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# DECAY CURVES FOR 23 FISSION PRODUCTS

by

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Process Design Section

Date Received: 6/30/48 Date Issued: 5/11/48
Figs. 5/10/48

April 23, 1948

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## 0. ABSTRACT

A series of decay curves is presented whereby the total 23 fission product activity associated with one kilogram of thorium irradiated for various periods of time at various thermal neutron fluxes can be obtained. The following fluxes and irradiation periods are considered, and it is assumed that the mechanical design of the equipment is such that the fission heat can be removed.

| Thermal Flux Neutrons/Cm.$^2$/Sec. | Period of Irradiation Days |
|---|---|
| $10^{12}$ | 10 - 365 |
| $10^{13}$ | 10 - 365 |
| $10^{14}$ | 10 - 365 |
| $10^{15}$ | 10 - 365 |
| $10^{16}$ | 10 - 150 |

Fission product activities with thermal neutron fluxes less than $10^{12}$ can be obtained by using the chart for a flux of $10^{12}$ and the relationship, $\log_{10}$(total 23 fission product activity) $=$ 2 x $\log_{10}$(thermal neutron flux) $+$ B. The constant, B, is determined when the corresponding value with a flux of $10^{12}$ is introduced into the equation.

Tabulations from which growth curves for $U^{233}$ fission products, $U^{233}$, $Pa^{233}$, and $Th^{233}$ can be constructed are included.

An analytical expression for the total activity from 23 fission products developed by N. M. Dismuke and K. Way of the Physics Division is also presented.

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## 1. INTRODUCTION

The literature does not contain decay curves for 23 fission products, and these curves are helpful, principally, in the determination of shielding and decontamination requirements. The decay curves for 25 fission products are not directly applicable when 23 fission products are concerned. In general, the situations are such that the rate of 25 fissioning is constant and the rate of 23 fissioning is variable. Decay curves for 23 fission products have been calculated and are presented in this report. These curves are based on the principle that small increments of 23 fission products are produced at a constant rate and that decay curves for 25 fission products can then be applied to these small increments.

## 2. CONSTRUCTION AND USE OF DECAY CURVES

The decay curves for 23 fission products present in one kilogram of thorium irradiated with thermal neutron fluxes of $10^{12}$ to $10^{16}$ are given in Figures 1 to 5. A tabulation of the total 23 fission product activity values from which these charts were constructed is given in Table I. A sample calculation of one decay curve (thermal flux-$10^{13}$ neutrons/cm.$^2$/sec., irradiation period - 100 days) is presented in Table II and in the tabulation given at the end of this paragraph.

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Figure 6 is the fission product growth curve used for these computations. A tabulation from which fission product growth curves can be constructed for all thermal fluxes between $10^{11}$ and $10^{16}$ is given in Table III. (Table IV contains similar tabulations for $U^{233}$, $Pa^{233}$, and $Th^{233}$.) Figure 7 is a cross-plot based on Table III. The nuclear constants, cross-sections and half-lives, used in the calculations are included in Figure 8. The rate of 23 fissioning is not constant, but it is reasonable to consider that small increments of 23fission products are produced at a constant rate. Decay curves for 25 fission products can then be applied to these small increments. The Borst-Wheeler curves (Figure 9) are probably as satisfactory as any of the decay curves for 25 fission products for this purpose(1). A cross-plot of the Borst-Wheeler curves is presented in Figure 10, and an extrapolation to cooling periods greater than 300 days is given in Figure 11. When cooling periods of 200 days or more are considered for situations wherein the periods of irradiation are 100 days or less, it is no longer necessary to use increments of fission product production. An average internal decay period (for example, an average of column 6 in Table II) can be calculated for the total mass of 23 fission products, and this time is added to the cooling period.

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| Cooling Period Days | Average Internal Decay Period Days | Total Cooling Period Days | Activity watts/gram | Total Activity Watts |
|---|---|---|---|---|
| 200 | 15 | 215 | 2.08 | 0.013 |
| 300 | 15 | 315 | 1.18 | 0.0075 |
| 400 | 15 | 415 | 0.775 | 0.0049 |
| 600 | 15 | 615 | 0.444 | 0.0028 |

Note: Total production of 23 fission products - 6.37 milligrams

Attention is directed again to the sample calculation presented in Table II. The fission products produced during the last day represent most of the fission product activity when the irradiated thorium if first removed from the pile. In connection with the calculation of the decay curves it was the policy to limit the size of the last increment to the production during the last day or two. Concerning the fission products produced earlier in the irradiation period, relatively large increments were used because they do not represent a major fraction of the initial fission product activity. These relatively large increments were also used in the calculation of fission product activity for finite cooling periods because the activity then is less dependent upon the rate at which the fission products were originally produced.

The values of the fission product growth curves for a flux of $10^{13}$ are approximately a factor of 100 greater than the corresponding values

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on the growth curves for a flux of $10^{12}$. Consequently, the decay curves for a flux of $10^{12}$ (Figure 1) were calculated directly from the decay curves for a flux of $10^{13}$ (Figure 2). The factors used in these transformations are given in Table V.

The general equation,

$\log_{10}$(fission product production) = 2 x $\log_{10}$(thermal neutron flux) + $B_1$ ,

represents the curves in Figure 7 at fluxes below $10^{12}$. Therefore, fission product activities with thermal neutron fluxes less than $10^{12}$ can be obtained by using the chart for a flux of $10^{12}$ (Figure 1) and the relationship,

$\log_{10}$(total 23 fission product activity) = 2 x $\log_{10}$(thermal neutron flux) + B. The constant, B, is determined when the corresponding value with a flux of $10^{12}$ is introduced into the equation.

A study of the breakdown of the total 23 fission product activities given in Figures 1 to 5 into $\beta$ and $\gamma$ radiations has not been made. However, it is reasonable to assume that approximately fifty per cent of the energy is $\beta$, and approximately fifty per cent is $\gamma$ (1,3). Attention is directed to a detailed discussion of the breakdown of 25 fission product activities presented in reference 2.

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## 3.0 TOTAL 23 FISSION PRODUCT ACTIVITY (AN ANALYTICAL EXPRESSION)

### 3.1 Derivation of the Analytical Expression

The total energy emitted per second per fission by 25 fission products at decay times between one second and one hundred days is given approximately by the following relationship which is based on reference 10.

$$E = 2.66\ t'^{-1.2} \qquad (1)$$

$E$ = Energy, Mev/fission/second

$t'$ = decay time, seconds

It is assumed here that this expression can be applied to 23 fission products.

$$E = \int_o^{\mathscr{t}} N_4(t)\sigma_f \phi\ 2.66\ t'^{-1.2}\ dt \qquad (2)$$

where $t + t' = \mathscr{t} + T$ (3)

$E$ = energy or total 23 fission product activity, Mev/second

$t$ = irradiation time, seconds

$\mathscr{t}$ = total irradiation period, seconds

$N_4$ = number of atoms of 23 present at time t

$\sigma_f$ = fission cross-section for 23, 505 barns (see Fig. 8)

$\phi$ = thermal neutron flux, neutrons/cm.$^2$/second

$t'$ = decay time, seconds

$T$ = total decay time, seconds

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The growth curve for 23 is given by equation 4.

$$N_4 = No \left[ Ae^{-\lambda_1 t} + Be^{-\lambda_2 t} + Ce^{-\lambda_3 t} + De^{-\lambda_4 t} \right] \qquad (4)$$

$N_4$ = total number of atoms of 23 present at time t

No = initial number of atoms of $Th^{232}$ irradiated

t = irradiation time, seconds

$\lambda_1$ = total reaction rate constant for $Th^{232}$, reciprocal seconds

$\lambda_2$ = total reaction rate constant for $Th^{233}$, reciprocal seconds

$\lambda_3$ = total reaction rate constant for $Pa^{233}$, reciprocal seconds

$\lambda_4$ = total reaction rate constant for $U^{233}$, reciprocal seconds

A, B, C, and D are constants. The determination of these constants is discussed in detail in reference 5. Equation 5 results when equations 3 and 4 are incorporated in equation 2. Note also that the units have been changed.

$$E = 0.575 \times 10^{-13} M\phi \int_T^{\tau + T} \left[ Ae^{-\lambda_1(\tau + T - t')} + Be^{-\lambda_2(\tau + T - t')} + Ce^{-\lambda_3(\tau + T - t')} + De^{-\lambda_4(\tau + T - t')} \right] t'^{-1.2} \, dt' \qquad (5)$$

E = energy or total 23 fission product activity, watts

M = Mass of thorium irradiated, grams

$\phi$ = thermal neutron flux, neutrons/$cm.^2$/ second

$\tau$ = total irradiation time, days

T = total decay time, days

t' = decay time, days

3.2 An Example

In the example the total 23 fission product activity associated with one kilogram of thorium, irradiated with a flux of $10^{14}$ for 60 days and cooled for

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80 days, is calculated.

