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ABSTRACT

The irradiation of ytterbium-168 in the Hollow Fuel Element facilities of the AAEC research reactor HIFAR was studied to determine the optimum conditions for the production of ytterbium-169 for industrial radiography sources.

The thermal neutron activation cross-section of ytterbium-168 is 3,470 barns; in core positions in the reactor this is significantly increased by the contribution of epithermal neutron activation. Flux depression and target burnup are such that the activation formula normally used for radioisotope production calculations is inadequate. Therefore, a modified formula which includes corrections for these effects, combined with iterative computer calculations to correct for effects resulting from the change in target mass during irradiation, was used to calculate ytterbium-169 yields.

It was found that for targets containing 10 mg and 20 mg of Yb_2O_3, there is an optimum ytterbium-168 enrichment of approximately 20 per cent. The activation of such targets can be increased significantly by diluting the Yb_2O_3 with a low neutron cross-section material such as graphite. The optimum irradiation time in HIFAR in a thermal neutron flux of 1.0×10^{14} n $cm^{-2}s^{-1}$ is approximately one operating period of 24 days.

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BURNUP; CROSS SECTIONS; GAMMA RADIATION; GRAPHITE; HIFAR REACTOR; ISOTOPE PRODUCTION; ISOTOPE SEPARATION; NEUTRON BEAMS; NEUTRON FLUX; NUCLEAR REACTIONS; RADIATION SOURCES; YTTERBIUM 168; YTTERBIUM 169

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1. INTRODUCTION

Ytterbium-169 is an ideal radioisotope for the radiography of thin sections of aluminium, steel and light alloys (Clarke & Coenraads 1967, Halmshaw, Manly & Dowd, 1971, Wood & Gillespie 1972). It is produced in a reactor by the irradiation of ytterbium-168 (^{168}Yb (n,γ) ^{169}Yb) for which the thermal neutron activation cross-section is 3,470 barns (Sims & Juhnke 1970). Because of this large cross-section, target burnup during an irradiation in a high neutron flux is considerable and must be assessed together with the flux depression when estimating target activation. An activation model, developed originally for the study of the activation of iridium-191, has been used to calculate the activation of ytterbium-168 in the AAEC research reactor HIFAR. By combining these theoretical studies with the results of experimental irradiations, the optimum irradiation conditions and target composition have been determined.

2. ACTIVATION MODEL

2.1 The Basic Equation

Provided that there is no significant flux depression, target activation, including a correction for burnup, is given by:

$$S = \frac{No\ \sigma\ \phi\ \lambda}{3.7 \times 10^{10} A\ (\lambda - \phi\sigma)} \left(e^{-\phi\sigma t} - e^{-\lambda t}\right)$$

where S = activity in curies per gram of target element

ϕ = thermal neutron flux in n cm^{-2}s^{-1}

σ = target activation cross-section in cm^2

A = atomic weight of target

t = irradiation time in seconds

$\lambda = \frac{0.693}{\text{Half-life}}$ = decay constant of product in s^{-1}

No = Avogadro's number

A feature of the activation process calculated by this formula is the absence of a saturation activity similar to that obtained under low flux no burnup conditions. If the specific activity of an irradiated target is plotted against the irradiation time (Figure 1), it can be seen that for any given flux there will be an optimum irradiation time, and that the optimum time is flux dependent. The higher the flux the shorter is this optimum time.

The curves of Figure 1 are for negligible target mass for which there is no flux depression. The activation of actual targets is affected greatly by this effect. In studies on iridium activation (Hetherington 1969) it was found that the position of the peak of the activation curve was dominated by the flux at the surface of the target because of the greater surface activation. However the total activity produced was more easily related to the average flux in the target. This suggested an activation formula in which the surface flux ϕ_s would be used in those terms affecting the general shape of the activation curve, and the average flux in the sample ϕ_{av} would dominate the average activation. Since the flux is strongly attenuated in the target it was assumed that the activation could be calculated separately for a thin outer shell of volume v_s, in which the average flux is ϕ_s, and the interior volume v_i, in which the average flux is ϕ_i. If $\phi_i << \phi_s$, and assuming that burnup in the interior is negligible (hence $\phi_i\sigma << \lambda$), it can be shown that the activation equation becomes

$$S = \frac{No\ \sigma\ \phi_{av}\lambda}{3.7 \times 10^{10} A\ (\lambda - \phi_s\sigma)} \quad (e^{-\phi_s\sigma t} - e^{-\lambda t})$$

where $\phi_{av} = \dfrac{\phi_s v_s + \phi_i v_i}{\text{Total Volume}}$

It was found that, for iridium-192, this formula gave a calculated activity and optimum irradiation time in good agreement with observed activation results (Table 1). The calculations assumed a reactor period of 24 days' operation and 4 days' shutdown. As the capture of neutrons by iridium-192 (cross-section 1,100 barns) has been ignored, the long term activation will be overestimated.

