^{235} 7.6d Ag^{111} - Irradiation A-40

Sample	1	2	3
Counts/min	7950	9710	3920
Hours Decay	120	120	120
Decay Factor	0.634	0.634	0.634
Weight of Sample, mg	13.0	14.8	5.9
Chemical Yield	0.504	0.573	0.229
Total Absorber, mg/cm^2	11.2	11.6	9.4
Beta Absorption Factor*	0.828	0.822	0.853
Geometry Factor	0.312	0.312	0.312
Weight of Uranium Taken, g	0.8174	0.8174	0.8174
Dis/min per g Uranium at end of Irradiation $\times 10^{-5}$	1.180	1.278	1.242
Rate of Formation, atoms/min per g of Uranium $\times 10^{-6}$	2.41	2.61	2.54

Average = 2.52×10^6 atoms/min per g Uranium

Fission Yield = 0.000178

*Half-thickness = $41 mg/cm^2$.

TABLE 7

THERMAL FISSION YIELDS IN U^{235} 21h Pd^{112} - Irradiation A-40

Sample	1	2	3
Counts/min through 405 mg/cm ² of Al	1225	4950	4575
Hours Decay	36.5	36.5	36.5
Decay Factor	0.300	0.300	0.300
Weight of Sample, mg	10.6	38.5	34.6
Chemical Yield	0.194	0.753	0.675
Total Absorber, mg/cm ²	413	417	416
Beta Absorption Factor ^a	0.378	0.378	0.378
Geometry Factor	0.283	0.283	0.283
Weight of Uranium Taken, g	0.4087	0.4087	0.4087
Transient Equilibrium Factor ^b	1.180	1.180	1.180
Dis/min per g Uranium at end of Irradiation x 10 ⁻⁵	4.10	4.25	4.38
Rate of Formation, atoms/min per g of Uranium x 10 ⁻⁶	1.156	1.198	1.233

Average = 1.196×10^6 atoms/min per g Uranium

Fission Yield = 0.0000843

^aOnly the betas of the 3.2h Ag daughter in equilibrium with the 21h Pd were counted through 405 mg/cm² of Al. The absorption factor was obtained from an absorption curve taken on separated 3.2h Ag.

^bAt equilibrium, the activity of the 3.2h Ag will be higher than that of the 21h Pd by the factor:

$$\lambda_2/(\lambda_2 - \lambda_1) = 1.180.$$

Therefore, the observed disintegration rate of the 3.2h Ag is divided by 1.180 to give the disintegration rate of the 21h Pd.

TABLE 8

THERMAL FISSION YIELDS IN U^{235} 2.33d Cd^{115} - Irradiation A-40

Sample	1	2	3
Counts/min of Cd^{115} at Time of In Separation ^a	5700	5700	5700
Hours Decay	39.5	39.5	39.5
Decay Factor	0.613	0.613	0.613
Weight of Sample, mg	19.3	18.7	19.8
Chemical Yield	0.405	0.392	0.415
Total Absorber, mg/cm^2	12.7	12.7	12.7
Beta Absorption Factor ^b	0.783	0.783	0.783
Geometry Factor	0.322	0.322	0.322
Weight of Uranium Taken, g	0.2452	0.2452	0.2452
Dis/min per g Uranium at End of Irradiation $\times 10^{-5}$	3.73	3.85	3.65
Rate of Formation, atoms/min per g of Uranium $\times 10^{-6}$	2.46	2.54	2.41

Average = 2.47×10^6 atoms/min per g UraniumFission Yield for 2.33d Cd^{115} = 0.000174Assumed Fission Yield for 44d Cd^{115} = 0.000013^c

Total Yield for Mass 115 Chain = 0.000187

^aSee section on calculations for method of correcting for 4.53h In growth.

^bHalf-thickness of 2.33d Cd^{115} = 36 mg/cm^2 .

^cThe same yield relative to the 2.33d Cd^{115} as was found in ordinary pile irradiations and reported in reference (3) was assumed.