$A = 1.216 \times 10^{-2}$

$B = -0.822 \times 10^{-9}$

$C = 2.790 \times 10^{-3}$

$D = -1.495 \times 10^{-2}$

$\lambda_1 = 5.9 \times 10^{-5}$ days-1

$\lambda_2 = 42.5$

$\lambda_3 = 2.57 \times 10^{-2}$

$\lambda_4 = 4.84 \times 10^{-3}$

For irradiation periods between 0 and 60 days $e^{-\lambda_1 t}$ is approximately unity. Since the term, $Be^{-\lambda_2 t}$, is much smaller than the other three terms, it can be neglected. In addition, since $\lambda_4 t$ is relatively small, the term, $e^{-\lambda_4 t}$, can be replaced by the term, $1-\lambda_4 t$.

$$E(\text{watts}) = 5750 \int_{80}^{140} \left[\left[1.216 \times 10^{-2}\right] + \left[2.790 \times 10^{-3} e^{-2.57 \times 10^{-2} \times 140} \times e^{+2.57 \times 10^{-2} t'}\right] + \left[\left[-1.495 \times 10^{-2}\right]\left[1 - 4.84 \times 10^{-3} (t' + T - t')\right]\right] t'^{-1.2} dt'$$

The first and third terms are integrated analytically, and the second term is integrated graphically.

$E = 15.4 + 1.7 - 15.9 = 1.2$ watts

The corresponding value obtained from Figure 3 is 1.3 watts.

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## 4. ACKNOWLEDGMENT

The author is indebted to N. M. Dismuke and K. Way of the Physics Division for the analytical expression concerning total 23 fission product activity and for the associated discussion. The author also wishes to acknowledge the assistance of J. R. Huffman, J. A. Lane, R. W. Stoughton, W. S. Farmer, and J. W. Hanson.

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Table I

TOTAL 25 FISSION PRODUCT ACTIVITIES (WATTS)

Basis: One Kilogram of Thorium Irradiated

Basis: One Kilogram of Thorium Irradiated

| Irradiation Period (Days) | Cooling Period - Time after Removal from Pile: 1 Minute | 10 Minutes | 1 Hour | 1 Day | 10 Days | 100 Days | 200 Days | 300 Days | 400 Days | 500 Days |
|---|---|---|---|---|---|---|---|---|---|---|
| **Thermal Flux : $10^{13}$ Neutrons / Cm.$^2$ / Sec.** | | | | | | | | | | |
| 10 | 0.00082 | 0.00080 | 0.0001? | $0.087\times10^{-3}$ | $0.0198\times10^{-3}$ | $0.0010\times10^{-3}$ | $0.24\times10^{-6}$ | $0.168\times10^{-6}$ | $0.121\times10^{-6}$ | $0.089\times10^{-6}$ |
| 15 | 0.00107 | 0.00103 | 0.00037 | 0.078 | 0.0259 | 0.00248 | 0.61 | 0.44 | 0.288 | 0.184 |
| 20 | 0.00203 | 0.00125 | 0.00077 | 0.157 | 0.052 | 0.0056 | 1.03 | 0.89 | 0.86 | 0.27 |
| 30 | 0.0042 | 0.00294 | 0.00177 | 0.41 | 0.151 | 0.0170 | 5.7 | 3.1 | 2.0 | 1.1 |
| 40 | 0.0084 | 0.0051 | 0.00292 | 0.78 | 0.21 | 0.037 | 12.6 | 6.8 | 4.5 | 2.5 |
| 60 | 0.0171 | 0.0102 | 0.0060 | 1.78 | 0.81 | 0.102 | 37. | 20. | 13.4 | 7.6 |
| 80 | 0.025 | 0.0151 | 0.0092 | 3.0 | 1.28 | 0.208 | 77. | 42. | 28.5 | 16.2 |
| 100 | 0.037 | 0.0235 | 0.0148 | 4.7 | 2.38 | 0.38 | 134. | 76. | 50. | 28.6 |
| 150 | 0.064 | 0.041 | 0.026 | 9.2 | 5.1 | 0.87 | 280. | 197. | 152. | 77. |
| 200 | 0.094 | 0.060 | 0.039 | 16.1 | 8.5 | 1.58 | 630. | 370. | 260. | 148. |
| 300 | 0.157 | 0.102 | 0.066 | 27. | 15.5 | 3.4 | 1810. | 990. | 610. | 370. |
| 365 1/4 | 0.187 | 0.123 | 0.081 | 34. | 20.7 | 4.7 | 2130. | 1216. | 820. | 550. |
| **Thermal Flux : $10^{12}$ Neutrons / Cm.$^2$ / Sec.** | | | | | | | | | | |
| 10 | 0.082 | 0.080 | 0.011? | 0.0087 | 0.00198 | $0.108\times10^{-5}$ | $0.054\times10^{-5}$ | $0.0186\times10^{-5}$ | $0.0121\times10^{-5}$ | $0.0089\times10^{-5}$ |
| 15 | 0.107 | 0.083 | 0.037 | 0.0078 | 0.00259 | 0.248 | 0.061 | 0.044 | 0.029 | 0.0184 |
| 20 | 0.203 | 0.125 | 0.072 | 0.0157 | 0.0052 | 0.56 | 0.183 | 0.099 | 0.085 | 0.027 |
| 30 | 0.46 | 0.29 | 0.169 | 0.040 | 0.0146 | 1.6 | 0.65 | 0.20 | 0.20 | 0.11 |
| 40 | 0.85 | 0.60 | 0.29 | 0.078 | 0.020 | 3.8 | 1.25 | 0.67 | 0.44 | 0.25 |
| 60 | 1.88 | 1.00 | 0.59 | 0.172 | 0.079 | 10.0 | 3.6 | 2.0 | 1.32 | 0.76 |
| 80 | 2.48 | 1.49 | 0.80 | 0.20 | 0.151 | 20.7 | 7.6 | 4.2 | 2.8 | 1.80 |
| 100 | 3.7 | 2.32 | 1.44 | 0.47 | 0.335 | 36. | 13. | 7.5 | 4.5 | 2.8 |
| 150 | 6.3 | 4.0 | 2.59 | 0.91 | 0.60 | 86. | 34. | 19. | 13.0 | 7.5 |
| 200 | 9.2 | 5.8 | 3.8 | 1.48 | 0.84 | 152 | 60. | 36. | 25. | 14.5 |
| 300 | 15.2 | 9.8 | 6.4 | 2.81 | 1.51 | 330 | 140. | 87. | 60. | 36. |
| 365 1/4 | 18.0 | 11.8 | 7.8 | 3.5 | 1.99 | 490 | 220. | 126. | 88. | 55. |
| **Thermal Flux : $10^{14}$ Neutrons / Cm.$^2$ / Sec.** | | | | | | | | | | |
| 10 | 5.2 | 3.0 | 1.7 | 0.37 | 0.105 | 0.0054 | 0.00185 | 0.00121 | 0.00089 | |
| 15 | 10.7 | 6.3 | 3.7 | 0.78 | 0.258 | 0.0248 | 0.0081 | 0.0044 | 0.0029 | 0.00184 |
| 20 | 20.3 | 12.3 | 7.2 | 1.57 | 0.52 | 0.056 | 0.0182 | 0.0099 | 0.0065 | 0.0037 |
| 30 | 41. | 22.8 | 14.3 | 3.5 | 1.38 | 0.16 | 0.054 | 0.029 | 0.0192 | 0.0108 |
| 40 | 72. | 42. | 25.8 | 6.8 | 2.66 | 0.34 | 0.117 | 0.064 | 0.042 | 0.024 |
| 60 | 142. | 85. | 51. | 15.4 | 7.2 | 0.96 | 0.34 | 0.188 | 0.122 | 0.069 |
| 80 | 230. | 139. | 85. | 28.8 | 15.5 | 1.89 | 0.69 | 0.38 | 0.254 | 0.144 |
| 100 | 310. | 182. | 109. | 39. | 20.4 | 3.0 | 1.12 | 0.63 | 0.43 | 0.25 |
| 150 | 510. | 310. | 196. | 78. | 40. | 6.8 | 2.9 | 1.65 | 1.11 | 0.65 |
| 200 | 690. | 422. | 278. | 107. | 61. | 11.6 | 4.8 | 2.8 | 1.93 | 1.13 |
| 300 | 910. | 580. | 393. | 153. | 96. | 20.4 | 9. | 5.6 | 3.9 | 2.4 |
| 365 1/4 | 1000. | 650. | 470. | 184. | 113. | 25.4 | 12. | 7.7 | 5.4 | 3.4 |
| **Thermal Flux : $10^{15}$ Neutrons / Cm.$^2$ / Sec.** | | | | | | | | | | |
| 10 | 580. | 350. | 170. | 37. | 10.4 | 1.06 | 0.24 | 0.125 | 0.121 | 0.066 |
| 15 | 1070. | 630. | 372. | 78. | 25.8 | 2.40 | 0.81 | 0.44 | 0.29 | 0.164 |
| 20 | 1430. | 870. | 500. | 118. | 41. | 4.8 | 1.48 | 0.81 | 0.53 | 0.30 |
| 30 | 2520. | 1860. | 940. | 268. | 98. | 11. | 5.9 | 2.10 | 1.37 | 0.78 |
| 40 | 3900. | 2340. | 1470. | 420. | 161. | 20. | 7.6 | 4.2 | 2.72 | 1.55 |
| 60 | 6230. | 3790. | 2350. | 770. | 360. | 41. | 18.1 | 10.1 | 6.8 | 3.8 |
| 80 | 7800. | 4800. | 3000. | 1080. | 570. | 65. | 31. | 17.7 | 11.7 | 6.7 |
| 100 | 9900. | 5620. | 3500. | 1320. | 730. | 100. | 46. | 25.8 | 17.6 | 10.0 |
| 150 | 13000. | 8300. | 4500. | 1780. | 1040. | 184. | 80. | 47. | 32. | 18.8 |
| 200 | 14800. | 8600. | 4400. | 1910. | 1140. | 280. | 110. | 67. | 46. | 27.4 |
| 300 | 17000. | 8500. | 4400. | 2030. | 1260. | 540. | 180. | 98. | 69. | 42. |
| 365 1/4 | 18200. | 8200. | 4300. | 2010. | 1280. | 670. | 170. | 112. | 81. | 51. |
| **Thermal Flux : $10^{16}$ Neutrons / Cm.$^2$ / Sec.** | | | | | | | | | | |
| 10 | 15000. | 7700. | 4400. | 870. | 255. | 25.4 | 8.3 | 4.4 | 2.8 | 1.65 |
| 15 | 22700. | 12600. | 8000. | 1760. | 570. | 58. | 19.2 | 10.4 | 6.8 | 3.9 |
| 20 | 25800. | 18000. | 10600. | 2510. | 930. | 115. | 34. | 18.4 | 12.1 | 6.8 |
| 30 | 34000. | 21600. | 12100. | 3700. | 1620. | 195. | 67. | 37. | 24. | 13.7 |
| 40 | 39000. | 24400. | 13200. | 4900. | 2280. | 290. | 105. | 57. | 38. | 21.4 |
| 60 | 43000. | 25600. | 13500. | 6000. | 2800. | 450. | 172. | 97. | 64. | 37. |
| 80 | 45000. | 24600. | 13500. | 6530. | 3600. | 660. | 231. | 130. | 88. | 51. |
| 100 | 45000. | 23500. | 13400. | 6600. | 3900. | 890. | 278. | 160. | 107. | 63. |
| 150 | 39400. | 19200. | 12000. | 6800. | 3800. | 850. | 280. | 215. | 147. | 86. |

