TRANS-PLUTONIUM ISOTOPE BUILDUP
BY NEUTRON IRRADIATION OF PLUTONIUM

F. P. BRAUER and HELEN H. BURLEY

DECEMBER 15, 1958

HANFORD LABORATORIES
HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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BY NEUTRON IRRADIATION OF PLUTONIUM

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Graphs suitable for estimating the plutonium and trans-plutonium isotopic content of irradiated plutonium reactor fuel of various initial isotopic compositions are presented. The curves were computed for a neutron flux of $5 \times 10^{13}$ n/cm$^2$/sec and for irradiation times up to ten years.
TRANS-PLUTONIUM ISOTOPE BUILDUP
BY NEUTRON IRRADIATION OF PLUTONIUM

INTRODUCTION AND SUMMARY

The recycle of plutonium fuel through a nuclear reactor will result in the buildup of the higher plutonium and trans-plutonium isotopes in the reactor fuel (1)(2). The quantities of the various plutonium and trans-plutonium isotopes which will be formed in the fuel is of interest to the chemical processor. The production of trans-plutonium isotopes by irradiation of high Pu\textsuperscript{242} plutonium and of americium, and curium is also of interest (14). Graphs useful in estimating the plutonium and trans-plutonium isotopic content of irradiated uranium of various initial isotopic compositions have been presented by several investigators (3)(4)(5). This report contains curves suitable for estimating the buildup of trans-plutonium isotopes in plutonium fuel elements or in plutonium, americium, or curium samples irradiated in a $5 \times 10^{13}$ thermal neutron/cm\textsuperscript{2}/sec flux.

CALCULATIONS

The main chain of slow neutron capture reactions and beta decays which result in the formation of trans-plutonium isotopes during neutron irradiation of plutonium is shown in Figure 1. Differential equations expressing the production and destruction of each isotope along the chain whose half life is greater than one day were set up. The equations are given below, together with the values of the nuclear constants used in the calculations.

Definitions of Terms

$\phi$ = pile neutron flux
$\sigma$ = pile neutron cross section for n, $\gamma$ reactions
$\sigma'$ = pile neutron cross section for other reactions (mostly fission)
\[ \lambda = \text{radioactive decay constant} \]
\[ t = \text{irradiation time} \]
\[ N = \text{number of atoms present at time } t \]

The subscripts denote the isotopes by use of the last digits of the atomic numbers and the atomic weights in the conventional manner.

**Equations**

1. \[ \frac{1}{\phi} \frac{dN_{48}}{dt} = \frac{\lambda_{62}}{\phi} N_{62} - \sigma_{48} N_{48} \]
2. \[ \frac{1}{\phi} \frac{dN_{49}}{dt} = \sigma_{48} N_{48} - \sigma_{49} N_{49} - \sigma_{49}^' N_{49} \]
3. \[ \frac{1}{\phi} \frac{dN_{40}}{dt} = \sigma_{49} N_{49} - \sigma_{40} N_{40} \]
4. \[ \frac{1}{\phi} \frac{dN_{41}}{dt} = \sigma_{40} N_{40} - \sigma_{41} N_{41} - \sigma_{41}^' N_{41} - \frac{\lambda_{41}}{\phi} N_{41} \]
5. \[ \frac{1}{\phi} \frac{dN_{42}}{dt} = \sigma_{41} N_{41} - \sigma_{42} N_{42} + x \sigma_{51}^' N_{51} \]
6. \[ \frac{1}{\phi} \frac{dN_{51}}{dt} = \frac{\lambda_{41}}{\phi} N_{41} - \sigma_{51} N_{51} - \sigma_{51}^' N_{51} \]
7. \[ \frac{1}{\phi} \frac{dN_{52}}{dt} = \sigma_{51} N_{51} - \sigma_{52} N_{52} - \sigma_{52}^' N_{52} \]
8. \[ \frac{1}{\phi} \frac{dN_{53}}{dt} = \sigma_{52} N_{52} + \sigma_{42} N_{42} - \sigma_{53} N_{53} \]
9. \[ \frac{1}{\phi} \frac{dN_{62}}{dt} = y \sigma_{51}^' N_{51} - \sigma_{62} N_{62} - \frac{\lambda_{62}}{\phi} N_{62} \]
\[ \frac{1}{\phi} \frac{dN_{63}}{dt} = \sigma_{62} N_{62} - \sigma_{63} N_{63} - \sigma_{63}^' N_{63} - \frac{\lambda_{63}}{\phi} N_{63} \]