TABLE 9

THERMAL FISSION YIELDS IN U^{235} 93h Sb^{127} - Irradiation A-40

Sample	1	2
Counts/min of Sb^{127} at Time of Te Separation ^a	1105	3650
Hours Decay	205.5	207.2
Decay Factor	0.215	0.213
Weight of Sample, mg	6.6	22.3
Chemical Yield	0.229	0.775
Total Absorber, mg/cm^2	9.5	13.6
Beta Absorption Factor ^b	0.820	0.753
Geometry Factor	0.281	0.281
Weight of Uranium Taken, g	0.08174	0.08174
Dis/min per g Uranium at End of Irradiation $\times 10^{-6}$	1.192	1.280
Rate of Formation, atoms/min per g of Uranium $\times 10^{-7}$	1.270	1.362

Average = 1.316×10^7 atoms/min per g Uranium

Fission Yield = 0.000928

^aThe sample was counted after the 9.3h Te^{127} daughter had come to transient equilibrium with the 93h Sb^{127} . At equilibrium the ratio of the activity of the Sb plus Te to the activity of the Sb is given by:

$$(A_1 + A_2)/A_1 = 1 + \lambda_2/(\lambda_2 - \lambda_1) = 2.11.$$

^bCalculated assuming exponential absorption of the beta radiations with the following half-thicknesses:

$$93h \text{ } Sb^{127}: T_{1/2} = 45 \text{ } mg/cm^2,$$

$$9.3h \text{ } Te^{127}: T_{1/2} = 26 \text{ } mg/cm^2.$$

TABLE 10

THERMAL FISSION YIELDS IN U^{235} 15.4d Eu^{156} - Irradiation A-40

Sample	1	2	3
Counts/min	1770	1210	2960
Days Decay	24.0	24.0	24.0
Decay Factor	0.340	0.340	0.340
Weight of Sample, mg	7.9	4.8	11.0
Chemical Yield	0.419	0.255	0.584
Total Absorber, mg/cm^2	9.9	9.1	10.7
Beta Absorption Factor*	0.775	0.790	0.762
Geometry Factor	0.295	0.295	0.295
Weight of Uranium Taken, g	1.227	1.227	1.227
Dis/min per g Uranium at End of Irradiation $\times 10^{-4}$	4.44	4.89	5.42
Rate of Formation, atoms/min per g of Uranium $\times 10^{-6}$	1.810	1.993	2.21

Average = 2.01×10^6 atoms/min per g Uranium

Fission Yield = 0.000142

*Calculated assuming exponential absorption of the following components:

$$T_{1/2} = 13.4 \text{ mg/cm}^2 - 50 \text{ per cent,}$$

$$T_{1/2} = 140 \text{ mg/cm}^2 - 50 \text{ per cent.}$$

TABLE 11

THERMAL FISSION YIELDS IN U^{235} 12.8d Ba^{140} - Irradiation A-86

Sample	1	2	3	4
Counts/min Corrected for La Growth	2571	1288	2516	1942
Hours Decay	58.3	58.3	58.3	58.3
Decay Factor	0.876	0.876	0.876	0.876
Weight of Sample, mg	20.0	9.5	18.8	14.2
Chemical Yield	0.476	0.226	0.448	0.338
Total Absorber, mg/cm^2	12.9	10.3	12.6	11.5
Beta Absorption Factor*	0.690	0.738	0.695	0.714
Geometry Factor	0.274	0.274	0.274	0.274
Aliquot, ml	0.100	0.100	0.100	0.100
Dis/min per ml Solution at End of Irradiation $\times 10^{-5}$	3.26	3.22	3.36	3.36
Rate of Formation, atoms/min per ml Solution $\times 10^{-7}$	1.148	1.133	1.182	1.182

Average = 1.161×10^7 atoms/min per ml solution

Fission Yield = 0.0637 (used as standard yield)