Drawing # 76-5

TABLE II

SAMPLE CALCULATION OF 25 FISSION PRODUCT DECAY CURVE

Basis: Mass of Thorium Irradiated: One Kilogram
Thermal Flux: $10^{13}$ neutrons/cm.$^2$/sec.
Period of Irradiation: 100 days
Total Production of 25 Fission Products: 8.87 milligrams

| Production of Fission Products Group | Production Period days | Production Rate mgs/day | 1 Minute after Removal from Pile (a) Internal Cooling Period days | 1 Minute after Removal from Pile (a) Activity watts/gram | 1 Minute after Removal from Pile (a) Total Activity watts | 10 Minutes after Removal from Pile (b) Total Cooling Period days | 10 Minutes after Removal from Pile (b) Activity watts/gram | 10 Minutes after Removal from Pile (b) Total Activity watts | 1 Hour after Removal from Pile Total Cooling Period days | 1 Hour after Removal from Pile Activity watts/gram | 1 Hour after Removal from Pile Total Activity watts | 1 Day after Removal from Pile Total Cooling Period days | 1 Day after Removal from Pile Activity watts/gram | 1 Day after Removal from Pile Total Activity watts | 10 Days after Removal from Pile Total Cooling Period days | 10 Days after Removal from Pile Activity watts/gram | 10 Days after Removal from Pile Total Activity watts | 100 Days after Removal from Pile Total Cooling Period days | 100 Days after Removal from Pile Activity watts/gram | 100 Days after Removal from Pile Total Activity watts |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0000 - 0.0015 | 0.0 - 87.6 | 87.6 | 42.4 | 15. | 0.0225 | 42.4 | 15. | 0.0225 | 42.4 | 15. | 0.0225 | 42.4 | 14.5 | .023 | 32.4 | 13. | .019 | 342.4 | 5.6 | .0036 |
| 0.0015 - 0.0080 | 87.6 - 74.7 | 12.1 | 29.5 | 25. | 0.0825 | 29.5 | 25. | 0.0825 | 29.5 | 24. | .021 | 29.5 | 23. | .068 | 29.5 | 22. | .065 | 329.5 | 5.3 | .0076 |
| 0.0080 - 0.0068 | 74.7 - 87.6 | 12.9 | 17. | 37. | 0.0858 | 17. | 37. | 0.0858 | 17. | 34. | .062 | 17. | 34. | .062 | 17. | 33. | .060 | 317. | 5.2 | .0068 |
| 0.0068 - 0.0068 | 87.6 - 87.6 | 7.2 | 5.0 | 90. | 0.707 | 5.0 | 90. | 0.707 | 5.0 | 82. | 0.580 | 5.0 | 80. | .566 | 5.0 | 65. | .460 | 305.0 | 5.05 | .0357 |
| 0.0068 - 0.0068 | 87.6 - 88.6 | 1.0 | 0.0 | 280. | 0.278 | 0.0 | 280. | 0.278 | 0.0 | 270. | 0.268 | 0.0 | 176. | .175 | 0.0 | 70. | .069 | 300.0 | 7.11 | .0068 |
| 0.0068 - 0.00887 | 88.0 -100.0 | 1.0 | 0.0 | 18000. | 5.05 | 0.009 | 11300. | 1.67 | 0.042 | 6030. | 0.806 | 1.0 | 650. | .197 | 10.0 | 81.5 | .023 | 300.0 | 7.80 | .0022 |
| | | | | | 1.88 | | | 2.78 | | | 1.44 | | | .659 | | | .256 | | | .0868 |

(a) Internal cooling period: decay period while pile is still operating.

(b) Total cooling period: time after removal from pile plus decay period while pile is still operating.

Table III

PRODUCTION OF 23 FISSION PRODUCTS

(Grams per Kilogram of Thorium)

| Irradiation Period (Days) | Thermal Flux Neutrons / Cm.$^2$ / Sec. | | | | | |
|---|---|---|---|---|---|---|
| | $10^{11}$ | $10^{12}$ | $10^{13}$ | $10^{14}$ | $10^{15}$ | $10^{16}$ |
| 10 | $0.015\times10^{-7}$ | $0.015\times10^{-5}$ | $0.015\times10^{-3}$ | $0.015\times10^{-1}$ | 0.15 | 3.6 |
| 15 | 0.036 | 0.036 | 0.036 | 0.036 | 0.36 | 8.5 |
| 20 | 0.081 | 0.081 | 0.081 | 0.081 | 0.66 | 15.1 |
| 30 | 0.26 | 0.26 | 0.25 | 0.24 | 1.7 | 30.4 |
| 40 | 0.57 | 0.57 | 0.56 | 0.53 | 3.4 | 47.5 |
| 50 | 1.04 | 1.04 | 1.03 | 0.96 | 5.7 | 65.2 |
| 60 | 1.70 | 1.70 | 1.68 | 1.55 | 8.5 | 82.7 |
| 70 | 2.56 | 2.56 | 2.53 | 2.31 | 11.6 | 99.8 |
| 80 | 3.63 | 3.63 | 3.59 | 3.24 | 15.1 | 116.1 |
| 90 | 4.92 | 4.92 | 4.87 | 4.34 | 18.8 | 131.7 |
| 100 | 6.43 | 6.43 | 6.37 | 5.60 | 22.7 | 146.5 |
| 110 | 8.18 | 8.18 | 8.10 | 7.04 | 26.7 | 160.5 |
| 120 | 10.2 | 10.2 | 10.1 | 8.63 | 30.9 | 173.6 |
| 130 | 12.4 | 12.4 | 12.3 | 10.4 | 35.1 | 185.9 |
| 140 | 14.9 | 14.9 | 14.7 | 12.3 | 39.3 | 197.6 |
| 150 | 17.7 | 17.7 | 17.3 | 14.4 | 43.6 | 208.6 |
| 160 | 20.7 | 20.7 | 20.2 | 16.6 | 48.0 | |
| 170 | 24.0 | 23.9 | 23.4 | 18.9 | 52.3 | |
| 180 | 27.5 | 27.4 | 26.8 | 21.4 | 56.6 | |
| 190 | 31.3 | 31.2 | 30.4 | 24.0 | 60.9 | |
| 200 | 35.3 | 35.2 | 34.3 | 26.7 | 65.3 | |
| 210 | 39.6 | 39.5 | 38.4 | 29.5 | 69.6 | |
| 220 | 44.2 | 44.0 | 42.7 | 32.5 | 73.8 | |
| 230 | 49.0 | 48.8 | 47.2 | 35.5 | 78.1 | |
| 240 | 54.0 | 53.8 | 52.0 | 38.7 | 82.3 | |
| 250 | 59.3 | 59.1 | 57.1 | 41.9 | 86.5 | |
| 260 | 64.9 | 64.6 | 62.3 | 45.3 | 90.7 | |
| 270 | 70.7 | 70.4 | 67.8 | 48.7 | 94.9 | |
| 280 | 76.8 | 76.5 | 73.6 | 52.2 | 99.0 | |
| 290 | 83.2 | 82.8 | 79.5 | 55.8 | 103.1 | |
| 300 | 89.8 | 89.3 | 85.7 | 59.5 | 107.2 | |
| 310 | 96.6 | 96.1 | 92.1 | 63.2 | 111.3 | |
| 320 | 103.7 | 103.2 | 98.7 | 67.0 | 115.4 | |
| 330 | 111.1 | 110.5 | 105.5 | 70.9 | 119.4 | |
| 340 | 118.7 | 118.1 | 112.6 | 74.8 | 123.4 | |
| 350 | 126.6 | 125.9 | 119.9 | 78.8 | 127.4 | |
| 360 | 134.7 | 134.0 | 127.4 | 82.9 | 131.3 | |
| 365 | 139.1 | 138.4 | 131.5 | 85.0 | 133.4 | |