\[ \frac{1}{\phi} \frac{dN_{64}}{dt} = \sigma_{53} N_{53} + \sigma_{63} N_{63} - \sigma_{64} N_{64} - \frac{\lambda_{64}}{\phi} N_{64} \]

\[ \frac{1}{\phi} \frac{dN_{65}}{dt} = \sigma_{64} N_{64} - \sigma_{65} N_{65} - \sigma_{65}^' N_{65} \]

\[ \frac{1}{\phi} \frac{dN_{66}}{dt} = \sigma_{65} N_{65} - \sigma_{66} N_{66} \]

\[ \frac{1}{\phi} \frac{dN_{67}}{dt} = \sigma_{66} N_{66} - \sigma_{67} N_{67} \]

\[ \frac{1}{\phi} \frac{dN_{68}}{dt} = \sigma_{67} N_{67} - \sigma_{68} N_{68} \]

\[ \frac{1}{\phi} \frac{dN_{79}}{dt} = \sigma_{68} N_{68} - \sigma_{79} N_{79} - \frac{\lambda_{79}}{\phi} N_{79} \]

\[ \frac{1}{\phi} \frac{dN_{89}}{dt} = \frac{\lambda_{79}}{\phi} N_{79} - \sigma_{89} N_{89} - \sigma_{89}^' N_{89} \]

\[ \frac{1}{\phi} \frac{dN_{80}}{dt} = \sigma_{79} N_{79} + \sigma_{89} N_{89} - \sigma_{80} N_{80} - \frac{\lambda_{80}}{\phi} N_{80} \]

\[ \frac{1}{\phi} \frac{dN_{81}}{dt} = \sigma_{80} N_{80} - \sigma_{81} N_{81} - \sigma_{81}^' N_{81} \]

\[ \frac{1}{\phi} \frac{dN_{82}}{dt} = \sigma_{81} N_{81} - \sigma_{82} N_{82} - \frac{\lambda_{82}}{\phi} N_{82} \]
## Constants

<table>
<thead>
<tr>
<th>Decay Constants (sec(^{-1}))</th>
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</tr>
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<tbody>
<tr>
<td>(\lambda_{62}) = 4.92 \times 10^{-8}</td>
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</tr>
<tr>
<td>(\lambda_{41}) = 1.66 \times 10^{-9}</td>
<td>6</td>
</tr>
<tr>
<td>(\lambda_{63}) = 6.27 \times 10^{-10}</td>
<td>6</td>
</tr>
<tr>
<td>(\lambda_{64}) = 1.19 \times 10^{-9}</td>
<td>6</td>
</tr>
<tr>
<td>(\lambda_{79}) = 2.76 \times 10^{-8}</td>
<td>6</td>
</tr>
<tr>
<td>(\lambda_{80}) = 2.36 \times 10^{-9}</td>
<td>7</td>
</tr>
<tr>
<td>(\lambda_{82}) = 9.98 \times 10^{-9}</td>
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</table>

### Branching

<table>
<thead>
<tr>
<th>(x)</th>
<th>0.19</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(y)</td>
<td>0.81</td>
<td>6</td>
</tr>
</tbody>
</table>