*Calculated assuming exponential absorption of the following components:

$$T_{1/2} = 7.9 \text{ mg/cm}^2 - 22 \text{ per cent,}$$

$$T_{1/2} = 38.5 \text{ mg/cm}^2 - 78 \text{ per cent.}$$

TABLE 12

THERMAL FISSION YIELDS IN U^{235} 8.0d I^{131} - Irradiation A-86

Sample	1	2	3	4
Counts/min	2383	2168	2006	2462
Days Decay	8.57	8.57	8.57	8.57
Decay Factor	0.476	0.476	0.476	0.476
Weight of Sample, mg	23.5	22.7	20.1	24.1
Chemical Yield	0.629	0.606	0.537	0.645
Total Absorber, mg/cm^2	13.8	13.6	12.9	13.9
Beta Absorption Factor*	0.620	0.624	0.640	0.618
Geometry Factor	0.261	0.261	0.261	0.261
Aliquot, ml	0.200	0.200	0.200	0.200
Dis/min per ml Solution and End of Irradiation $\times 10^{-5}$	2.46	2.31	2.35	2.49
Rate of Formation, atoms/min per ml Solution $\times 10^{-6}$	5.46	5.13	5.22	5.53

Average = 5.33×10^6 atoms/min per ml solution

Fission Yield = 0.0292

*Half-thickness = 20 mg/cm^2 .

TABLE 13

THERMAL FISSION YIELDS IN U^{235} 47h Sm^{153} - Irradiation A-86

Sample	1	2
Counts/min	995	5380
Days Decay	1.608	1.958
Decay Factor	0.565	0.515
Weight of Sample, mg	7.5	11.8
Chemical Yield	0.181	0.284
Total Absorber, mg/cm^2	9.8	10.9
Beta Absorption Factor*	0.754	0.709
Geometry Factor	0.261	0.267
Aliquot, ml	1.00	4.00
Dis/min per ml Solution at End of Irradiation $\times 10^{-4}$	4.95	4.87
Rate of Formation, atoms/min per ml Solution $\times 10^{-5}$	2.88	2.83

Average = 2.86×10^5 atoms/min per ml solution

Fission Yield = 0.00157

*Half-thickness = $24 mg/cm^2$.

TABLE 14

FAST FISSION YIELDS IN U^{238} 12.8d Ba^{140} - Irradiation A-50Measurement of Depletion Ratio of U_3O_8

Sample	Normal U		Depleted U_3O_8	
	1	2	1	2
Counts/min Corrected for La Growth	4690	4630	4060	4810
Days Decay	3.68	3.68	3.68	3.68
Decay Factor	0.819	0.819	0.819	0.819
Weight of Sample, mg	13.6	13.4	12.9	15.9
Chemical Yield	0.648	0.638	0.615	0.722
Total Absorber, mg/cm^2	11.3	11.3	11.1	11.9
Beta Absorption Factor*	0.718	0.718	0.721	0.708
Geometry Factor	0.286	0.286	0.286	0.286
Weight of Uranium Taken, $g \times 10^3$	2.01	2.01	42.8	42.8
Dis/min per g Uranium at End of Irradiation $\times 10^{-6}$	21.4	21.5	0.914	0.940
Rate of Formation, atoms/min per g of Uranium $\times 10^{-7}$	74.0	74.4	3.16	3.25
Average, atoms/min per g of U	74.2×10^7		3.20×10^7	

$$\text{Depletion Ratio} = 74.2/3.20 = 23.2$$

*Calculated assuming exponential absorption of the following components:

$$T_{1/2} = 7.9 \text{ mg/cm}^2 - 22 \text{ per cent,}$$

$$T_{1/2} = 38.5 \text{ mg/cm}^2 - 78 \text{ per cent.}$$

TABLE 15

FAST FISSION YIELDS IN U^{238} 7.6d Ag^{111} - Irradiation A-50Measurement of Depletion Ratio of U_3O_8