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## Table IV

### PRODUCTION OF $U^{233}$, $Pa^{233}$, and $Th^{233}$

(Grams of $U^{233}$, $Pa^{233}$, and $Th^{233}$ Present per Kilogram of Thorium at Moment Thorium is Removed from Pile)

| Irradiation Period (Days) | Thermal Flux Neutrons / $Cm.^2$ / Sec. $10^{11}$ | $10^{12}$ | $10^{13}$ | $10^{14}$ | $10^{15}$ | $10^{16}$ |
|---|---|---|---|---|---|---|
| | | | $U^{233}$ | | | |
| 15 | 0.00016 | 0.0015 | 0.015 | 0.143 | 1.17 | 2.62 |
| 30 | 0.00054 | 0.0054 | 0.053 | 0.501 | 3.24 | 3.80 |
| 60 | 0.00173 | 0.0173 | 0.172 | 1.55 | 6.79 | 3.98 |
| 100 | 0.00376 | 0.0376 | 0.369 | 3.10 | 9.10 | 3.29 |
| 150 | 0.00658 | 0.0655 | 0.638 | 4.89 | 9.87 | 2.47 |
| 200 | 0.00950 | 0.0944 | 0.912 | 6.39 | 9.85 | |
| 250 | 0.0125 | 0.124 | 1.18 | 7.55 | 9.63 | |
| 300 | 0.0154 | 0.153 | 1.44 | 8.49 | 9.36 | |
| 365 1/4 | 0.0193 | 0.191 | 1.78 | 9.39 | 9.02 | |
| | | | $Pa^{233}$ | | | |
| 15 | $0.73\times10^{-3}$ | $0.73\times10^{-2}$ | $0.73\times10^{-1}$ | $0.73\times10^{0}$ | $0.71\times10^{1}$ | $0.552\times10^{2}$ |
| 30 | 1.24 | 1.24 | 1.24 | 1.24 | 1.18 | 0.741 |
| 60 | 1.82 | 1.82 | 1.82 | 1.81 | 1.66 | 0.755 |
| 100 | 2.15 | 2.15 | 2.14 | 2.12 | 1.87 | 0.622 |
| 150 | 2.28 | 2.28 | 2.28 | 2.24 | 1.90 | 0.466 |
| 200 | 2.32 | 2.32 | 2.32 | 2.27 | 1.87 | |
| 250 | 2.33 | 2.33 | 2.33 | 2.28 | 1.82 | |
| 300 | 2.33 | 2.33 | 2.33 | 2.27 | 1.77 | |
| 365 1/4 | 2.33 | 2.33 | 2.33 | 2.26 | 1.70 | |
| | | | $Th^{233}$ | | | |
| 15 | $1.39\times10^{-6}$ | $1.39\times10^{-5}$ | $1.39\times10^{-4}$ | $1.39\times10^{-3}$ | $1.38\times10^{-2}$ | $1.25\times10^{-1}$ |
| 30 | 1.39 | 1.39 | 1.39 | 1.39 | 1.37 | 1.14 |
| 60 | 1.39 | 1.39 | 1.39 | 1.39 | 1.34 | 0.95 |
| 100 | 1.39 | 1.39 | 1.39 | 1.38 | 1.31 | 0.75 |
| 150 | 1.39 | 1.39 | 1.39 | 1.38 | 1.27 | 0.56 |
| 200 | 1.39 | 1.39 | 1.39 | 1.37 | 1.24 | |
| 250 | 1.39 | 1.39 | 1.39 | 1.37 | 1.20 | |
| 300 | 1.39 | 1.39 | 1.39 | 1.37 | 1.17 | |
| 365 1/4 | 1.39 | 1.39 | 1.39 | 1.36 | 1.11 | |

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## Table V

FACTORS USED TO CALCULATE 23 FISSION PRODUCT ACTIVITIES FOR A FLUX OF $10^{12}$ FROM FISSION PRODUCT ACTIVITIES FOR A FLUX OF $10^{13}$

| | (1) | (2) | (1) / (2) |
|---|---|---|---|
| Irradiation Period | Thermal Flux Neutrons / Cm.$^2$ / Sec. | | |
| (Days) | $10^{12}$ | $10^{13}$ | Factor |
| 10 | $0.015 \times 10^{-5}$ | $0.015 \times 10^{-3}$ | $1.000 \times 10^{-2}$ |
| 15 | 0.051 | 0.051 | 1.000 |
| 20 | 0.132 | 0.132 | 1.000 |
| 30 | 0.389 | 0.382 | 1.018 |
| 40 | 0.958 | 0.937 | 1.022 |
| 60 | 3.79 | 3.65 | 1.016 |
| 80 | 9.89 | 9.77 | 1.012 |
| 100 | 21.24 | 21.01 | 1.011 |
| 150 | 84.60 | 83.44 | 1.014 |
| 200 | 223.0 | 218.5 | 1.0207 |
| 300 | 851.6 | 824.7 | 1.0326 |
| 365 1/4 | 1677.9 | 1612.5 | 1.0406 |

(1) Cumulative addition of column 3 - Table III

(2) Cumulative addition of column 4 - Table III

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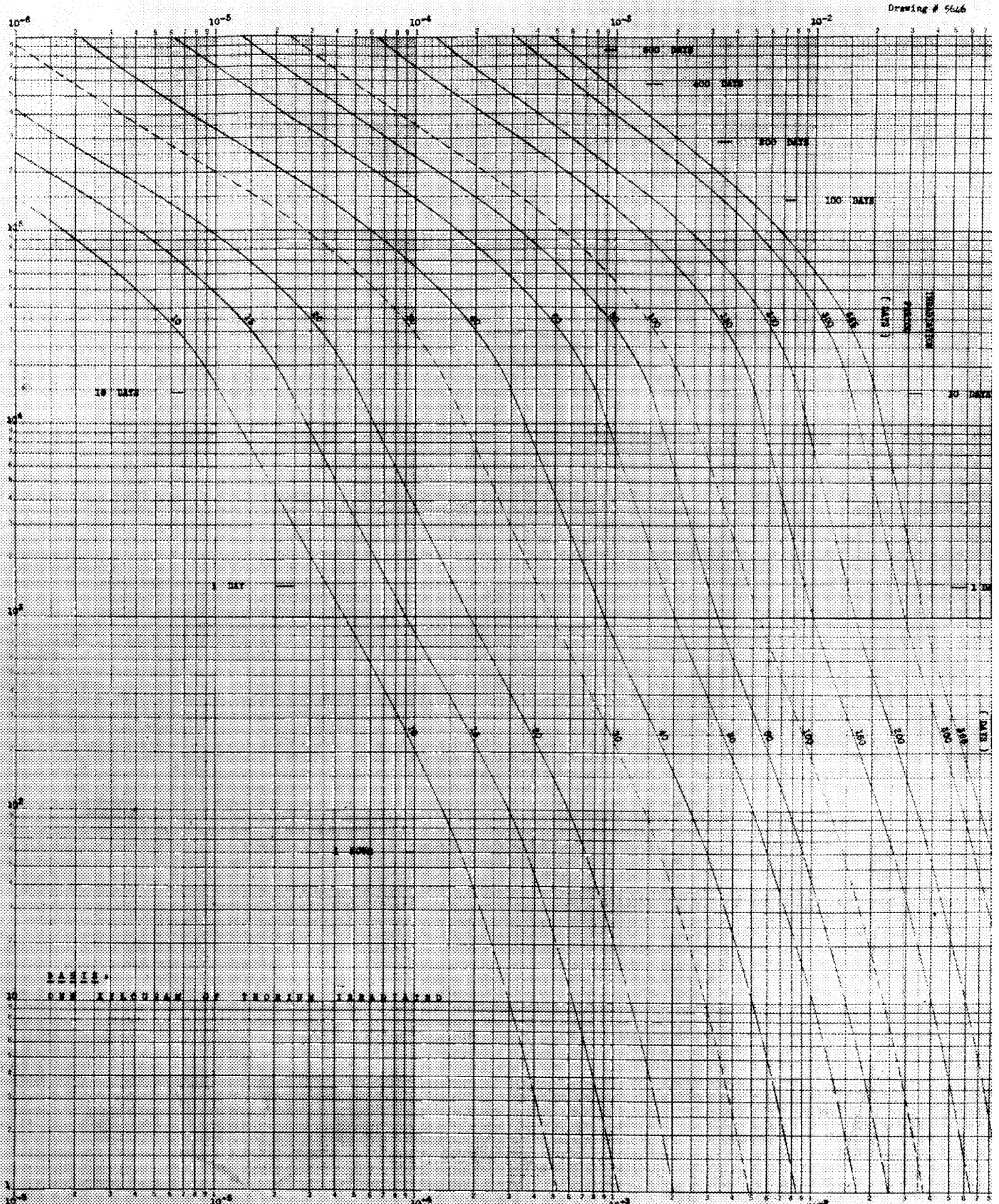
[redacted]