### Pile Cross Sections (cm\(^2\))

| \(\sigma_{48}\) = 489 \times 10^{-24} | 8         |
| \(\sigma_{49}\) = 446 \times 10^{-24} | 9         |
| \(\sigma_{41}'\) = 922 \times 10^{-24} | 9         |
| \(\sigma_{40}\) = 383 \times 10^{-24} | 9         |
| \(\sigma_{41}\) = 407 \times 10^{-24} | 9         |
| \(\sigma_{41}'\) = 1116 \times 10^{-24} | 9         |
| \(\sigma_{42}\) = 52 \times 10^{-24} | 10        |
| \(\sigma_{51}\) = 225 \times 10^{-24} | 10        |
| \(\sigma_{51}'\) = 675 \times 10^{-24} | 10        |
| \(\sigma_{52}\) = 3400 \times 10^{-24} | 11        |
| \(\sigma_{52}\) = 4600 \times 10^{-24} | 11        |
| \(\sigma_{53}\) = 137.5 \times 10^{-24} | 10        |
| \(\sigma_{62}\) = 20 \times 10^{-24} | 11        |
| \(\sigma_{63}\) = 250 \times 10^{-24} | 11        |
| \(\sigma_{63}\) = 490 \times 10^{-24} | 11        |
### Constants (Cont'd)

<table>
<thead>
<tr>
<th>Pile Cross Sections (Cm$^2$)</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>$\sigma_{64}$ = $25 \times 10^{-24}$</td>
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</tr>
<tr>
<td>$\sigma_{65}$ = $200 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{65}'$ = $1500 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{66}$ = $15 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{67}$ = $200 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{68}$ = $2 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{79}$ = $400 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{89}$ = $270 \times 10^{-24}$</td>
<td>11</td>
</tr>
<tr>
<td>$\sigma_{89}'$ = $600 \times 10^{-24}$</td>
<td>11</td>
</tr>
<tr>
<td>$\sigma_{80}$ = $1500 \times 10^{-24}$</td>
<td>11</td>
</tr>
<tr>
<td>$\sigma_{81}$ = $3000 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{81}'$ = $3000 \times 10^{-24}$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{82}$ = $30 \times 10^{-24}$</td>
<td>11</td>
</tr>
</tbody>
</table>

Flux (n/cm$^2$/sec)

\[ d = 5 \times 10^{13} \]

Initial Condition (at time zero)

- a) $N_{49} = 1$ all other $N$'s = 0
- b) $N_{40} = 1$ all other $N$'s = 0
- c) $N_{41} = 1$ all other $N$'s = 0
- d) $N_{42} = 1$ all other $N$'s = 0
- e) $N_{51} = 1$ all other $N$'s = 0
- f) $N_{53} = 1$ all other $N$'s = 0
- g) $N_{64} = 1$ all other $N$'s = 0
The set of simultaneous differential equations was solved with a Goodyear analog computer for each of the initial conditions and a constant neutron flux of $5 \times 10^{13}$ n/cm$^2$/sec. The concentrations of all the isotopes described by the equations were plotted as functions of irradiation time by an eight-pen Sanborn recorder associated with the computer. Figures 2 through 113 are curves drawn from the results of the computations. The numbers of atoms of $^{238}\text{Pu}$, $^{239}\text{Pu}$, $^{240}\text{Pu}$, $^{241}\text{Pu}$, $^{242}\text{Pu}$, $^{241}\text{Am}$, $^{242}\text{Am}$, $^{243}\text{Am}$, $^{242}\text{Cm}$, $^{243}\text{Cm}$, $^{244}\text{Cm}$, $^{245}\text{Cm}$, $^{246}\text{Cm}$, $^{247}\text{Cm}$, $^{248}\text{Cm}$, $^{249}\text{Bk}$, $^{249}\text{Cf}$, $^{250}\text{Cf}$, $^{251}\text{Cf}$, and $^{252}\text{Cf}$ per initial atoms of $^{239}\text{Pu}$, $^{240}\text{Pu}$, $^{241}\text{Pu}$, $^{242}\text{Pu}$, $^{241}\text{Am}$, $^{243}\text{Am}$, or $^{244}\text{Cm}$ are plotted as functions of irradiation times. The accuracy of the results are limited by the uncertainties in the cross sections rather than by the precision of the computations or the precision of reproduction of the curves. The over-all computation and reproduction error is estimated to be less than ten per cent.

