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DESCRIPTION OF AN "AVERAGE" FISSION

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Report Written by: K. Way

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DESCRIPTION OF AN "AVERAGE" FISSION

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Description of an "Average" Fission

K. Way

B.* The Average Neutron Fission in U^{235} and Pu^{239}

The fact that a great many different pairs of fission products are found after the thermal fission of a number of nuclei of the same kind shows very clearly that the fission of a given isotope can take place in a number of different ways. Each different mode of splitting probably results in the emission of different numbers of fission neutrons and γ-rays and the release of different amounts of energy as well as in the production of different end products. The possible variations of the fission process are of great practical as well as theoretical interest. However, the way that fission takes place on the average is a matter of fundamental importance for it is the average number of fission neutrons, the average energy release, and the average amount of radiation emitted which determine the way in which any reactor making use of the fission process is going to operate.

The average fission brought about by the capture of a slow neutron by the nucleus of U^{235} can now be fairly accurately described. It is an event resulting in the production of two principle fragments whose mass numbers are $\sim$95 and $\sim$139 and of 2.5 new neutrons. These neutrons are ejected from the fragments after the main division has taken place. At the time of fission 5.1 mev of γ-rays are emitted whose average energy is $\sim$1 mev. The total energy released in the disruption amounts to $\sim$175 mev. After the fission the two principal fragments decay radioactively with the emission of β and γ-rays. The energy released per sec at time t between 10 sec and 100 days after a fission has taken place is given approximately by

* Originally intended to be part B of a longer report.

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γ mev/sec/fission $1.26t^{-1.2}$

$\beta + \gamma$ mev/sec/fission $2.66t^{-1.2}$

where t is in seconds. (For shorter times see the curves of W.2.) The total decay energy is equal to about 22 mev. This figure includes energy carried away by neutrinos. Thus the total energy released per fission before stable end products are produced is equal to about 175 + 22 or 197 mev. In a pile more energy than this primary amount is released per process on account of secondary events such as the capture of the fission neutrons, γ - n reactions, etc.

It would be very interesting to know in just how many ways the average fission in other nuclei differs from this average neutron fission in U^{235}. Not very much information is available at present. A little is known about differences in the end products and in the number of fission neutrons produced. The most probable fragments from the neutron induced fission of Pu^{239} are elements of mass 139 and 98 and the average number of fission neutrons is 2.95. In the slow neutron fission of U^{233} the most probable fragments have masses of 139 and 93 and an average of 2.66 neutrons are produced per fission. The striking fact that the maximum of the heavy fragment group seems always to come at the same place, namely at mass number 139, will be discussed in a later report.

B.1 <u>The Most Probable Fission Fragments</u>

The most probable fission fragments are found from the curves of the radiochemists showing the yields of products of different

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masses. By yield of a mass number is meant the fraction of fissions in which the given mass number is produced. If there are always two fragments, that is if three particle fission does not take place to any appreciable extent, the sum of all the yields will be equal to two. This value is found for the total yield of U^{235}. The value for Pu^{239} is more uncertain. Yield curves for both U^{235} and Pu^{239} are to be found in F.6 and S.2.

B.2 <u>The Fission Neutrons</u>

The number of neutrons emitted in a neutron induced fission became of the greatest interest after the discovery of fission itself since it was realized almost immediately that if this number were greater than one it might be possible to establish a chain reaction in fissionable material.

The approximate number of the new neutrons produced by fission was soon established in various ways. It was also shown that these neutrons are fast. Von Halban, Joliot, and Kowarski (H.1) studied the neutron distribution around a source in a large container filled with a solution of uranyl nitrate and found that the addition of the fast fission neutrons changed the neutron distribution from that found when the container was filled with ammonium nitrate. They estimated the number of fast neutrons produced per fission to be 3.5 ± 0.7. Anderson, Fermi, and Hanstein (A.1) studied the distribution of neutrons in a large tank of water with and without a spherical bulb containing uranium around the source and determined the number of fission neutrons to be ~ 2. Zinn and Szilard (Z.1) observed protons projected by the fast fission

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neutrons in an ionization chamber filled with hydrogen. By determining in addition the number of fissions which had taken place they were able to estimate the number of fission neutrons as 2.3.