Drawing # 5646




BASIS:
ONE KILOGRAM OF URANIUM IRRADIATED

FIGURE 1 DECAY CURVES FOR 25 FISSION PRODUCTS ( THERMAL FLUX , $10^{12}$ NEUTRONS / CM.$^2$ / SEC. )

G.H.H. 4-9-46

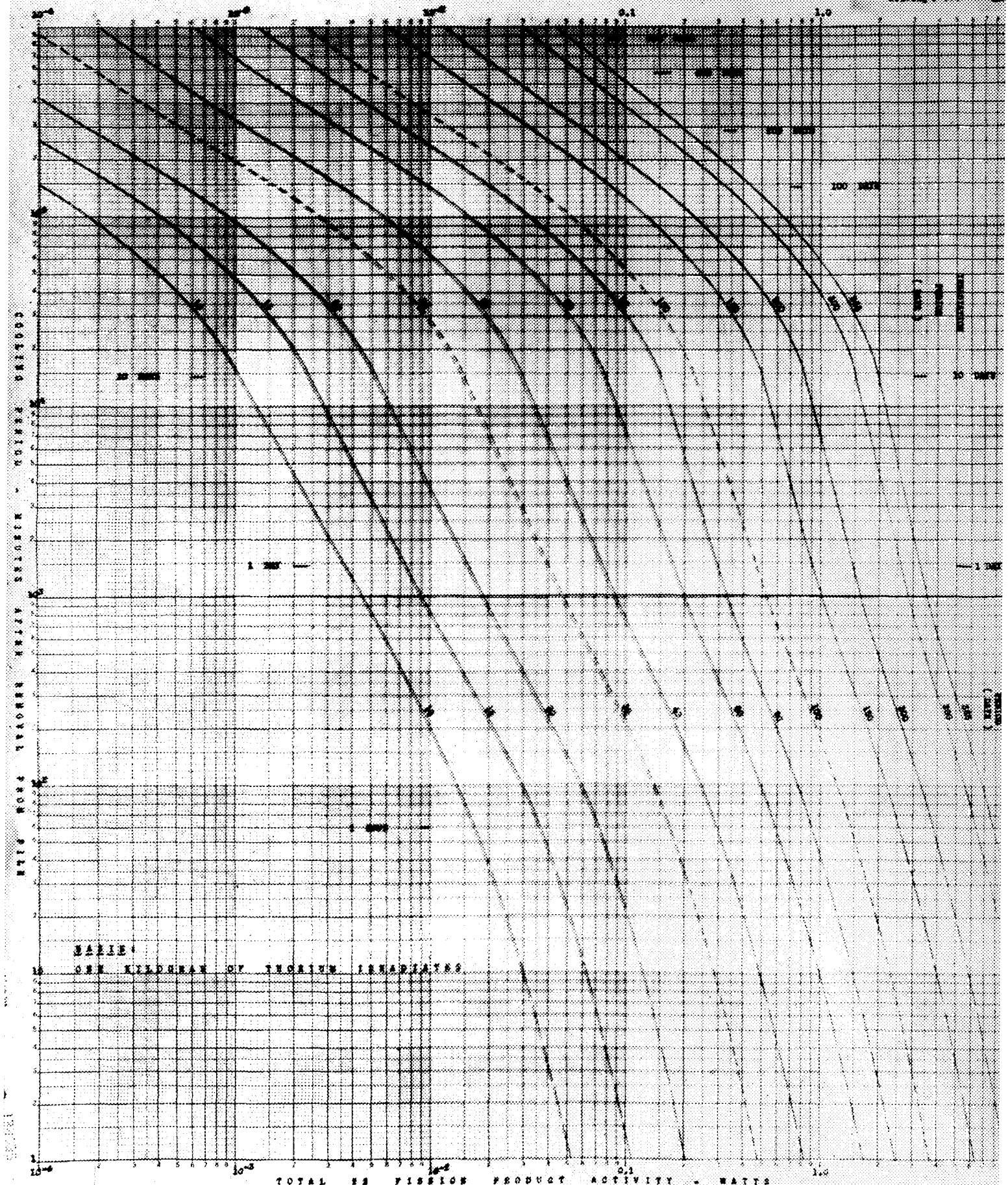



FIGURE 2 DECAY CURVES FOR ββ FISSION PRODUCTS

J.R.H. 4-8-41

[redacted]

Drawing # 5628

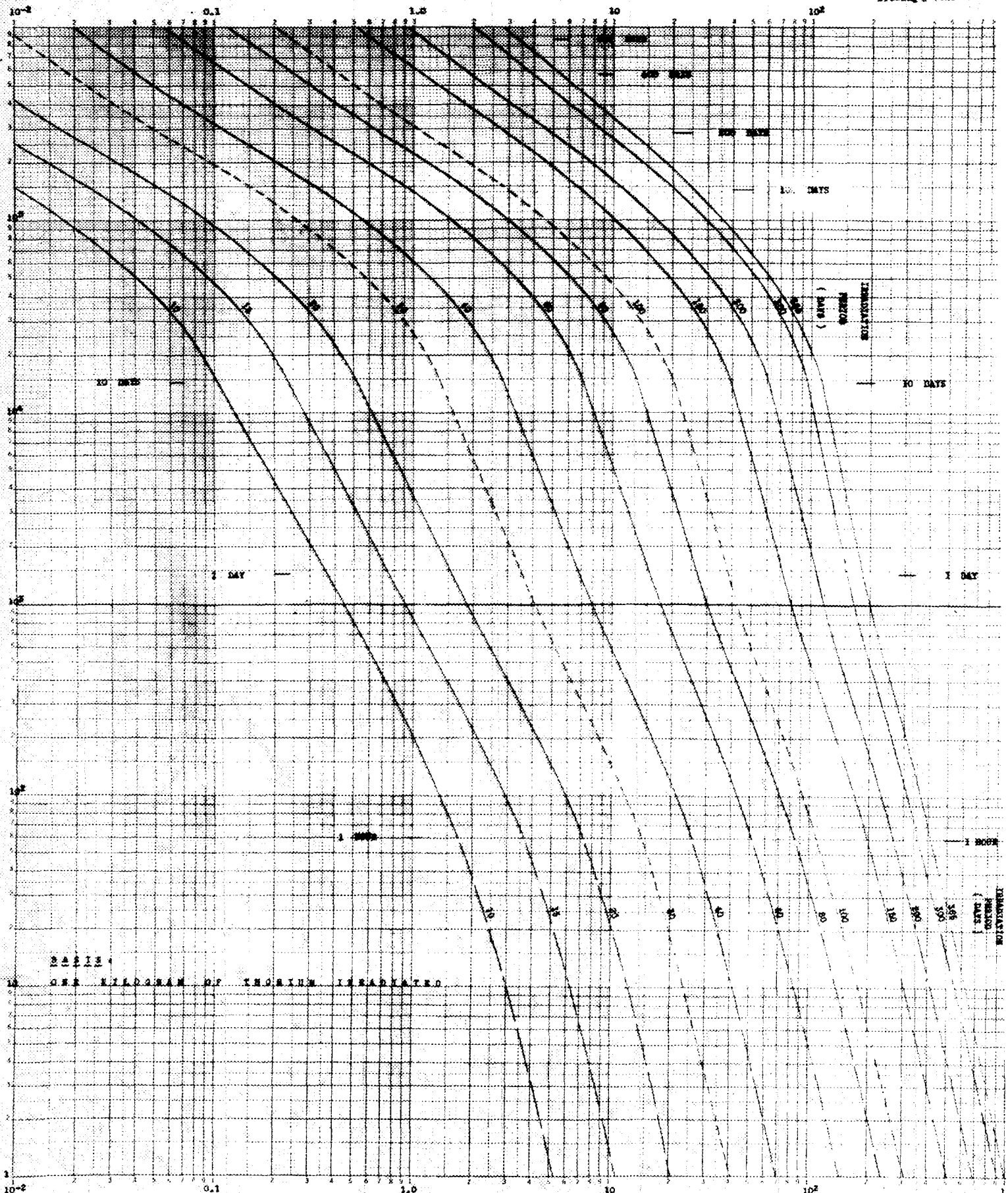



FIGURE 3 DECAY CURVES FOR 23 FISSION PRODUCTS ( THERMAL FLUX : $10^{14}$ NEUTRONS / CM.$^2$ / SEC. )