**DISCUSSION**

The curves presented in this report can be used to estimate the americium, curium, berkelium, and californium buildup in plutonium of any likely initial isotopic composition or in $^{241}\text{Am}$, $^{243}\text{Am}$, and $^{244}\text{Cm}$ irradiated in a thermal neutron flux of $5 \times 10^{13}$. The accuracy of such estimates will depend on the agreement of the neutron cross section for the reactor under consideration with the cross section values used in these computations. The $^{240}\text{Pu}$ effective pile cross section in particular is strongly influenced by the reactor neutron spectrum and the $^{240}\text{Pu}$ concentration at any given time. (12)(13).

As an example of the use of Figures 2 through 113, the plutonium and trans-plutonium isotopic content of a one kilogram plutonium sample irradiated for two years in a $5 \times 10^{13}$ neutron/cm$^2$/sec flux has been calculated. The plutonium was assumed to be twenty-two per cent $^{239}\text{Pu}$, twenty-four per cent $^{240}\text{Pu}$, six per cent $^{241}\text{Pu}$, and forty-eight per cent $^{242}\text{Pu}$. The sample was assumed to be initially free of americium and
other trans-plutonium isotopes. Figures 2 through 21 can be used to estimate the amounts of the various isotopes present in the sample at the end of the two-year irradiation per initial Pu$^{239}$ content of the sample as shown in Table I. The use of the correction of atom ratio to weight ratio is not justified by the precision of the computation but is included for completeness. Likewise Figures 20 through 72 can be used to estimate the amounts of the various isotopes present at the end of the irradiation which result from initial neutron capture events with Pu$^{240}$, Pu$^{241}$, and Pu$^{242}$ contained in the sample at the start of the irradiation. The results for all isotopes included in this example are tabulated in Table II.
## TABLE I

### ISOTOPES PRODUCED FROM $\text{Pu}^{239}$ INITIALLY PRESENT

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Kilograms $\text{Pu}^{239}$ Initially Present</th>
<th>Atoms Per Initial Atom From Figures</th>
<th>Conversion Factor Of Atom Ratio To Weight Ratio</th>
<th>Kilograms $\text{Pu}^{239}$ At End of Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Pu}^{238}$</td>
<td>0.22</td>
<td>$1 \times 10^{-3}$</td>
<td>238/239</td>
<td>0.22 x 10^{-3}</td>
</tr>
<tr>
<td>$\text{Pu}^{239}$</td>
<td>0.22</td>
<td>$1 \times 10^{-2}$</td>
<td>239/239</td>
<td>0.22 x 10^{-2}</td>
</tr>
<tr>
<td>$\text{Pu}^{240}$</td>
<td>0.22</td>
<td>$1.5 \times 10^{-1}$</td>
<td>240/239</td>
<td>0.33 x 10^{-1}</td>
</tr>
<tr>
<td>$\text{Pu}^{241}$</td>
<td>0.22</td>
<td>$3.7 \times 10^{-2}$</td>
<td>241/239</td>
<td>0.81 x 10^{-2}</td>
</tr>
<tr>
<td>$\text{Pu}^{242}$</td>
<td>0.22</td>
<td>$3.4 \times 10^{-2}$</td>
<td>242/239</td>
<td>0.75 x 10^{-2}</td>
</tr>
<tr>
<td>$\text{Am}^{241}$</td>
<td>0.22</td>
<td>$1.6 \times 10^{-3}$</td>
<td>241/239</td>
<td>0.35 x 10^{-3}</td>
</tr>
<tr>
<td>$\text{Am}^{242}$</td>
<td>0.22</td>
<td>$3.8 \times 10^{-5}$</td>
<td>242/239</td>
<td>0.84 x 10^{-5}</td>
</tr>
<tr>
<td>$\text{Am}^{243}$</td>
<td>0.22</td>
<td>$2 \times 10^{-3}$</td>
<td>243/239</td>
<td>0.44 x 10^{-3}</td>
</tr>
<tr>
<td>$\text{Cm}^{242}$</td>
<td>0.22</td>
<td>$5.5 \times 10^{-4}$</td>
<td>242/239</td>
<td>1.2 x 10^{-4}</td>
</tr>
<tr>
<td>$\text{Cm}^{243}$</td>
<td>0.22</td>
<td>$6 \times 10^{-6}$</td>
<td>243/239</td>
<td>1.3 x 10^{-6}</td>
</tr>
<tr>
<td>$\text{Cm}^{244}$</td>
<td>0.22</td>
<td>$2.6 \times 10^{-4}$</td>
<td>244/239</td>
<td>0.57 x 10^{-4}</td>
</tr>
<tr>
<td>$\text{Cm}^{245}$</td>
<td>0.22</td>
<td>$2 \times 10^{-6}$</td>
<td>245/239</td>
<td>0.44 x 10^{-6}</td>
</tr>
<tr>
<td>$\text{Cm}^{246}$</td>
<td>0.22</td>
<td>$2 \times 10^{-7}$</td>
<td>246/239</td>
<td>0.44 x 10^{-7}</td>
</tr>
<tr>
<td>$\text{Cm}^{247}$</td>
<td>0.22</td>
<td>$1 \times 10^{-9}$</td>
<td>247/239</td>
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</tr>
<tr>
<td>$\text{Cm}^{248}$</td>
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<td>248/239</td>
<td>0.22 x 10^{-11}</td>
</tr>
<tr>
<td>$\text{Bk}^{249}$</td>
<td>0.22</td>
<td>$5 \times 10^{-15}$</td>
<td>249/239</td>
<td>1.1 x 10^{-15}</td>
</tr>
<tr>
<td>$\text{Cf}^{249}$</td>
<td>0.22</td>
<td>$5 \times 10^{-16}$</td>
<td>249/239</td>
<td>1.1 x 10^{-16}</td>
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<tr>
<td>$\text{Cf}^{250}$</td>
<td>0.22</td>
<td>$8 \times 10^{-16}$</td>
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<tr>
<td>$\text{Cf}^{251}$</td>
<td>0.22</td>
<td>$1 \times 10^{-16}$</td>
<td>251/239</td>
<td>0.22 x 10^{-16}</td>
</tr>
<tr>
<td>$\text{Cf}^{252}$</td>
<td>0.22</td>
<td>$5 \times 10^{-17}$</td>
<td>252/239</td>
<td>1.1 x 10^{-17}</td>
</tr>
</tbody>
</table>
## ISOTOPES PRODUCED BY TWO YEAR IRRADIATION OF PLUTONIUM SAMPLE