Sample	Normal U		Depleted U_3O_8	
	1	2	1	2
Counts/min	3727	3786	292	232
Days Decay	4.77	4.77	4.77	4.77
Decay Factor	0.647	0.647	0.647	0.647
Weight of Sample, mg	8.8	9.4	11.9	10.5
Chemical Yield	0.341	0.364	0.462	0.407
Total Absorber, mg/cm^2	9.9	10.0	10.9	10.5
Beta Absorption Factor*	0.846	0.844	0.832	0.837
Geometry Factor	0.288	0.288	0.288	0.288
Weight of Uranium Taken, g	0.669	0.669	0.857	0.771
Dis/min per g Uranium at End of Irradiation $\times 10^{-3}$	103.8	99.0	4.76	4.73
Rate of Formation, atoms/min per g of Uranium $\times 10^{-5}$	21.5	20.5	0.988	0.982
Average, atoms/min per g of U	21.0×10^5		0.985×10^5	

$$\text{Depletion Ratio} = 21.0/0.985 = 21.3$$

* Half-thickness = 41 mg/cm^2 .

TABLE 16

FAST FISSION YIELDS IN U^{238} 12.8d Ba^{140}

Sample	Depleted Uranium			Normal Uranium		
	1	2	3	4	5	6
Counts/min Corrected for La Growth	5580	5360	4580	7520	6650	7200
Days Decay	10.21	10.21	10.21	10.35	10.35	10.35
Decay Factor	0.576	0.576	0.576	0.571	0.571	0.571
Weight of Sample, mg	13.3	13.3	10.8	13.6	12.3	12.7
Chemical Yield	0.708	0.708	0.575	0.724	0.655	0.676
Total Absorber, mg/cm^2	10.9	10.9	10.3	11.0	10.7	10.8
Beta Absorption Factor*	0.726	0.726	0.737	0.724	0.729	0.727
Geometry Factor	0.364	0.364	0.364	0.361	0.361	0.361
Weight of U Taken, $g \times 10^4$	3.39	3.39	3.39	2.46	2.46	2.46
Dis/min per g Uranium at End of Irradiation $\times 10^{-8}$	1.528	1.460	1.520	2.83	2.75	2.89
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	6.58	6.30	6.55	12.20	11.85	12.44
Average, atoms/min per g of Uranium	6.48×10^8			12.16×10^8		

Rate of Formation of Ba^{140} from $U^{238} = 6.13 \times 10^8$ atoms/min per g UFission Yield of Ba^{140} in $U^{238} = 0.0637$ (arbitrarily assigned value)

*Calculated assuming exponential absorption of the following components:

$$T_{1/2} = 7.9 \text{ mg/cm}^2 - 22 \text{ per cent,}$$

$$T_{1/2} = 38.5 \text{ mg/cm}^2 - 78 \text{ per cent.}$$

TABLE 17

FAST FISSION YIELDS IN U^{238} $40h As^{77}$

Sample	Depleted Uranium		Normal Uranium	
	1	2	3	4
Counts/min at Time of Separation from Ge	184	588	224	227
Elapsed Time Between End of Irradiation and Separation of As from Ge, hours	171	171	219	219
Weight of Sample, mg	15.8	3.5	20.3	6.9
Chemical Yield	0.466	0.103	0.599	0.204
Total Absorber, mg/cm^2	11.5	8.5	12.7	9.3
Beta Absorption Factor*	0.727	0.790	0.704	0.773
Geometry Factor	0.368	0.368	0.368	0.368
Weight of Uranium Taken, g	0.0712	0.890	0.0615	0.1231
Rate of Formation, atoms/min per g of Uranium $\times 10^{-5}$	3.80	4.06	9.91	13.43
Average, atoms/min per g of U	3.93×10^5		11.67×10^5	

Rate of Formation of As^{77} from $U^{238} = 3.46 \times 10^5$ atoms/min per g UFission Yield of As^{77} in $U^{238} = 0.000036$ *Half-thickness = $25 mg/cm^2$.