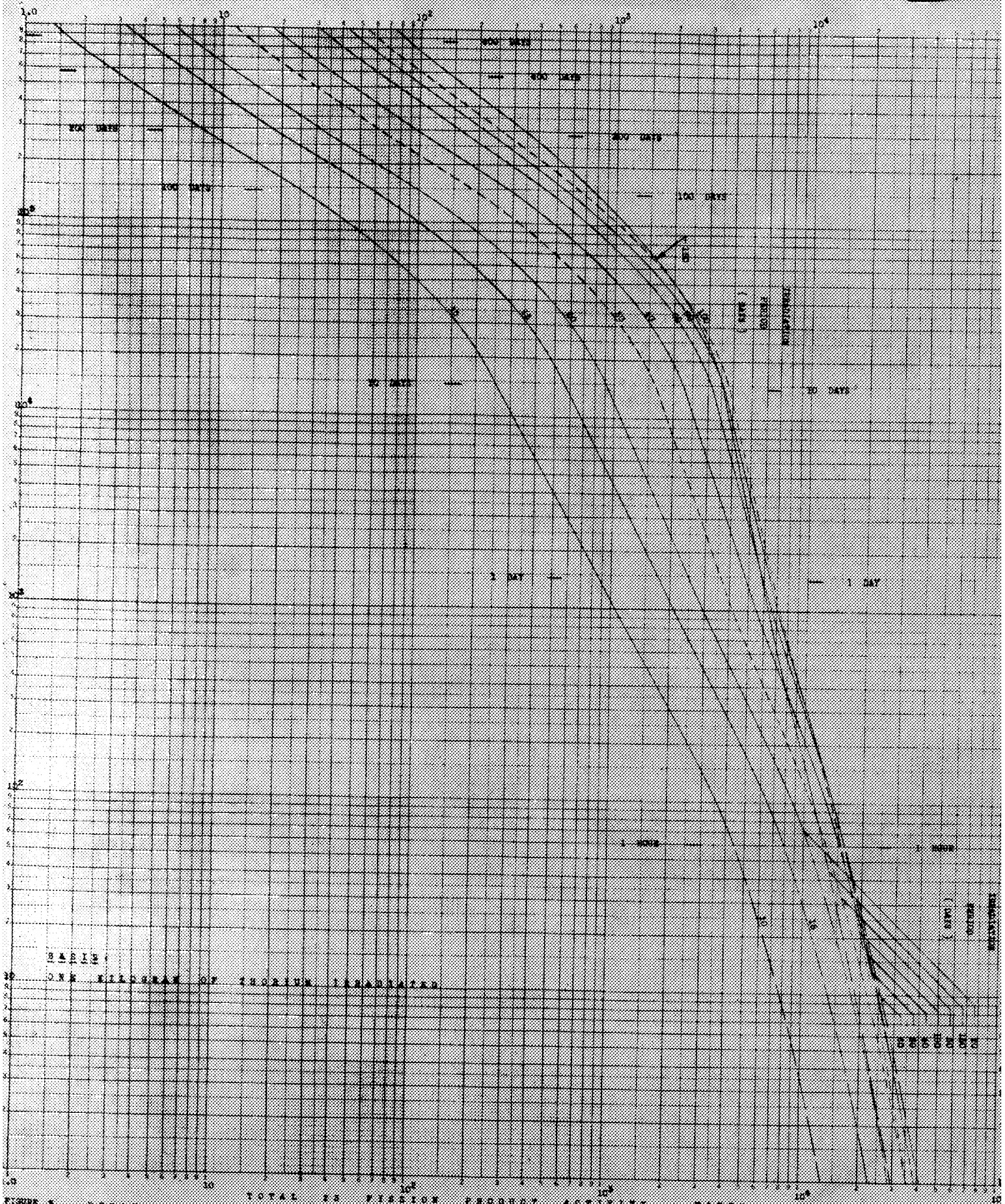
G.H.H. 4-9-48

Drawing # 5639 [redacted]

FIGURE 4 DECAY CURVES FOR 23 FISSION PRODUCTS

TOTAL 23 FISSION PRODUCT ACTIVITY - WATTS (THERMAL FLUX, $10^{13}$ NEUTRONS / CM.$^2$ / SEC.)

Drawing # 5650 [redacted]




TOTAL 23 FISSION PRODUCT ACTIVITY WATTS

FIGURE 5 DECAY CURVES FOR 23 FISSION PRODUCTS ( THERMAL FLUX : $10^{16}$ NEUTRONS / CM.$^2$ / SEC. )