The best value for the number of new neutrons produced per fission of U^{235}, ν_{25}, is now believed to be 2.50. Snyder and Williams (S.1) working at Los Alamos found $\nu_{25} = 2.54 \pm .10$ in an experiment which measured the fast neutrons produced per fission directly. They established the rate at which thermal fissions were taking place in a sample of U^{235} placed in a thermal column and then compared the number of fast neutrons emitted by this sample per sec with the number coming from a Ra-Be source of known strength.

The number of fast neutrons emitted per slow neutron absorbed in U^{235}, η_{25} or $\bar{\nu}_{25}$, was determined by Fermi, Marshall, and Marshall at the Argonne (F.3). Expressed in terms of symbols

$$\eta_{25} = \left[\nu_f \, \sigma_f / \sigma_a \right]_{25}$$

where σ_a and σ_f denote the absorption and fission cross sections respectively and the subscript 25 indicates that all values are to be taken for the isotope U^{235}. In the Argonne experiment the effect on the reactivity of the graphite pile of a sample of uranium enriched in the 235 isotope was compared with the effect produced by a boron sample of identical neutron absorbing power. The value found for η_{25} or $\bar{\nu}_{25}$ was 2.15. When this number is multiplied by the ratio of the absorption to fission cross section, 1.18, one finds again $\nu_{25} = 2.54$.

The value of N_{25} can also be found from measurements of the

value of η for natural uranium which is defined as the number of new neutrons emitted per thermal neutron absorbed in the mixture of U^{235} and U^{238} found in nature.

$$\eta = \nu_{25} \Big/ \left[\frac{\sigma a\ 25}{\sigma f\ 25} + \frac{\sigma a\ 28}{F\sigma_f\ 25}\right]$$

where the subscripts 25 and 28 mean that the cross section in question is to be taken for U^{235} or U^{238} and F is the number of atoms of U^{235} per atom of U^{238} in the natural mixture or 1/139. The ratios in the denominator of the right hand side are now well established as 1.18 and 0.66 respectively. The value of η has been determined in two long series of exponential experiments in graphite and water lattices to be 1.345 (W.1). Making use of these three numbers one finds $\nu_{25} = 2.48$. In spite of the fact this method of finding ν is an indirect one, involving the results of several experiments, the value derived from it carries a good deal of weight because the three numbers involved are probably accurate to $\pm 1\%$ so that the probable error in ν is only $\sim 2\%$. It is for this reason that the best value is given as 2.50 rather than a number slightly higher.

It is interesting to note that the value of ν does not change with the energy of the neutrons inducing fission. Experiments of Wilson, Woodward, and DeWire at Los Alamos (W.6) showed that ν_{25} remained constant as the energy of the fission producing neutrons was raised from thermal to several hundred kilovolts.

The experiments just described give the total number of new neutrons emitted per fission without reference to the time after

the fission at which they are produced. It was observed shortly after the discovery of fission that some of the fission neutrons appeared some seconds after irradiation of the fissioning material with neutrons had stopped. These "delayed" neutrons have been shown, in two cases at least, (L.1) to come from the fission products and to amount to only a small percentage of the total number of fission neutrons, 0.73% in the case of U^{235}, 0.24 for U^{233}, 0.36% in the case of Pu^{239}. It is of a good deal of interest to know whether the other, the so-called "prompt" fission neutrons are also emitted by the fragments but at very much earlier times or whether they are ejected along with the main fission fragments at the moment of disruption of the original nucleus.

Experiments performed at Los Alamos by Wilson (W.7) indicate that they come from the fragments in most cases. In these experiments the fission fragments were channelized in a certain direction. The number of neutrons emitted in this direction was found to be much greater than the number emitted perpendicular to it showing that the neutrons possess the fragment velocity, and are thus emitted after the fragments are formed. However, the possibility that some of the neutrons may be ejected at the moment of division does not seem to be excluded.