TABLE 18
FAST FISSION YIELDS IN U^{238}
 $^{53d}Sr^{89}$

Sample	Depleted Uranium		Normal Uranium	
	1	2	3	4
Counts/min	4992	4876	5775	5142
Days Decay	64.5	64.5	64.5	64.5
Decay Factor	0.430	0.430	0.430	0.430
Weight of Sample, mg	25.5	24.8	28.0	24.8
Chemical Yield	0.700	0.681	0.769	0.681
Total Absorber, mg/cm^2	14.3	14.1	14.9	14.1
Beta Absorption Factor*	0.896	0.897	0.892	0.897
Geometry Factor	0.257	0.257	0.257	0.257
Weight of Uranium Taken, $g \times 10^3$	3.38	3.38	1.471	1.471
Dis/min per g Uranium at End of Irradiation $\times 10^{-7}$	2.14	2.14	5.18	5.17
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	3.47	3.47	8.39	8.38
Average, atoms/min per g of U	3.47×10^8		8.38×10^8	

Rate of Formation of Sr^{89} from $U^{238} = 3.17 \times 10^8$

Fission Yield of Sr^{89} in $U^{238} = 0.0330$

*Half-thickness = $90 mg/cm^2$.

TABLE 19

FAST FISSION YIELDS IN U^{238} $^{65}\text{d Zr}^{95}$

Sample	Depleted Uranium			Normal Uranium	
	1	2	3	4	5
Counts/min	3103	3138	2834	6378	6393
Days Decay	44.1	44.5	44.5	45.2	45.2
Decay Factor	0.625	0.622	0.622	0.617	0.617
Weight of Sample, mg	15.4	14.7	14.2	15.4	15.4
Chemical Yield	0.524	0.500	0.483	0.524	0.524
Total Absorber, mg/cm^2	11.7	11.6	11.4	11.7	11.7
Beta Absorption Factor*	0.462	0.465	0.471	0.462	0.462
Geometry Factor	0.257	0.254	0.255	0.252	0.254
Weight of Uranium Taken, $\text{g} \times 10^3$	2.37	2.37	2.37	2.46	2.46
Dis/min per g Uranium at End of Irradiation $\times 10^{-7}$	3.37	3.60	3.30	6.90	6.85
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	6.65	7.10	6.50	13.60	13.50
Average, atoms/min per g of U	6.75×10^8			13.55×10^8	

Rate of Formation of Zr^{95} from $U^{238} = 6.34 \times 10^8$ Fission Yield of Zr^{95} in $U^{238} = 0.0659$ *Half-thickness = $10.5 \text{ mg}/\text{cm}^2$.

TABLE 20
FAST FISSION YIELDS IN U^{238}
 $67h Mo^{99}$

Sample	Depleted Uranium		Normal Uranium	
	1	2	3	4
Counts/min	2670	2120	2660	2960
Hours Decay	220.0	220.0	247.4	247.4
Decay Factor	0.1029	0.1029	0.0774	0.0774
Weight of Sample, mg	21.5	17.9	14.9	16.5
Chemical Yield	0.544	0.452	0.376	0.417
Total Absorber, mg/cm^2	13.0	12.1	11.3	11.7
Beta Absorption Factor*	0.849	0.858	0.867	0.863
Geometry Factor	0.363	0.363	0.361	0.361
Weight of Uranium Taken, $g \times 10^4$	3.56	3.56	3.69	3.69
Dis/min per g Uranium at End of Irradiation $\times 10^{-8}$	4.36	4.12	7.92	7.99
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	6.21	5.87	11.30	11.38
Average, atoms/min per g of Uranium	6.04×10^8		11.34×10^8	

Rate of Formation of Mo^{99} from $U^{238} = 5.71 \times 10^8$

Fission Yield of Mo^{99} in $U^{238} = 0.0594$

* Half-thickness = $55 mg/cm^2$.