In addition to the results shown in Table 1, the formula has proved to be very reliable in the calculation of routine iridium-192 source production. In view of this, it was decided to apply it to the calculation of ytterbium-168 activation.

If the target nuclide is less than 100 per cent of the total target element, the formula becomes

$$A = \frac{No\ \sigma_E\ M\ \phi_{av}\ \lambda}{3.7 \times 10^{10} A\ (\lambda - \phi_s\sigma)} \quad (e^{-\phi_s\sigma t} - e^{-\lambda t})$$

where A = activity produced in curies

σ_E = effective cross-section of the target element in cm^2 and is the product of σ and the fractional abundance of the target nuclide in the element

M = mass of target element in grams

Hence, provided the cross-section and the appropriate flux terms are known, the activation of any target can be calculated.

2.2 Effective Activation Cross-Section

According to Connolly, Culley & McCulloch (1968) the neutron spectrum in HIFAR consists of a Maxwellian distribution at thermal energies joined to a $\frac{1}{E}$ distribution of slowing down (epithermal) neutrons. Under these conditions, the effective activation cross-section can be calculated by the method of Westcott (1957, 1960). The total cross-section σ is given by

$$\sigma = \sigma_o (g + rs),$$

where σ_o is the 2,200 m s^{-1} cross-section, g and s are functions of temperature which depend on the departure of the cross-section from a $\frac{1}{v}$ form in the thermal and epithermal regions respectively, and r represents the relative density of the epithermal component of the flux. In practice, since neutron temperatures are not measured, s is usually replaced by a temperature independent term s_o such that

$$s = s_o\left(\frac{T}{To}\right)^{½},$$

where T is the actual neutron temperature and To is the temperature corresponding to a Maxwellian velocity distribution having a peak at 2,200 m s^{-1}.

The Westcott formula then becomes

$$\sigma = \sigma_o\left(g + r \left(\frac{T}{To}\right)^{½} s_o\right) .$$

The combined term $r\left(\frac{T}{To}\right)^{½}$ is then taken as the epithermal flux index and can be measured by the cadmium ratio technique (Westcott, Walker & Alexander 1958). Values of this index for HIFAR have been published by Connolly *et al* (1968).

The value of s_o can be calculated from the reduced resonance integral Σ^1 using the relation

$$s_o = \frac{2}{\sqrt{\pi}} \frac{\Sigma^1}{\sigma_o} \qquad \text{(Westcott 1957, 1960).}$$

The resonance integral is defined by

$$\Sigma = \int_{E_c}^{\infty} \sigma(E) \frac{dE}{E}$$

where σ_E is the cross-section at energy E and E_c is the effective lower limit to the $\frac{1}{E}$ distribution of epithermal neutrons. The reduced resonance integral is this value minus the $\frac{1}{v}$ cross-section component. The reduced resonance integral for ytterbium-168 was calculated from cross-sections generated by the computer code GUNYA (Ferguson 1969). This value was preferred to the experimental determination of Sims & Juhnke (1970), since the position of the resonance at 0.597 eV is not compatible with the cadmium ratio technique.

2.3 Flux Depression

The activation of typical ytterbium-168 targets is affected considerably by depression of both the epithermal and thermal conponents of the neutron flux. To allow for depression of the epithermal flux, a factor G_r is included in the Westcott formula which then becomes

$$\sigma = \sigma_o \left(g + G_r\, r\left(\frac{T}{To}\right)^{½} s_o\right) .$$

As outlined by Stewart & Zweifel (1958) and Baumann (1963), G_r can be expressed as a function of τ:

$$\tau = \frac{2V}{S} \; Na \; \sigma_a^{max}$$

where Na = number of target atoms per cm^3

V = target volume in cm^3

S = surface area in cm^2.

σ_a^{max} = the peak resonance absorption cross-section.

The value of σ_a^{max} was calculated from published resonance data (Hughes & Swartz 1960), using the Breit-Wigner formula, and found to be 187,500 barns.