### Kilograms at End of Irradiation

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Pu(^{239})</th>
<th>Pu(^{240})</th>
<th>Pu(^{241})</th>
<th>Pu(^{242})</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu(^{238})</td>
<td>0.22 x 10^{-3}</td>
<td>0.48 x 10^{-3}</td>
<td>0.3 x 10^{-3}</td>
<td>0.12 x 10^{-3}</td>
<td>1 x 10^{-3}</td>
</tr>
<tr>
<td>Pu(^{239})</td>
<td>0.22 x 10^{-2}</td>
<td>0.89 x 10^{-1}</td>
<td>0.3 x 10^{-4}</td>
<td>1.2 x 10^{-1}</td>
<td></td>
</tr>
<tr>
<td>Pu(^{240})</td>
<td>0.33 x 10^{-1}</td>
<td>0.24 x 10^{-1}</td>
<td>0.6 x 10^{-3}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu(^{241})</td>
<td>0.81 x 10^{-2}</td>
<td>0.13 x 10^{-1}</td>
<td>0.35 x 10^{-3}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu(^{242})</td>
<td>0.75 x 10^{-2}</td>
<td>0.11 x 10^{-2}</td>
<td>0.81 x 10^{-2}</td>
<td>0.75 x 10^{-1}</td>
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</tr>
<tr>
<td>Am(^{241})</td>
<td>0.35 x 10^{-3}</td>
<td>0.31 x 10^{-1}</td>
<td>0.84 x 10^{-3}</td>
<td>0.44 x 10^{-3}</td>
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<td>0.84 x 10^{-5}</td>
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<td>0.24 x 10^{-2}</td>
<td>0.18 x 10^{-2}</td>
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<tr>
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<td>0.48 x 10^{-3}</td>
<td>0.16 x 10^{-3}</td>
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<tr>
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<td>1.3 x 10^{-6}</td>
<td>0.65 x 10^{-5}</td>
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<td>0.76 x 10^{-3}</td>
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</tr>
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<td>Cm(^{244})</td>
<td>0.57 x 10^{-4}</td>
<td>0.29 x 10^{-3}</td>
<td>0.14 x 10^{-1}</td>
<td>1.2 x 10^{-5}</td>
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</tr>
<tr>
<td>Cm(^{245})</td>
<td>0.44 x 10^{-6}</td>
<td>0.29 x 10^{-5}</td>
<td>0.14 x 10^{-3}</td>
<td>0.15 x 10^{-1}</td>
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</tr>
<tr>
<td>Cm(^{246})</td>
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<td>0.14 x 10^{-1}</td>
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</tr>
<tr>
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<tr>
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<tr>
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</tr>
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<td>0.96 x 10^{-15}</td>
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<td>0.3 x 10^{-15}</td>
<td>0.14 x 10^{-13}</td>
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</tr>
</tbody>
</table>
REFERENCES