G.H.H. 4-10-48

[redacted] Drawing # 565

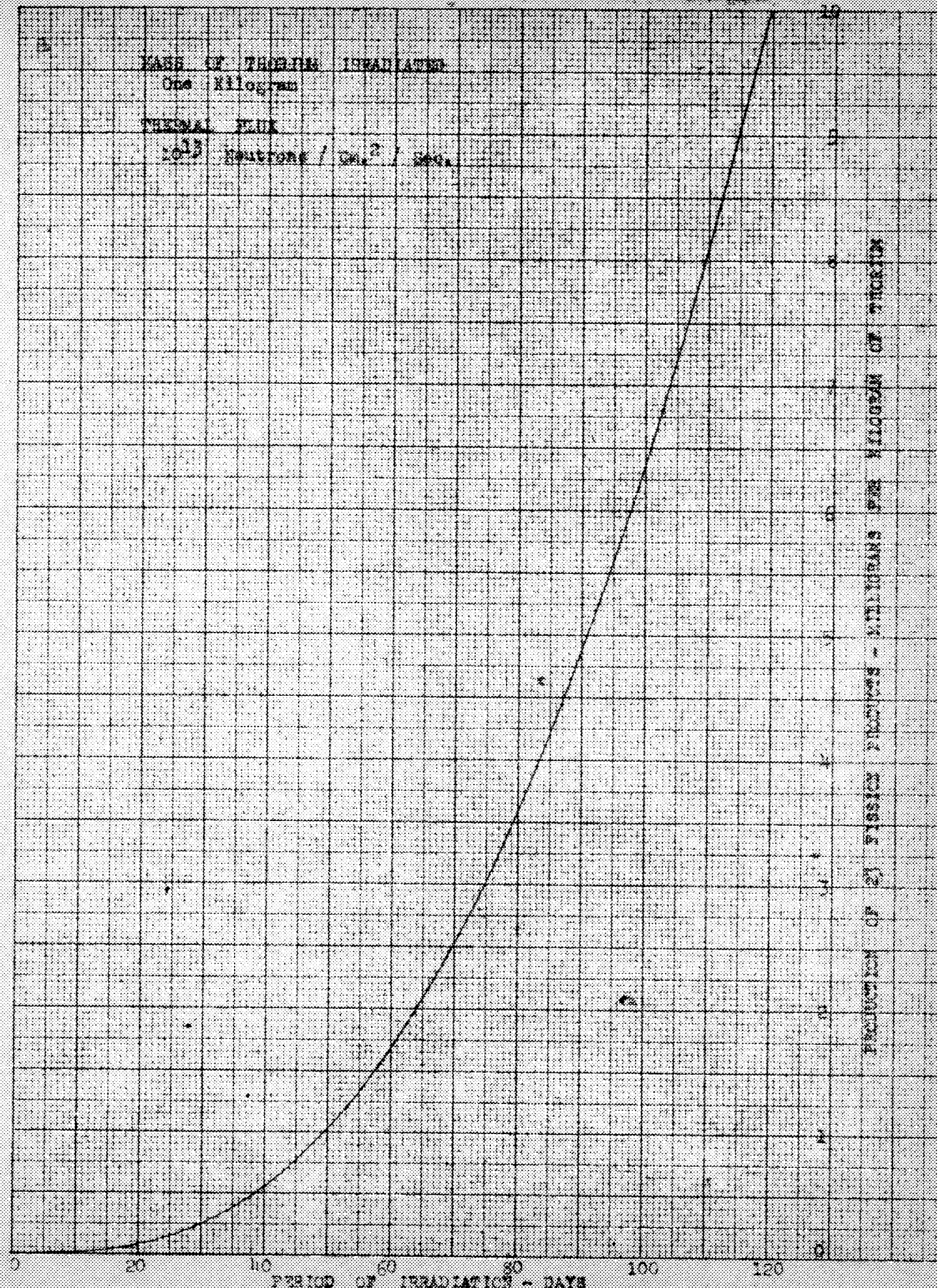
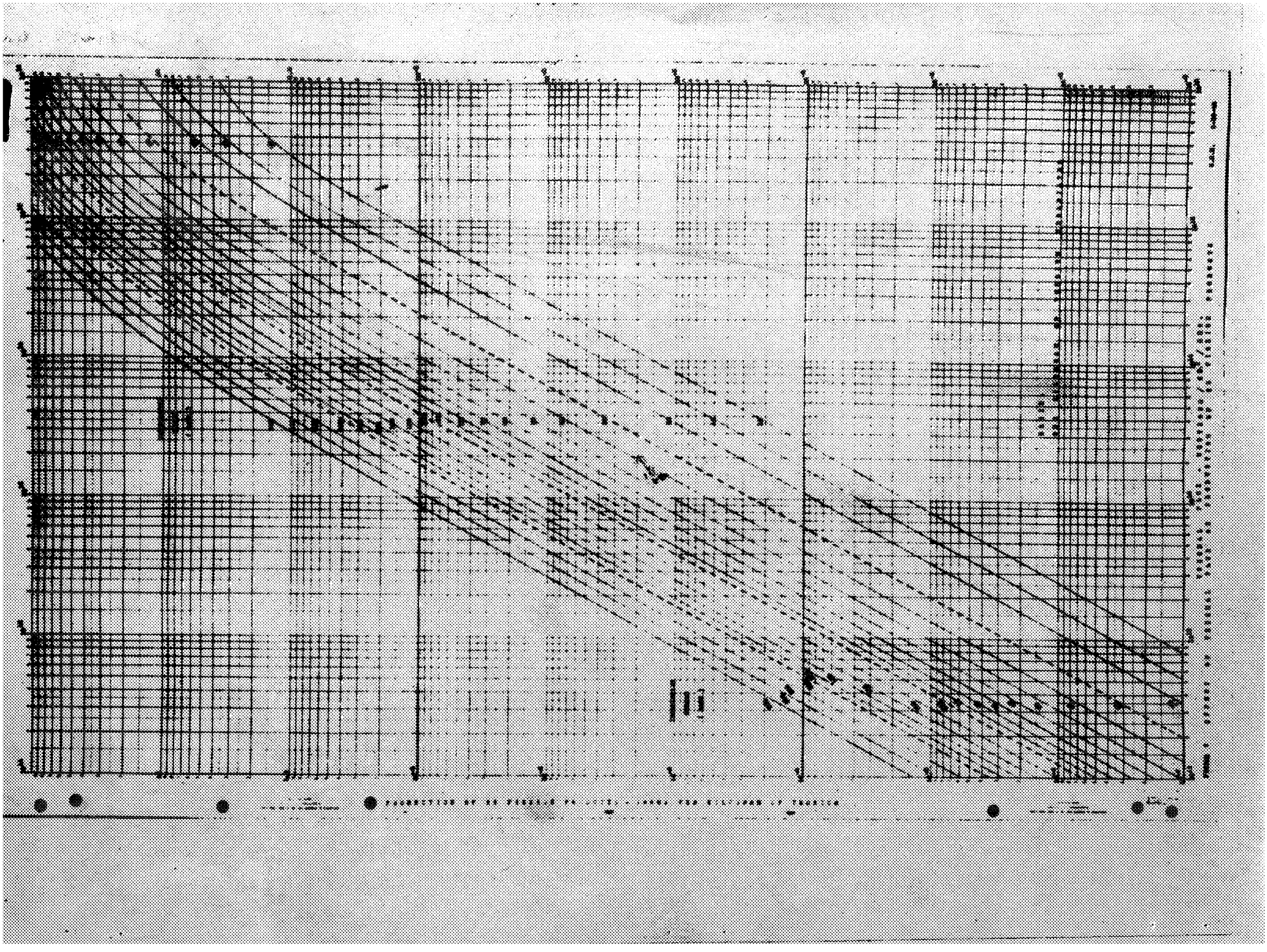
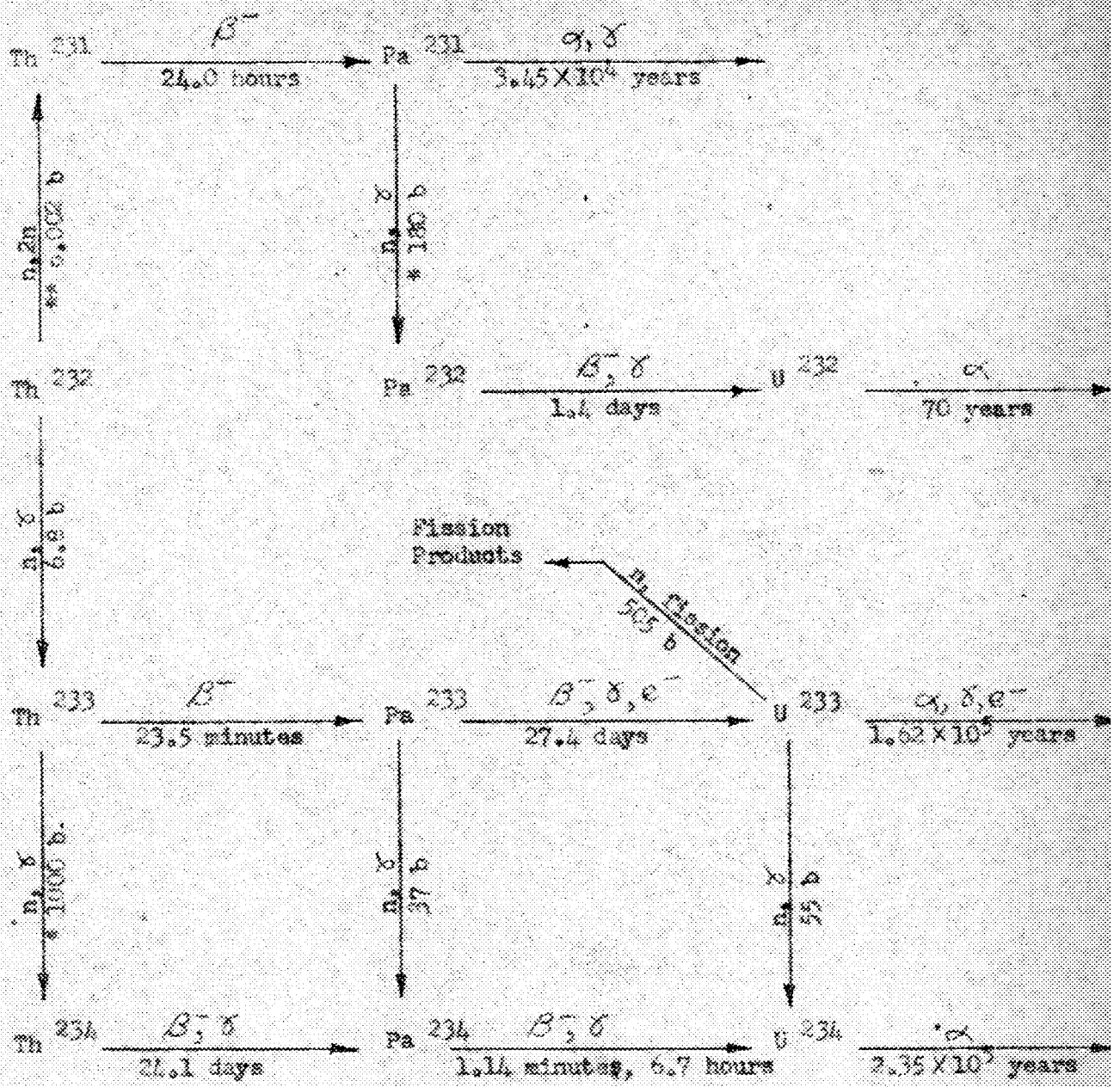



Figure 6 A GROWTH CURVE FOR 23 FISSION PRODUCTS C.U.M. 3-26-48






Note: * Indicates an approximate value obtained by members of the Chemistry Division ( at Argonne.
** Indicates an estimated value.
Half-lives are based on reference 7.
Cross-sections are based on references 6, 8 and 9.

FIGURE 8

SOME NUCLEAR REACTIONS RESULTING FROM THE IRRADIATION OF NATURAL THORIUM ( $Th^{232}$ )

Drawing # 5627

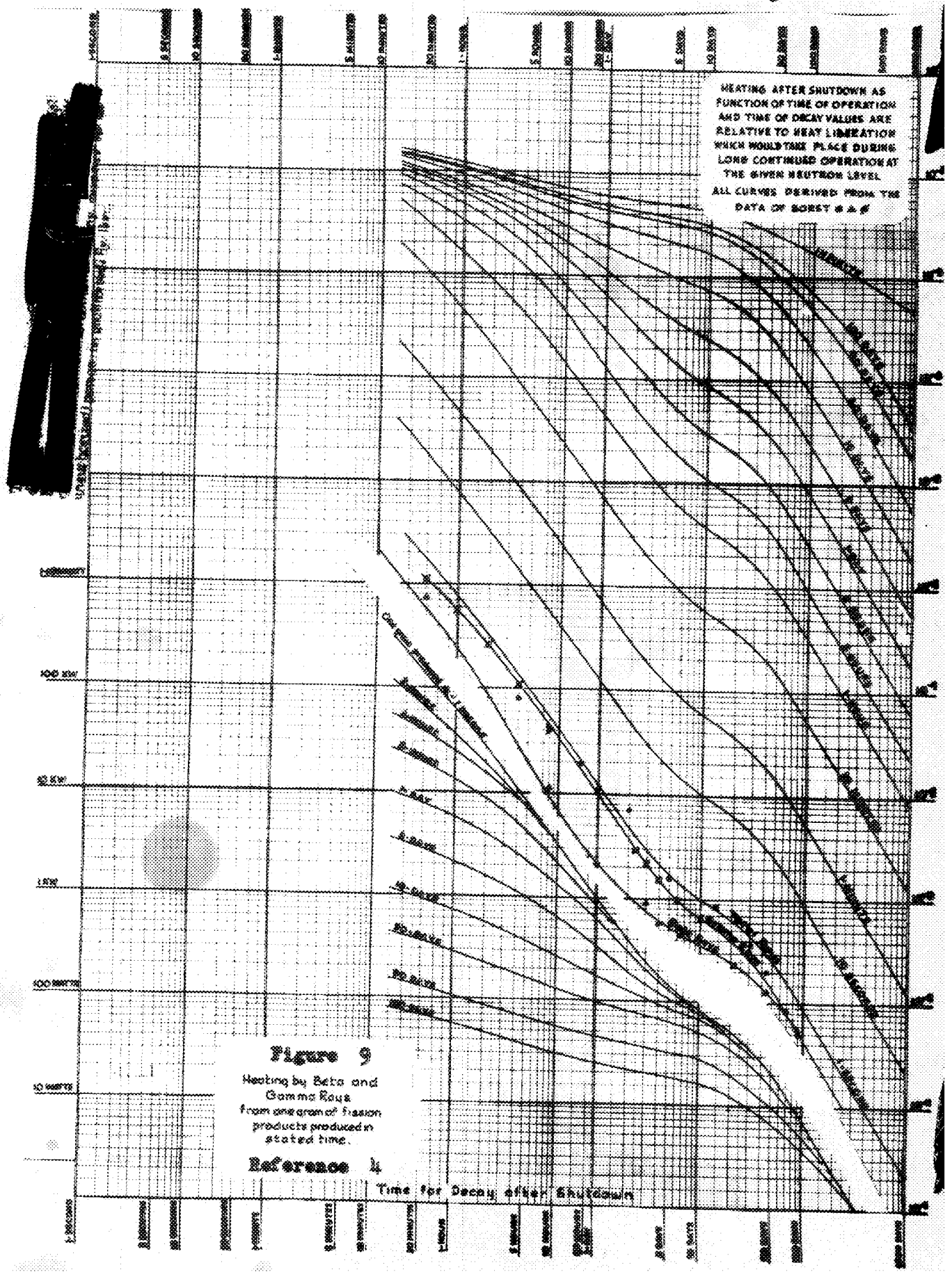



**Figure 9**

Heating by Beta and Gamma Rays from one gram of fission products produced in stated time.