It seems quite reasonable that the fission neutrons should be emitted by the fragments very soon after they are formed and before there has been time for any radioactive decay. Just after the disruption the fragments undoubtedly have shapes which are

very much distorted in comparison with their normal ones. The potential energy which is translated into kinetic energy as the normal shape is assumed could make possible the boiling off of some of the neutrons. The energy made available is a kind of "snap back" energy. The greater the distortions of the fragments the greater will be the possibility for the emission of fission neutrons. One would also expect that the greater the distortions, the smaller will be the kinetic energy of the fragments. If the fragments are very much stretched out at the instant of division, the distance between their centroids will be greater than if they were spheres. Distortions in which the reverse is true do not seem likely to lead to fission. The separation of the centroids at the moment of final cleavage determines the electrostatic repulsion of the two fragments and so to a large extent their final kinetic energy. Thus the greater the number of neutrons released because of distortion of the two fragments the smaller should be their final kinetic energy because of the large separation of their centroids. This picture will be discussed in more detail in a later report where deviations from the average fission are considered.

The number of neutrons emitted per fission, or the value of ν, seems to vary considerably with the fissioning nucleus. For Pu^{239} it is equal to 2.95 (S.1) and for U^{233} it is now thought to be 2.66 (I.1). The suggestion just made would imply that greater distortion is necessary to produce fission in the compound nucleus Pu^{240} than in U^{236} and less in U^{236} than in U^{234}. One might then expect the spontaneous fission rate of Pu^{240} to be lower than that of U^{236} and that of U^{234} to be ~~higher.~~ lower also The table on pg. 4, LA-140 shows that

just the opposite is true in the case of Pu^{240} and U^{236}. The relative rates of U^{234} and U^{236} are not yet established. Of course, because of spin or of nuclear moments, it may not be justifiable to compare the fissionability of a compound nucleus formed by neutron capture with that of a normal nucleus.

The energy spectrum of the fission neutrons was determined by Richards (R.1) by means of proton recoils in photographic emulsions. Calculations of the age of fission neutrons by Plass (P.1) based on Richard's results agree well with the value 35.6 cm measured by Fermi, Marshall, and Marshall (F.4). The average energy of a fission neutron as found from Richard's curve is 2.1 mev.

B.3 Delayed Neutrons

Although the delayed neutrons are counted as "fission neutrons" in all determinations of the number of new neutrons created per fission, their origin is so different from that of the prompt neutrons and their role in the control of a nuclear reactor is so important that they deserve special consideration.

The facts known at present are summarized below in Table B.1. The values of the half lives of the delayed neutron emitters and their relative yields when produced by the fission of U^{235} are taken from Hughes, Dabbs, and Cahn (H.6); the absolute yield for U^{235} from Hall, Hughes, and Spatz (H.2); that of Pu relative to U^{235} from Redman and Saxon (R.2) and Feld and de Hoffman (F.2); and that of U^{233} relative to U^{235} from Cahn, Hughes and Dabbs (C.1). The energy values are averages of those found by Hughes, Dabbs, and Cahn (H.6) and those found by Burgy (B.4).

Table B.1

Data on Delayed Neutrons

Half Life	Energy in KV	Yield in Units of 10^{-4}		
		U^{235}	U^{233}	Pu^{239}
55.6 sec	250	2.5	1.8	1.4
22.0	570	16.6	5.8	10.5
4.51	412	21.3	8.6	12.6
1.52	670	24.1	6.2	11.9
0.43	400	8.5	1.8	
	Total	73.0	24.2	36.4

Bohr and Wheeler (B.1) pointed out in their paper on the theory of fission that it might be expected that various nuclei created by the radioactive decay of the original fission fragments would be produced in excited states which had sufficient energy to boil off a neutron. Such excited states would be possible in a daughter nucleus if the energy emitted in the decay from parent to daughter were very much greater than the binding energy of a neutron in the daughter. Some transitions might then be expected to levels with more energy than the neutron binding energy. In such levels neutron evaporation would take place before gamma radiation

to the ground state occurred. Estimations of β decay energies and of neutron binding energy of fission products show that in a number of cases the former is greater than the latter. In fact from these estimations it is difficult to understand why there are not more delayed neutrons than have been observed. In explanation one can say that the mass formula used by Bohr and Wheeler to calculate the decay and binding energies must be regarded as only approximate. The β decay energies which it predicts (W.4), are not in very good agreement with observed values even when the disintegrating nucleus is near to stability. It is just in this region that the energy calculation is supposed to be the best. For nuclei that are far from stability there is at present no evidence as to the validity of the mass formula. Spin and nuclear moments which so far have not been taken into account in any way may also play important parts in delayed neutron emission.