(1) Jaffey, A. H., "Long Term Variation in Composition and Neutron Yield in Pile Plutonium", Nuclear Science and Engineering 1, 3 (1956).


FIGURE 1
Buildup of Plutonium and Trans-Plutonium Isotopes by Neutron Irradiation
**FIGURE 2**
Burnup of Pu$^{239}$

**FIGURE 3**
Atoms Pu$^{238}$ per Initial Atom Pu$^{239}$

**FIGURE 4**
Atoms Pu$^{240}$ per Initial Atom Pu$^{239}$

**FIGURE 5**
Atoms Pu$^{241}$ per Initial Atom Pu$^{239}$
FIGURE 6
Atoms Pu$^{242}$ per Initial Atom Pu$^{239}$

FIGURE 7
Atoms Am$^{241}$ per Initial Atoms Pu$^{239}$

FIGURE 8
Atoms Am$^{242}$ per Initial Atoms Pu$^{239}$

FIGURE 9
Atoms Am$^{243}$ per Initial Atom Pu$^{239}$
FIGURE 10
Atoms Cm$^{242}$ per Initial Atoms Pu$^{239}$

FIGURE 11
Atoms Cm$^{243}$ per Initial Atom Pu$^{239}$

FIGURE 12
Atoms Cm$^{244}$ per Initial Atom Pu$^{239}$

FIGURE 13
Atoms Cm$^{245}$ per Initial Atom Pu$^{239}$
FIGURE 14
Atoms Cm\(^{246}\) per Initial Atom Pu\(^{239}\)

FIGURE 15
Atoms Cm\(^{247}\) per Initial Atom Pu\(^{239}\)

FIGURE 16
Atoms Cm\(^{248}\) per Initial Atom Pu\(^{239}\)

FIGURE 17
Atoms Bk\(^{249}\) per Initial Atom Pu\(^{239}\)
Atoms $^{249}\text{Cf}$ per Initial Atom $^{239}\text{Pu}$

Atoms $^{250}\text{Cf}$ per Initial Atom $^{239}\text{Pu}$

Atoms $^{251}\text{Cf}$ per Initial Atom $^{239}\text{Pu}$

Atoms $^{252}\text{Cf}$ per Initial Atom $^{239}\text{Pu}$
FIGURE 22
Burnup of Pu$^{240}$

FIGURE 23
Atoms Pu$^{238}$ per Initial Atom Pu$^{240}$

FIGURE 24
Atoms Pu$^{241}$ per Initial Atom Pu$^{240}$

FIGURE 25
Atoms Pu$^{242}$ per Initial Atom Pu$^{240}$
FIGURE 26
Atoms $\text{Am}^{241}$ per Initial Atom $\text{Pu}^{240}$

FIGURE 27
Atoms $\text{Am}^{242}$ per Initial Atom $\text{Pu}^{240}$

FIGURE 28
Atoms $\text{Am}^{243}$ per Initial Atom $\text{Pu}^{240}$

FIGURE 29
Atoms $\text{Cm}^{242}$ per Initial Atom $\text{Pu}^{240}$
FIGURE 30
Atoms Cm$^{243}$ per Initial Atom Pu$^{240}$