For the case of HIFAR, the recommended value of $r\left(\frac{T}{To}\right)^{½}$ is 0.119 (Connolly *et al* 1968). Using the GUNYA cross-sections, the value of g for ytterbium-168 was found to be close to unity, and g = 1 was used in the Westcott formula. For a thermal cross-section of 3,470 barns and a reduced resonance integral of 16,060 barns, s_o is equal to 5.22. Hence, the effective cross-section to be used in calculating the activation of ytterbium-168 is given by $\sigma = \sigma_o\ (1 + 0.621\ G_r)$. In practice, the values of G_r were such that the epithermal contribution to the effective cross-section was less than 15 per cent. In view of this it was decided to equate σ to the thermal cross-section when calculating the thermal flux depression. Consequently ϕ_s and ϕ_{av} are derived from the HIFAR thermal (2,200 m s^{-1}) flux.

In a more rigorous treatment thermal flux depression depends on the value of σ_o.

The total perturbation of the thermal neutron flux by a target is the combination of two effects. The flux at the surface is reduced by a factor

H due to the presence of the source in the flux, and the average internal flux in the sample is reduced by a factor G due to neutron absorption.

The total flux perturbation F is the product of the two separate effects,

i.e. $F = GH$

If the undisturbed flux is ϕ_o then

$$\phi_s = H\phi_o$$

and $$\phi_{av} = F\phi_o$$

Both G and H can be found as functions of b_{avg} which is the number of neutron relaxation lengths in the average path length through the target, thus

$$b_{avg} = \frac{4V}{S} \Sigma_a$$

where Σ_a = macroscopic thermal neutron cross-section of the target material in cm^{-1}. It is the product of the number of ytterbium-168 atoms per cm^3 of total volume and the ytterbium-168 cross-section σ. Of the methods available for the calculation of flux depressions, the simplest and most widely accepted for isotope production calculations are those of Lewis (1955) and Nisle (1960). Values of H were found using curves published by Lewis while the Nisle formula was used to calculate G,

i.e. $$G = \frac{1 - e^{-b_{avg}}}{b_{avg}}$$

2.4 Enrichment Change During Irradiation

As it stands, the activation formula does not allow for the progressive change in the effective cross-section σ_E, and hence in b_{avg}, due to the reduction in available ytterbium-168 target. A change in b_{avg} will alter the values of ϕ_{av} and ϕ_s.

To allow for this effect, an iterative method of calculation using an IBM360 computer was used. For an initial set of conditions the activation formula was used to calculate the activity produced in one day's irradiation. A separate calculation gave the change in target nuclide abundance. This is given by

$$\frac{E}{E_o} = e^{-\phi_{av} \sigma t}$$

where E_o = initial enrichment

E = target enrichment after irradiation

By using the Westcott method of dealing with epithermal neutron absorption, the value of σ depends slightly on target enrichment. However the change in G_r with target burnup is small and a constant value of σ is used, depending on the initial value of enrichment for a given target geometry. The activity produced in the first day was then assumed to decay for the remainder of the total activation period and an additional activation was calculated for the second day using the revised value of the enrichment. This procedure was repeated for each day of irradiation. With each change in enrichment ϕ_s and ϕ_{av} were also recalculated. For irradiation longer than one reactor operating period, allowance was made for decay during the four-day shutdown. The total activity produced is then the sum of the contributions of each day's irradiation still present on completion of the irradiation.

3. APPLICATION OF MODEL TO PRODUCTION PROBLEMS

3.1 Target Material and Ytterbium-168 Enrichment

Ytterbium-169 sources are produced by the activation of compressed and sometimes sintered ytterbium oxide (Yb_2O_3). The abundance of ytterbium-168 in natural ytterbium is 0.138 per cent, so to produce practical radiography sources enriched target material must be used. An increase in enrichment increases neutron absorption and, as this increases the flux depression, the point could be reached where a further increase in ytterbium-168 enrichment would yield little increase in ytterbium-169 production. Also, for a given target size, an increase in enrichment increases epithermal neutron absorption. The value of G_r is reduced and the value of σ, calculated by the Westcott formula, approaches σ_o.

The activation model outlined above was used to calculate the effect of enrichment on the activity produced for four practical target types irradiated in a HIFAR Hollow Fuel Element position.