TABLE 21
FAST FISSION YIELDS IN U^{238}
 $^{42d}Ru^{103}$

Sample	Depleted Uranium			Normal Uranium		
	1	2	3	4	5	6
Counts/min	7351	5863	4973	5111	5073	5238
Days Decay	64.1	64.1	64.1	64.1	64.1	64.1
Decay Factor	0.347	0.347	0.347	0.347	0.347	0.347
Weight of Sample, mg	14.7	11.4	9.4	13.6	13.7	13.7
Chemical Yield	0.931	0.722	0.595	0.861	0.868	0.868
Total Absorber, mg/cm^2 ^a	10.7	10.26	10.13	10.4	10.42	10.42
Beta Absorption Factor ^b	0.227	0.240	0.246	0.237	0.237	0.237
Geometry Factor	0.259	0.259	0.259	0.259	0.259	0.259
Weight of Uranium Taken, $g \times 10^3$	6.78	6.78	6.78	3.69	3.69	3.69
Dis/min per g Uranium at End of Irradiation $\times 10^{-7}$	5.71	5.71	5.59	7.57	7.45	7.70
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	7.40	7.40	7.25	9.81	9.65	9.98
Average, atoms/min per g of Uranium	7.37×10^8			9.81×10^8		

Rate of Formation of Ru^{103} from $U^{238} = 7.22 \times 10^8$

Fission Yield of Ru^{103} in $U^{238} = 0.0751$

^aArea of precipitates not all $2.0 cm^2$; each sample corrected for its own area.

^bHalf-thickness = $5.0 mg/cm^2$.

TABLE 22

FAST FISSION YIELDS IN U^{238} 7.6d Ag^{111}

Sample	Depleted Uranium		Normal Uranium	
	1	2	3	4
Counts/min	5327	4853	4210	3964
Days Decay	14.08	14.08	14.08	14.08
Decay Factor	0.277	0.277	0.277	0.277
Weight of Sample, mg	18.7	17.2	17.8	17.8
Chemical Yield	0.725	0.667	0.690	0.690
Total Absorber, mg/cm ²	12.3	11.9	12.0	12.0
Beta Absorption Factor*	0.812	0.818	0.816	0.816
Geometry Factor	0.364	0.364	0.364	0.364
Weight of Uranium Taken, g	0.0356	0.0356	0.0246	0.0246
Dis/min per g Uranium at End of Irradiation x 10 ⁻⁶	2.52	2.48	3.02	2.84
Rate of Formation, atoms/min per g of Uranium x 10 ⁻⁶	7.02	6.92	8.42	7.92
Average, atoms/min per g of Uranium	6.97 x 10 ⁶		8.17 x 10 ⁶	

Rate of Formation of Ag¹¹¹ from U²³⁸ = 6.90 x 10⁶

Fission Yield of Ag¹¹¹ in U²³⁸ = 0.000717

*Half-thickness = 41 mg/cm^2 .

TABLE 23
FAST FISSION YIELDS IN U^{238}
2.33d and 44d Cd^{115}
Normal Uranium Samples^a

Sample	2.33d Cd^{115}		43d Cd^{115}	
	1	2	1	2
Counts/min of Cd^{115} at Time of In Separation ^b	1996	2030	173	180
Days Decay	8.26	8.26	28	28
Decay Factor	0.0857	0.0857	0.644	0.644
Weight of Sample, mg	23.4	21.9	23.4	21.9
Chemical Yield	0.598	0.559	0.598	0.559
Total Absorber, mg/cm^2	13.3	13.0	13.3	13.0
Beta Absorption Factor ^c	0.725	0.729	0.907	0.909
Geometry Factor	0.370	0.370	0.370	0.370
Weight of Uranium Taken, g	0.0246	0.0246	0.0246	0.0246
Dis/min per g Uranium at End of Irradiation $\times 10^{-5}$	55.1	59.0	0.556	0.618
Rate of Formation, atoms/min per g of Uranium $\times 10^{-6}$	7.20	7.71	0.753	0.838
Average, atoms/min per g of Uranium	7.45×10^6		0.795×10^6	