B.4 <u>The Fission Gamma Rays</u>

It had always been supposed that γ-rays were emitted by the two fragments just after the disruption since these fragments must in general be formed in excited states. One would not expect the total amount of this γ-ray energy to be more than $\sim$10 mev, or $\sim$5 mev per fragment, since if energy greater than the neutron binding energy were available in either fragment it is likely that additional neutrons would be emitted.

An experiment of Deutsch and Rotblat (D.3) performed at Los Alamos showed that there are definitely coincidences between fissions and γ-rays. The total γ-ray energy emitted by both

fragments turns out however, to be only 5.1 ± 0.3 mev, a value considerably lower than the 10 mev estimated above as an upper limit. Absorption measurements showed the γ-rays to have an average energy of about 1.0 mev. The constants of the circuits were such that it could be said that the γ-rays were emitted within two microseconds of the time the fission took place. The results were unchanged when adjustments were made so that a coincidence would still be recorded if four microseconds elapsed between fission and γ-ray emission. The experiment, of course, did not rule out the possibility that the γ-rays are emitted by the compound nucleus before the instant of division. It also indicated that there is a fairly wide spread about the average quantum energy found.

B.5 Fission Product Radiations

Strictly speaking the fission process has been completed when the division of the original nucleus has taken place and the resulting fragments have lost their excitation energy. But even when the fragments have reached their ground states energy continues to be released because they are nuclei whose ratio of neutrons to protons is much too great for permanent stability. The excess neutrons are converted into protons through the successive emission of β particles until a stable proportion has been attained. The β decays are in general accompanied by γ rays so that penetrating as well as easily absorbable radiation continues to come from the fission fragments for some time.

In a broad sense the fission process can be regarded as extending from the moment of disruption until the time when the

fragments reach forms of lasting stability. Certainly from a practical point of view the slow energy evolution which forms an aftermath to the sudden release of the original disruption is of very great importance. Any reactor which makes use of the fission energy must be so designed that the radioactive fission products are not harmful either to operators or apparatus. Here again the quantity that is of interest is an average quantity, the average amount of energy released per fission as β or γ rays at different times after the fission has taken place.

The radiochemists of the project have identified chemically many fission products, determined genetic relationships among them, and measured the energies of the β and γ rays emitted in various transitions. They have also established the yields of different products or the fraction of fissions in which a specific product is formed. At very long times after a fission has taken place their data has been used to calculate directly the average radiation emitted per unit time (T.1). The calculation is possible because at such times only a few long-lived fission products make an important contribution to the total energy ejected. The yields of these products are generally well known since long-lived products were naturally selected for yield measurements, and the energies of their radiations have also been determined.

For many shorter lived products, however, neither the decay energies nor the yields are known. Although genetic relationships may have been established with longer lived products, it is not at all certain yet how the yield varies along a chain, with which

member the chain usually ~~beings~~ begins or how often it is formed on one side or another of the most probable place. Since calculation from the individual data is impossible, experimental determinations of the average energy released are needed. A number of such measurements have been made on the project. Wigner and Way have collected the data in a report (W.2) which gives references to all the original work. Rules of thumb which fit the experimental data to within a factor of 2 for times between 10 seconds and 100 days after a fission has taken place have already been given in the general discussion of the average fission.

A theoretical calculation of the ratio of decay of fission products and of their energy emission is also given in the paper just referred to. The results are in fairly good agreement with the experimental ones except at times of the order of 0.1 sec after fission has taken place. Recent experimental evidence of the radiochemists presented by L. E. Glendenin, C. D. Coryell, R. R. Edwards, and M. H. Feldman, CL-LEG-1, in support of the hypothesis that the chain lengths of the light and heavy groups are about equal points to a change in the theoretical treatments which leads to better agreement with experiment at very short times after fission. A revised edition of the paper will be issued soon.