**Reference 4**

[redacted]

Drawing # 5653

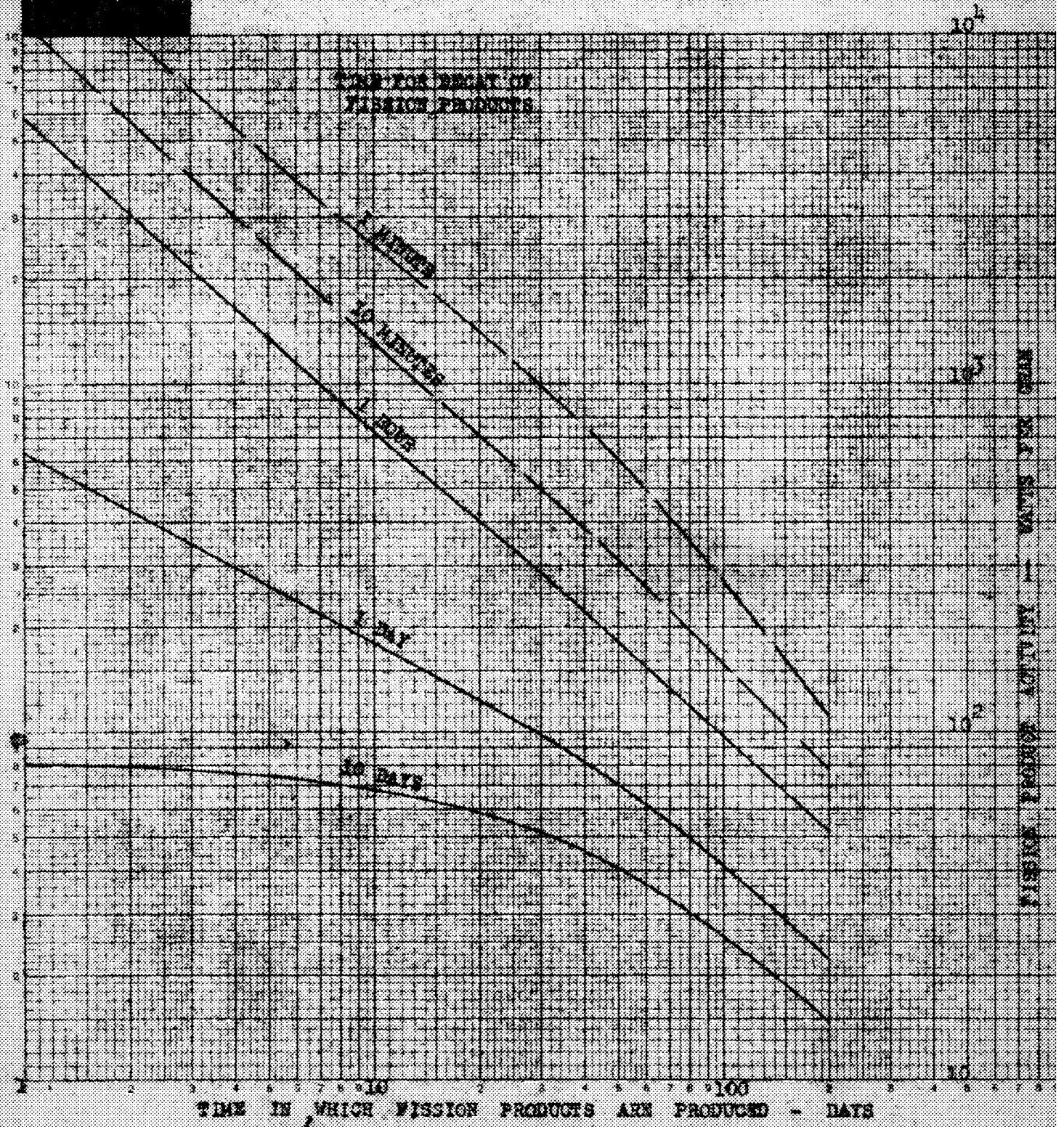



Fig.10 HEATING BY BETA AND GAMMA RAYS FROM FISSION PRODUCTS PRODUCED IN STATED TIME (CROSS-PLOT OF BORST-WHEELER CURVES)

Drawing # 5654

[redacted]

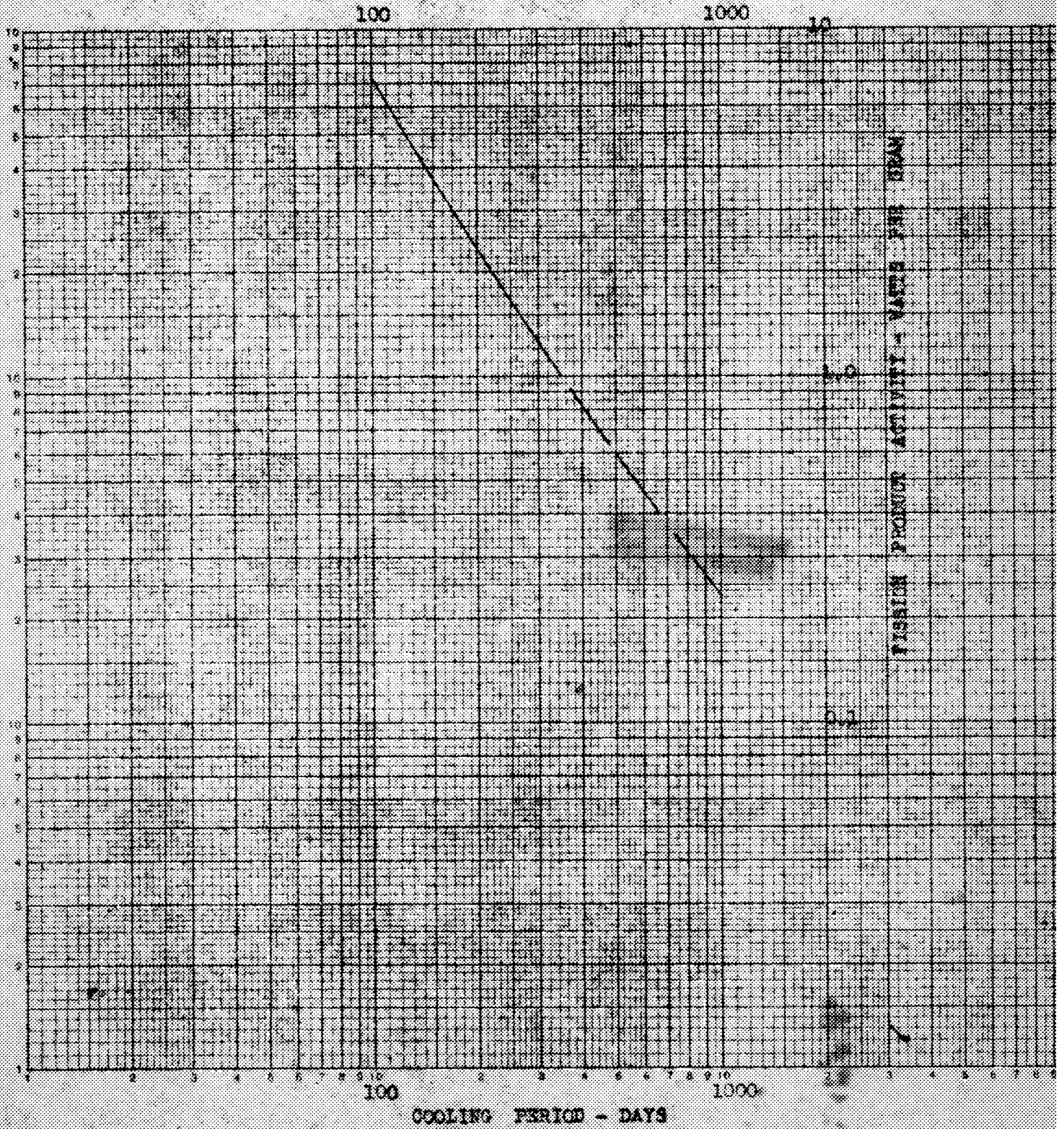



Figure 11 EXTRAPOLATION OF BORST - WHEELER "BOMBER CURVE"