The correction for thermal fission was made by using the data of Table 16 to obtain the rate of formation of Ba^{140} from U^{235} in the normal metal sample. The thermal fission yields of the two isomers of Cd^{115} were then used to compute their rates of formation from U^{235} .

$$\begin{aligned}
 \text{Rate of formation of } Ba^{140} \text{ in normal uranium} &= 12.16 \times 10^8 \\
 \text{Rate of formation of } Ba^{140} \text{ from } U^{238} &= 6.13 \times 10^8 \\
 \text{Rate of formation of } Ba^{140} \text{ from } U^{235} &= 6.03 \times 10^8
 \end{aligned}$$

TABLE 23--Continued

	<u>2.33d Cd¹¹⁵</u>	<u>44d Cd¹¹⁵</u>
Measured rate of formation in normal uranium	7.45×10^6	0.795×10^6
Calculated rate of formation from U ²³⁵	1.65×10^6	0.123×10^6
Rate of formation from U ²³⁸	5.80×10^6	0.672×10^6

Fission yield of 2.33d Cd¹¹⁵ from U²³⁸ = 0.00060

Fission yield of 44d Cd¹¹⁵ from U²³⁸ = 0.00007

Total yield of mass 115 chain = 0.00067

These values are not as reliable as the other U²³⁸ fission yields since the correction for U²³⁵ fission was relatively large and was calculated rather than measured directly.

^aNormal metal only; depleted oxide samples discarded because of accidental inclusion of fragments of Cd shield.

^bSee section on calculations for method of correcting for 4.53h In growth from 2.33d Cd¹¹⁵.

^cHalf-thickness of 2.33d Cd¹¹⁵ = 36 mg/cm²; half-thickness of 44d Cd¹¹⁵ = 94 mg/cm².

TABLE 24

FAST FISSION YIELDS IN U^{238} 93h Sb^{127}

Sample	Depleted Uranium	
	1	2
Counts/min of Sb^{127} at Time of Te Separation ^a	214	503
Hours Decay	203	203
Decay Factor	0.220	0.220
Weight of Sample, mg	1.9	4.5
Chemical Yield	0.066	0.156
Total Absorber, mg/cm^2	8.0	8.7
Beta Absorption Factor ^b	0.846	0.834
Geometry Factor	0.370	0.370
Weight of Uranium Taken, $g \times 10^3$	6.78	6.78
Dis/min per g Uranium at End of Irradiation $\times 10^{-6}$	6.95	7.02
Rate of Formation, atoms/min per g of Uranium $\times 10^{-6}$	11.93	12.05
Average, atoms/min per g of Uranium	11.99×10^6	

The correction for thermal U^{235} fission in the depleted uranium was made in a way similar to that used for Cd^{115} .

Rate of formation of Ba^{140} from U^{235} in normal uranium = 6.03×10^8
 Rate of formation of Ba^{140} from U^{235} in depleted uranium = 3.47×10^7
 Rate of formation of Sb^{127} from U^{235} in depleted uranium = 5.05×10^5
 Rate of formation of Sb^{127} from U^{238} in depleted uranium = 11.49×10^6
 Fission yield of Sb^{127} in U^{238} = 0.0012

^aThe sample was counted after the 9.3h Te^{127} daughter had come to transient equilibrium with the 93h Sb^{127} . At equilibrium the ratio of the activity of the Sb plus Te to the activity of the Sb is given by:

$$(A_1 + A_2)/A_1 = 1 + \lambda_2/(\lambda_2 - \lambda_1) = 2.11.$$

TABLE 24--Continued

^bCalculated assuming exponential absorption of the beta radiations with the following half-thicknesses:

93h Sb¹²⁷: $T_{1/2} = 45 \text{ mg/cm}^2$,
9.3h Te¹²⁷: $T_{1/2} = 26 \text{ mg/cm}^2$.