Integration of the expression for the rate of energy emission with respect to time t after fission has taken place from $t = 0$ to $t = \infty$ gives the total decay energy emitted by the fission products before stable forms are finally reached. The result is

$$\left.\begin{array}{l}\text{Average total decay chain}\\ \text{energy released per fission}\end{array}\right\} = 22 \pm 3 \text{ mev.}$$

B.6 <u>The Energy Release</u>

With the help of project contributions to knowledge about the average decay energies of the fission fragments and of the average energies of the fission neutrons and γ-rays it is now possible to make a fairly good estimate of the average amount of energy released per fission. It is this average amount of energy which is, of course, of paramount importance in the operation of any nuclear reactor. The amount of energy absorbed per fission in a reactor is a quantity which can be measured and which affords a check on the energy release calculated by adding together the energies of the fragments and radiations.

If the mass difference between the initial fissioning nucleus and the final stable fragments were known, the total energy release could be found immediately. Unfortunately the differences between the packing fractions of uranium and of elements in the fission product region are not sufficiently well known to make accurate calculations of mass differences possible. Dempster (D.1) gives $10.41 \pm 0.1 \times 10^{-4}$ as the differences between the U^{238} - Sn^{119} packing fractions while Graves (G.3) gives $10.12 \pm .09 \times 10^{-4}$ for the same difference. Making $10.27 \pm .25$ as a reasonable value and assuming the split to be into two equal parts, one finds 238 x 10.27 = 242 mmu = 225 mev with a probable error of 5.6 mev as the energy released when the nucleus U^{238} divides symmetrically. If Dempster's packing fraction curve (D.2) is used, an energy release of 208 mev is found for the division of U^{236} into Mo^{95}, La^{139}, and two neutrons.*

The best estimate which can be made at present by adding together measured values of the different kinds of energy detected gives 197 mev for the average energy released by the time the fission products have become stable nuclei. The various contributions are listed in Table B.1.a

Table B.1 a

Average Amount of Energy Released by Neutron Fission of U^{235}

Kinetic Energy of Fission Fragments	165 ± 15** mev
Kinetic Energy of Fission Neutrons	5 ± .5
Energy of Fission γ -Rays	5 ± .3
Radioactive Decay Energy of Fission Frag.	22 ± 3
	197 ± 16 mev

* Rall, CP-3547 finds the packing fraction difference between U^{238} and $Zr^{92,94}$ to be $12.2 \pm 0.9 \times 10^{-4}$. This value is fairly close to the curve given by Dempster in D.2.

** This error figure is largely a guess. Kanner and Barschall estimate that their ionization measurements are good to 5% but can offer no opinion as to the validity of their absolute calibration.

No new information about the kinetic energy of the principal fission fragments has been obtained on the project. One would expect the values to be quite large. Two equal similarly charged spheres originally in contact will acquire kinetic energy of Z^2e^2/R_{12} where R_{12} is the distance between their centers. If R_{12} is equal to $2r_oA^{1/3}$ where A is the mass of each sphere and r_o is the radius of an elementary particle, $\sim e^2/2mc^2$, then the kinetic energy is equal to $Z^2mc^2/A^{1/3}$ or $\sim$ 215 mev. This is undoubtedly an overestimate since by the time the connection between the two fragments is broken, their centroids are probably a good deal farther apart than are those of two touching spheres.

The figure for the fragment kinetic energy given in the table is that due to Kanner and Barschall (K.1) who measured the ionization produced by the fission fragments ejected from both sides a thin foil of uranium. Correction was made for the energy lost by the fragments in the foil itself. The conversion of ionization values to energy values was accomplished by means of a calibration with the α particles of ThC'. The assumption underlying this method of calibration is that heavy particles lose the same amount of energy in the production of an ion pair as does an α particle. The correctness of this assumption was tested in one particular case by an experiment of Gerthsen and Grimm (G.1) who found that the nuclei of the ThC' which are given back kicks by the ejection of α particles expend an average of 36 ev in the production of an ion pair.