For an undisturbed thermal flux of 1.0×10^{14} n $cm^{-2}s^{-1}$, the activity produced in one operating period was calculated for 10 mg and 20 mg targets with the ytterbium-168 content varied from natural abundance to 100 per cent. The effect of diluting the target with non neutron absorbing material (that is reducing the value of Σ_a) was also investigated. It was found that, for the smallest practical targets of the given mass, the optimum enrichment is approximately 20 per cent (Figure 2). Dilution produces an increase in both the activity and optimum enrichment. Provided, therefore, that increased source size does not affect its radiographic properties, there is more to be gained by dilution than by increasing the enrichment beyond the small source optimum of 20 per cent. This is an important factor if source cost is considered. The cost per mg of the enriched target materials is approximately proportional to the enrichment. Thus, for a 20 mg, 20 per cent ytterbium-168 enriched target, increase in diameter by dilution from 1.5 mm to 2.0 mm increases the activity by a factor of 1.5 with virtually no increase in target cost. A twofold increase in the undiluted target only increases the activity by 30 per cent but doubles the target cost. In view of these results it was decided to limit further consideration to target material having 20 per cent ytterbium-168 enrichment only.

3.2 Target Irradiation Time

The activation formula with iterative correction for ytterbium-168 burnup and flux depression was used to calculate the long term activation of four target types based on 20 per cent ytterbium-168 enriched ytterbium oxide in a HIFAR Hollow Fuel Element.

The target mass, dimensions and cross-sections corrected for epithermal neutron activation are given below

Mass (mg)	Dimensions (Rt. Cylinder) (mm x mm)	Effective Cross-section (barns)
10	1.2 x 1.2	3,740
10	2.0 x 2.0 *(D)*	3,990
20	1.5 x 1.5	3,690
20	2.0 x 2.0 *(D)*	3,860

(D) indicates diluted target.

The activation was calculated for a range of neutron fluxes up to the maximum practical Hollow Fuel Element flux of 1.0×10^{14} n $cm^{-2}s^{-1}$. The results are shown graphically in Figures 3 to 6 where activity has been plotted as a function of time in the reactor. The zigzag form of the curves is due to the significant ytterbium-169 decay during the four-day shutdown at the end of each operating period. At high fluxes and long irradiation times the steps in the curve are masked by the effect of burnup whereby the rate of ytterbium-169 production is ultimately negligible compared with the rate of decay.

It can be seen that there would be little advantage in irradiations lasting longer than two operating periods. As most of the activation occurs in the first period, a single period irradiation would be adequate in most cases. It is obvious that there is a considerable improvement in the activity produced when diluted targets are used.

In source production, the question often arises as to whether spent sources should be reirradiated. The answer depends on whether the activity produced on reirradiation is comparable with the original activity. The activity produced in the first, second and third irradiations, each of one 24-day period, in a flux of 1.0 x 10^{14} n $cm^{-2}s^{-1}$ was calculated for the four listed source types. It was assumed that at the start of each irradiation the source activity was zero. The results of these calculations are summarised in Table 2; they indicate that reirradiation would not be practical.

4. EXPERIMENTAL SOURCE PRODUCTION AND MEASUREMENT

4.1 Target Irradiation

Because of the high cost of the target material, no large scale experimental activation programme could be undertaken. However, a number of irradiations were carried out to produce sources for the assessment of radiographic potential and for comparison with theoretical estimates. In some cases the target mass varied somewhat from the desired value due to fabrication difficulties. Hence, the dimensions which are given in Table 5 are nominal values only. Graphite was used to dilute the Yb_2O_3 to produce sources of other than minimum dimensions.

The irradiations were carried out in a Hollow Fuel Element Facility in a nominal thermal neutron flux of 1.0 x 10^{14} n $cm^{-2}s^{-1}$ with an epithermal component as outlined in Section 2.2. The irradiation time in all cases was one reactor operating period.

4.2 Activity Measurement

It has long been the practice to rate radiography sources in terms of effective or 'equivalent' activity (ICRU 1962). The equivalent activity is determined by dividing the measured exposure rate at one metre from the source by the Specific Gamma Ray Emission (Γ). However, the equivalent activity does not provide a means of comparison between theory and experimental activation - the total activity must be known.

Because of self-absorption, particularly of the low energy photon emissions of ytterbium-168, the equivalent activity of solid sources is considerably less than the theoretical disintegration rate. However, by using an effective Specific Gamma Ray Emission (Γ_{eff}) the total activity may be determined from the measured output. This effective Specific Gamma Ray Emission can be defined as the actual exposure rate in R h^{-1} per actual curie at one metre from the encapsulated source. Its value depends on the source form, dimensions and encapsulation.