FIGURE 31
Atoms Cm$^{244}$ per Initial Atoms Pu$^{240}$

FIGURE 32
Atoms Cm$^{245}$ per Initial Atom Pu$^{240}$

FIGURE 33
Atoms Cm$^{246}$ per Initial Atom Pu$^{240}$
FIGURE 34
Atoms Cm$^{247}$ per Initial Atom Pu$^{240}$

FIGURE 35
Atoms Cm$^{248}$ per Initial Atom Pu$^{240}$

FIGURE 36
Atoms Bk$^{249}$ per Initial Atom Pu$^{240}$

FIGURE 37
Atoms Cf$^{249}$ per Initial Atom Pu$^{240}$
FIGURE 38
Atoms Cf$^{250}$ per Initial Atom Pu$^{240}$

FIGURE 39
Atoms Cf$^{251}$ per Initial Atom Pu$^{240}$

FIGURE 40
Atoms Cf$^{252}$ per Initial Atom Pu$^{240}$

FIGURE 41
Burnup of Pu$^{241}$
FIGURE 42
Atoms Pu\textsuperscript{238} per Initial Atom Pu\textsuperscript{241}

FIGURE 43
Atoms Pu\textsuperscript{239} per Initial Atom Pu\textsuperscript{241}

FIGURE 44
Atoms Pu\textsuperscript{240} per Initial Atom Pu\textsuperscript{241}

FIGURE 45
Atoms Pu\textsuperscript{242} per Initial Atom Pu\textsuperscript{241}
FIGURE 46
Atoms Am$^{241}$ per Initial Atom Pu$^{241}$

FIGURE 47
Atoms Am$^{242}$ per Initial Atom Pu$^{241}$

FIGURE 48
Atoms Am$^{243}$ per Initial Atom Pu$^{241}$

FIGURE 49
Atoms Cm$^{242}$ per Initial Atom Pu$^{241}$
FIGURE 50
Atoms Cm$^{243}$ per Initial Atom Pu$^{241}$

FIGURE 51
Atoms Cm$^{244}$ per Initial Atom Pu$^{241}$

FIGURE 52
Atoms Cm$^{245}$ per Initial Atom Pu$^{241}$

FIGURE 53
Atoms Cm$^{246}$ per Initial Atom Pu$^{241}$
FIGURE 54
Atoms Cm\(^{247}\) per Initial Atom Pu\(^{241}\)

FIGURE 55
Atoms Cm\(^{248}\) Per Initial Atom Pu\(^{241}\)

FIGURE 56
Atoms Bk\(^{249}\) per Initial Atom Pu\(^{241}\)

FIGURE 57
Atoms Cf\(^{249}\) per Initial Atom Pu\(^{241}\)
FIGURE 58
Atoms $^{250}\text{Cf}$ per Initial Atom $^{241}\text{Pu}$

FIGURE 59
Atoms $^{251}\text{Cf}$ per Initial Atom $^{241}\text{Pu}$

FIGURE 60
Atoms $^{252}\text{Cf}$ per Initial Atom $^{241}\text{Pu}$

FIGURE 61
Burnup of $^{242}\text{Pu}$
**FIGURE 62**
Atoms Am\(^{243}\) per Initial Atom Pu\(^{242}\)

**FIGURE 63**
Atoms Cm\(^{244}\) per Initial Atom Pu\(^{242}\)

**FIGURE 64**
Atoms Cm\(^{245}\) per Initial Atom Pu\(^{242}\)

**FIGURE 65**
Atoms Cm\(^{246}\) per Initial Atom Pu\(^{242}\)
FIGURE 66
Atoms Cm$^{247}$ per Initial Atom Pu$^{242}$

FIGURE 67
Atoms Cm$^{248}$ per Initial Atom Pu$^{242}$

FIGURE 68
Atoms Bk$^{249}$ per Initial Atom Pu$^{242}$

FIGURE 69
Atoms Cf$^{249}$ per Initial Atom Pu$^{242}$
FIGURE 70
Atoms $^{250}\text{Cf}$ per Initial Atom $^{242}\text{Pu}$