Experiments similar to that of Kanner and Barschall were performed in Austria by Jentschke (J.1) and in Germany by Flammersfeld,

Jensen, and Gentner (F.5). These workers used a uranium foil to separate two ionization chambers so that the ionization due to each fission fragment could be determined separately. Their data give a great deal of insight into the deviations from an average fission which take place and will be discussed later in more detail. For the mean total kinetic energy of both fragments Jentschke found 160 mev and Flammersfeld, Jensen and Gentner, 148 mev. Their agreement on the deviations is good, so this discrepancy is presumably due to different methods of absolute calibration. Both assumed that the energy needed to produce an ion pair is the same for α particles and fission products but Jentschke took the value of this energy in air for α particles of velocity comparable with that of fission products to be 36.6 ev while Flammersfeld and his co-workers essentially established their own value (although it is not stated explicitly) as did Kanner and Barschall by determining the throw produced by α particles of known energy on an oscillograph whose linear response had been established.

In a very recent repetition of the Jentschke experiment Deutsch and Ramsey (D.4) find 153 mev for the mean value of the total kinetic energy of the fission fragments of U^{235}.

Measurements of fission energy release of an entirely different kind were made by Henderson (H.3) using a calorimeter technique. He found the energy which was absorbed in his calorimeter equal to 177 $\pm$ 5 mev per process. This energy was released in fission and during several minutes following fission. In addition to the kinetic energy of the fragments, soft X-rays and β-rays with energies less than 1 mev were absorbed. It is now

possible to estimate the total radioactive decay energy emitted at different times after a fission has occurred with the help of the curves of CC-3082. However, such an estimation gives only 9 mev as the total energy emitted within 20 minutes after a fission. This figure includes γ-ray and neutrino energy so it does not seem possible that more than $\sim$3 mev can be attributed to soft β-rays. Correction for the decay energy absorbed thus does not make it possible to account for the discrepancy between Henderson's experiment and that of Kanner and Barschall.

The value of 165 mev for the fragment kinetic energy determined by these latter workers and used in Table B.1 leads to a total energy release that is about 5% less than would be expected from the present packing fraction curve. Packing fraction values are in a good deal of doubt, however, in the fission product region as has already been emphasized. The value of the kinetic energy chosen gives, however, fairly good agreement with measurements of the energy absorbed in the Argonne and Clinton piles.

As has already been pointed out, the energy absorbed in a pile is not equal to the primary energy release since some of the primary energy escapes from the pile and secondary events releasing additional energy occur. The corrected primary energy release is, however, such a very large percentage of the total energy absorbed that a measurement of the latter affords a good check on the estimate of the former.

The figure found from Table B.1a of 197 mev for the average amount of energy released per neutron fission of U^{235} includes the radioactive decay energy of the fission products which is emitted in the form of β-rays, γ-rays, and neutrinos. Of the

total decay energy of the 22 mev, $\sim$17 mev belong to β-rays and neutrinos and $\sim$5 mev to gamma rays. If it is assumed that 0.6 of the total β-decay energy is removed by neutrinos which escape from the pile, then of the 17 mev belonging to β-rays and neutrinos 10 mev will not be absorbed in the pile. The total amount of primary energy absorbed per fission will thus be 197 - 10 or 187 mev.

The amount of secondary energy absorbed in any pile has to be calculated for the pile in question since this quantity depends very much on the materials from which the pile is made and the way in which the fissionable material is arranged in the moderator, i.e. the lattice constants. As an illustration, the calculation of the energy absorbed per fission in the Argonne pile is given in detail.

The lattice constants are taken to have the following values:

ε = fast effect constant = 1.04

1+d = total fissions/thermal fissions = 1.075

1-p = fraction of neutrons captured at resonance in U^{238} = .104

f = thermal utilization = .866

ℓ_1 = fraction of fast neutrons which leak out = $-\tau\Delta$ = .035

ℓ_2 = fraction of slow neutrons which leak out = $-\Delta L^2$ = .035

With these values one can trace the production and fate of neutrons in a cycle from thermal fission to thermal fission when the pile is just critical. The value of ν is taken equal to 2.48 since this is the number in agreement with the cross section ratios and the value of η found from exponential experiments.