Experimental values of Γ_{eff} were found for each type of source irradiated. The measurements were made on low activity sources which were either decayed high activity sources or sources specially prepared for the purpose.

The gamma ray spectrum of each source was obtained with a Ge(Li) detector of known energy response. The counts obtained in each peak were corrected for detector efficiency to obtain the relative gamma emission for each energy. These relative emissions were normalised to correspond to the expected attenuated emission of the highest energy gamma rays of ytterbium-169 (0.308 MeV) which was calculated by the method of Ayers, Lewis & Stevenson (1958). The value of Γ_{eff} was calculated for the emitted spectrum using the gamma ray exposure rate data of Slack & Way (1959). This value is the sum of the contribution of each component to the total emission from the source

i.e. $\Gamma_{eff} = \Sigma n_E \Gamma_E$

where n_E is the number of photons of energy E emitted from the source and Γ_E is the Specific Gamma Ray Emission for a source emitting one photon of energy E per disintegration. The calculation of Γ_{eff} for a 10 mg source (1.2 mm x 1.2 mm) is summarised in Table 3. The values of Γ_{eff} for all investigated source types are given in Table 4.

The efficiency of emission is much higher in sources where the Yb_2O_3 has been diluted with graphite.

The actual output of each source investigated was measured at a distance of one metre using a Victoreen Ionisation Chamber. The activity was then given by

$$\frac{\text{Exposure Rate at One Metre}}{\text{Effective Specific Gamma Ray Emission}}$$

5. COMPARISON WITH THE THEORETICAL MODEL

The activity produced in a number of irradiations is compared with calculated activities in Table 5. In some cases the agreement is not as good as that obtained for iridium-192 (Table 1). However, the iridium results represent the average of a large number of irradiations in which there were actually some significant variations from the mean. The number of ytterbium irradiations has been limited for the reasons mentioned previously. The larger discrepancies occur with the smaller undiluted targets, where the errors in estimation of the flux depression are greatest due to the uncertainty in the exact source size and therefore in the density and macroscopic cross-section (Σ_a). Such errors do not occur in the case of iridium, since the targets are accurately machined and there is no uncertainty in the density. Discrepancies between theoretical and actual activities also come from variation of the flux from the nominal 1.0×10^{14} n cm^{-2}s^{-1} As all irradiations have been limited to one reactor period, the value of the model in estimating long term activation has not been tested. The major sources of error in the model are due to inaccuracies in the estimated cross-section and, hence, errors in the values of ϕ_{av} and ϕ_s and in the assumptions regarding the nature of the activation in the surface and interior regions of a target. For irradiations comparable with the ytterbium-169 half-life, the error in activation can be shown to be of the same order as the error in the cross-section. However, for long irradiations the assumptions regarding surface and interior activation outlined in Section 2.1 will be invalidated and the differences between theoretical and experimental activities will increase, particularly for small targets in which appreciable internal burnup may occur.

6. CONCLUSIONS

Despite its obvious limitations the model provides a relatively simple method for dealing with a fairly complicated problem in radioisotope source activation. It is useful in both theoretical studies of such problems and in the planning of routine production irradiations.

On the basis of the results obtained in this study any programme for the production of ytterbium-169 sources should follow these guide lines:

(a) The ytterbium oxide target material should have an ytterbium-168 enrichment of approximately 20 per cent.

~~(b) The ytterbium oxide target mass need not exceed 20 mg.~~

(c) Provided there is no effect on radiographic quality related to source size, the target material should be diluted with graphite to give a target size of 2.0 mm x 2.0 mm for improved activation and output quality.

(d) Irradiation times should be of the order of one ytterbium-169 half-life (31 days) in a flux of the order of 1.0×10^{14} n cm^{-2}s^{-1}.

(e) Used sources should not be reactivated.

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TABLE 1

CALCULATED IRIDIUM-192 ACTIVATION USING THE THEORETICAL ACTIVATION FORMULA

Calculated results for a 1.0 mm x 1.0 mm iridium target are compared with the results of actual irradiations normalised to a flux of 7.0 x 10^{13} n $cm^{-2}s^{-1}$. In most cases the values given are the average of many irradiations.