FIGURE 71
Atoms $^{251}\text{Cf}$ per Initial Atom $^{242}\text{Pu}$

FIGURE 72
Atoms $^{252}\text{Cf}$ per Initial Atom $^{242}\text{Pu}$

FIGURE 73
Burnup of Am$^{241}$
FIGURE 74
Atoms $^{238}\text{Pu}$ per Initial Atom $^{241}\text{Am}$

FIGURE 75
Atoms $^{239}\text{Pu}$ per Initial Atom $^{241}\text{Am}$

FIGURE 76
Atoms $^{240}\text{Pu}$ per Initial Atom $^{241}\text{Am}$

FIGURE 77
Atoms $^{241}\text{Pu}$ per Initial Atom $^{241}\text{Am}$
Atoms Pu$^{242}$ per Initial Atom Am$^{241}$

Atoms Am$^{242}$ per Initial Atom Am$^{241}$

Atoms Am$^{243}$ per Initial Atom Am$^{241}$

Atoms Cm$^{242}$ per Initial Atom Am$^{241}$
FIGURE 82
Atoms Cm$^{243}$ per Initial Atom Am$^{241}$

FIGURE 83
Atoms Cm$^{244}$ per Initial Atom Am$^{241}$

FIGURE 84
Atoms Cm$^{245}$ per Initial Atom Am$^{241}$

FIGURE 85
Atoms Cm$^{246}$ per Initial Atom Am$^{241}$
FIGURE 86
Atoms Cm$^{247}$ per Initial Atom Am$^{241}$

FIGURE 87
Atoms Cm$^{248}$ per Initial Atom Am$^{241}$

FIGURE 88
Atoms Bk$^{249}$ per Initial Atom Am$^{241}$

FIGURE 89
Atoms Cf$^{249}$ per Initial Atom Am$^{241}$
FIGURE 90
Atoms $^{250}\text{Cf}$ per Initial Atom $^{241}\text{Am}$

FIGURE 91
Atoms $^{251}\text{Cf}$ per Initial Atom $^{241}\text{Am}$

FIGURE 92
Atoms $^{252}\text{Cf}$ per Initial Atom $^{241}\text{Am}$

FIGURE 93
Burnup of $^{243}\text{Am}$
FIGURE 94
Atoms Cm$^{244}$ per Initial Atom Am$^{243}$

FIGURE 95
Atoms Cm$^{245}$ per Initial Atom Am$^{243}$

FIGURE 96
Atoms Cm$^{246}$ per Initial Atom Am$^{243}$

FIGURE 97
Atoms Cm$^{247}$ per Initial Atom Am$^{243}$
FIGURE 98
Atoms Cm$^{248}$ per Initial Atom Am$^{243}$

FIGURE 99
Atoms Bk$^{249}$ per Initial Atom Am$^{243}$

FIGURE 100
Atoms Cf$^{249}$ per Initial Atom Am$^{243}$

FIGURE 101
Atoms Cf$^{250}$ per Initial Atom Am$^{243}$
FIGURE 102
Atoms Cf$^{251}$ per Initial Atom Am$^{243}$

FIGURE 103
Atoms Cf$^{252}$ per Initial Atom Am$^{243}$

FIGURE 104
Burnup of Cm$^{244}$

FIGURE 105
Atoms Cm$^{245}$ per Initial Atom Cm$^{244}$
FIGURE 106
Atoms Cm\(^{246}\) per Initial Atom Cm\(^{244}\)

FIGURE 107
Atoms Cm\(^{247}\) per Initial Atom Cm\(^{244}\)

FIGURE 108
Atoms Cm\(^{248}\) per Initial Atom Cm\(^{244}\)

FIGURE 109
Atoms Bk\(^{249}\) per Initial Atom Cm\(^{244}\)
FIGURE 110
Atoms $^{249}\text{Cf}$ per Initial Atom $^{244}\text{Cm}$

FIGURE 111
Atoms $^{250}\text{Cf}$ per Initial Atom $^{244}\text{Cm}$

FIGURE 112
Atoms $^{251}\text{Cf}$ per Initial Atom $^{244}\text{Cm}$

FIGURE 113
Atoms $^{252}\text{Cf}$ per Initial Atom $^{244}\text{Cm}$
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