Table B.2

Fate of Neutrons in Argonne Graphite Pile

<table>
<tr><td colspan="5">2.48 fast n's produced from 1 thermal fission</td></tr>
<tr><td colspan="5">ε x 2.48 = 2.57 fast n's produced from one thermal fission and subsequent fast fissions</td></tr>
<tr><td colspan="5">2.57 $(1 - \ell_1)$ = 2.48 fast n's remain after fast leakage</td></tr>
<tr><td>.26 n's captured at res. in 28</td><td colspan="4">p x 2.48 = 2.22 n's are slowed to thermal energies</td></tr>
<tr><td></td><td colspan="4">2.22 $(1 - \ell_2)$ = 2.13 slow n's remain after slow leakage</td></tr>
<tr><td></td><td>.29 slow n's capt. in C</td><td colspan="3">f x 2.13 = 1.84 slow n's captured in U</td></tr>
<tr><td></td><td></td><td>.66 slow n's capt. in 28</td><td>.18 capt. in 25</td><td>1.00 slow n produces the next fission</td></tr>
</table>

Some of the fast neutrons produced in thermal fission induce fast fission before they can be slowed down. In a cycle there are $1 + \delta$ or 1.075 fissions while only 2.48 fast neutrons are slowed down. The neutron kinetic energy absorbed per fission thus amounts to 2.48 x 2.1/1.075 mev or 4.85 mev. The value used in the estimation of the primary energy absorption is 5.0 so there is only a very small correction to the kinetic energy to be made on account of fast fission and fast leakage.

The primary and secondary energy absorbed per cycle can then be tallied up as follows:

1.075 fissions with 187 mev per fission	201.0 mev
.92 neutrons absorbed in 28 each releasing 5.1 mev* binding energy and 1.0 mev decay energy	5.6
.29 neutrons absorbed in C each releasing 6.0 mev** binding energy	1.7
.18 neutrons absorbed in 25 each releasing 6.4 mev* binding energy	1.2
	209.5 mev

Mev/fission = 209.5/1.075 = 195

The measured value given by Engelkemeier, and Hill, Friedman, and Anderson (E.1) is 199 ± 16 mev. Later calculations of the corrections (W.3) reduced this value to 196 ± 16 mev. In the experiment the number of fissions occurring in a special lump placed in the Argonne pile were determined from analysis of the Ba produced while the power developed was calculated from the temperature rise. The correction for the energy which escaped from or was not generated in the special lump amounted to about 10%. The probable error is quite large so the good agreement between measurement and calculation is not completely reassuring.

In experiments performed at Clinton by Borst (B.3), two quantities were determined independently; the number of captures in U^{238} per fission (often called the capture to fission ratio) and the grams of Pu^{239} produced per megawatt day. The energy absorbed per fission is related to these in the following simple way:

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* Binding energies calculated with Bohr-Wheeler mass formula. Phys. Rev. 56, 426, 1939

** Calculated from the masses assuming one fourth of the absorption is by C^{13}.

$$\text{Mev absorbed per fission} = 214 \times \frac{\text{captures in 28 per fission}}{\text{Gms 49 produced per megawatt day}}$$

Two determinations of the capture to fission ratio gave .877 and .883. These are in good agreement with the calculated value of .877. The number of grams of 49 produced per megawatt day was found by chemical analysis to be 0.91. From the above relation then

Energy absorbed per fission in Clinton pile =

$$\frac{214 \times .88}{.91} = 209 \text{ mev}$$

As a check the number of fissions which had taken place in the slugs in which the power had been measured was determined from the number of hard La^{140} γ-rays they emitted at a known time after the irradiation. This value together with the original power measurements gave

Energy absorbed per fission in Clinton pile = 191 mev

The value calculated for the X pile in the way that was used for the Argonne pile gives 196 mev.

The determinations of the amount of 49 produced were made from a number of slugs with plant equipment and although Perlman feels they are reliable to $\pm$ 3% it seems more likely that they should be low than high. It seems reasonable to suppose that the second value of 191 mev is somewhat more reliable than the first since it makes use of a method for the determination of the number of fissions which involves only the yield of 140 chain, a quantity very carefully established by the most careful laboratory methods.

Although the pile experiments thus support the estimate of the total energy release made by adding together known values of

energies emitted in different ways, the experiments are not sufficiently accurate to afford a really good test of the estimate. Data on the power-product ratio at Hanford should give further helpful information. ~~Accuration~~ Accurate determinations of packing fraction differences would probably provide the best check.

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