TABLE 25
FAST FISSION YIELDS IN U^{238}
 $33y\ Cs^{137}$

Sample	Depleted Uranium		Normal Uranium	
	1	2	3	4
Counts/min	11,200	13,110	2960	4600
Days Decay	45	45	45	45
Decay Factor	0.997	0.997	0.997	0.997
Weight of Sample, mg	10.7	13.2	9.8	16.1
Chemical Yield	0.312	0.386	0.286	0.470
Total Absorber, mg/cm^2	10.6	11.2	10.3	11.9
Beta Absorption Factor*	0.745	0.733	0.752	0.719
Geometry Factor	0.255	0.255	0.255	0.255
Weight of Uranium Taken, g	0.890	0.890	0.1231	0.1231
Dis/min per g Uranium at End of Irradiation $\times 10^{-5}$	2.13	2.05	4.37	4.35
Rate of Formation, atoms/min per g of Uranium $\times 10^{-8}$	7.60	7.31	15.60	15.51
Average, atoms/min per g of Uranium	7.46×10^8		15.56×10^8	

Rate of Formation of Cs^{137} from $U^{238} = 6.96 \times 10^8$

Fission Yield of Cs^{137} in $U^{238} = 0.0724$

*Half-thickness = $25\ mg/cm^2$.

TABLE 26

FAST FISSION YIELDS IN U^{238} 15.4 Eu^{156}

Sample	Depleted Uranium		Normal Uranium	
	1	2	3	4
Counts/min	4274	9815	2187	3676
Days Decay	14.29	14.29	15.32	15.32
Decay Factor	0.527	0.527	0.505	0.505
Weight of Sample, mg	8.6	8.8	5.1	8.0
Chemical Yield	0.318	0.356	0.271	0.424
Total Absorber, mg/cm^2	9.1	9.3	8.9	9.6
Beta Absorption Factor*	0.790	0.787	0.794	0.782
Geometry Factor	0.375	0.375	0.369	0.369
Weight of Uranium Taken, g	0.0712	0.1424	0.0369	0.0369
Dis/min per g Uranium at End of Irradiation $\times 10^{-6}$	1.210	1.245	1.480	1.613
Rate of Formation, atoms/min per g of Uranium $\times 10^{-6}$	6.11	6.28	7.47	8.15
Average, atoms/min per g of Uranium	6.20×10^6		7.81×10^6	

Rate of Formation of Eu^{156} from $U^{238} = 6.10 \times 10^6$ Fission Yield of Eu^{156} in $U^{238} = 0.000635$

*Calculated assuming exponential absorption of the following components:

Half-thickness = 13.4 mg/cm^2 (50 per cent),
 Half-thickness = 140 mg/cm^2 (50 per cent).

TABLE 27

TABULATION OF RESULTS

Mass Number	U ²³⁵		U ²³⁸	
	Nuclide Studied	% Yield	Nuclide Studied	% Yield
77	—	—	40h As	0.0036
89	—	—	53d Sr	3.3
95	—	—	65d Zr	6.6
99	—	—	67h Mo	5.9
103	—	—	42d Ru	7.5
109	13.4h Pd	0.026	—	—
111	7.6d Ag	0.018	7.6d Ag	0.072
112	21h Pd	0.0084	—	—
115	2.33d Cd	0.019	2.33d Cd	0.060
115	—	—	44d Cd	0.007
127	93h Sb	0.093	93h Sb	0.12
131	8.0d I	2.9	—	—
137	—	—	33y Cs	7.2
140	12.8d Ba	6.4	12.8d Ba	6.4*
153	47h Sm	0.16	—	—
156	15.4d Eu	0.014	15.4d Eu	0.064

* Arbitrarily assumed reference yield.

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