Activation Time (Reactor Periods)	Iridium-192 Activity (curies)	
	Calculated	Measured
1	2.4	2.6 *I*
2	4.1	4.0 *I*
3	5.4	5.0 *I*
4	6.3	6.0
5	6.8	6.5
6	7.1	7.0
7	7.4	7.2
8	7.5	7.4 *I*
9	7.6	7.6
10	7.5	7.4
11	7.5	7.4
12	7.5	7.2
13	7.3	6.8
14	7.1	6.4
15	6.7	6.0

I *Interpolated Values.*

TABLE 2

CALCULATED ACTIVITIES FOR REIRRADIATED YTTERBIUM OXIDE TARGETS

Target Mass (mg)	Dimension (mm x mm)	Activity Expected (curies)		
		First Irrad.	Second Irrad.	Third Irrad.
10	1.2 x 1.2	10.0	8.4	6.1
10	2.0 x 2.0	15.3	8.8	4.4
20	1.5 x 1.5	16.7	15.2	12.1
20	2.0 x 2.0	24.3	17.8	12.1

TABLE 3

EFFECTIVE SPECIFIC GAMMA RAY EMISSION (Γ_{eff}) FOR AN ENCAPSULATED YTTERBIUM-169 RADIOGRAPHY SOURCE

(10 mg Yb_2O_3 in 1.2 mm x 1.2 mm)

Gamma Energy keV	Peak Counts (Efficiency corrected. Normalised to 10^6 at 53-63 keV)	Per Cent Emission (Relative to 9.2% at 308 keV) (100 n_E)	Exposure Rate ($R\ h^{-1}Ci^{-1}$ at 1 m for 100% emission) Γ_E	Effective Output ($R\ h^{-1}Ci^{-1}$ at 1 m) $n_E\Gamma_E$
53 63	1.00×10^6	75.41	0.034	0.0256
94	1.24×10^4	0.94	0.042	0.0004
110	1.22×10^5	9.20	0.051	0.0047
118	1.69×10^4	1.27	0.056	0.0007
130	1.02×10^5	7.69	0.062	0.0048
177	2.30×10^5	17.34	0.092	0.0160
198	4.42×10^5	33.33	0.103	0.0343
261	4.91×10^4	1.44	0.145	0.0021
308	1.22×10^5	9.20 *	0.175	0.0161
			$\Sigma n_E \Gamma_E$	= 0.105

Total value of Γ_{eff} = 0.105 $R\ h^{-1}Ci^{-1}$ at 1 m.

* *Calculated by method of Ayers et al (1958).*

TABLE 4

EFFECTIVE SPECIFIC GAMMA RAY EMISSION (Γ_{eff}) OF YTTERBIUM-169 RADIOGRAPHY SOURCES

(Variation with Source Size)

Target Mass (mg)	Dimensions Diameter x Length (mm x mm)	Γ_{eff} ($R\,h^{-1}\,Ci^{-1}$ at 1 m)
8	1.2 x 1.0	0.105
10	1.2 x 1.2	0.105
10	2.0 x 2.0 *D*	0.133
17	2.0 x 2.0 *D*	0.100
20	1.5 x 1.5	0.097
20	2.0 x 2.0 *D*	0.125

D *indicates target diluted with graphite to decrease* Σ_a.

TABLE 5

COMPARISON BETWEEN THEORETICAL ESTIMATES AND ACTUAL PRODUCTION OF YTTERBIUM-169 RADIOGRAPHY SOURCES IN ONE REACTOR PERIOD IN A NOMINAL HOLLOW FUEL ELEMENT THERMAL NEUTRON FLUX OF 1.0×10^{14} n cm^{-2}s^{-1}

Target Mass (mg)	Dimensions Diameter x Length (mm x mm)	Type	Activity (curies)	
			Calculated	Actual
8.0	1.2 x 1.0	*S*	8.3	12.0
8.0	1.2 x 1.0	*S*	8.3	10.9
10.3	1.2 x 1.2	*S*	10.3	14.3
10.0	2.0 x 2.0	*D*	15.3	15.0
19.4	1.5 x 1.5	*S*	16.3	18.9
19.4	1.5 x 1.5	*S*	16.3	20.1
19.0	2.0 x 2.0	*D*	23.1	22.8
17.0	2.0 x 2.0	*D*	20.6	22.3
20.0	2.0 x 2.0	*D*	24.3	25.0

S *solid source material.*

D *diluted source material.*

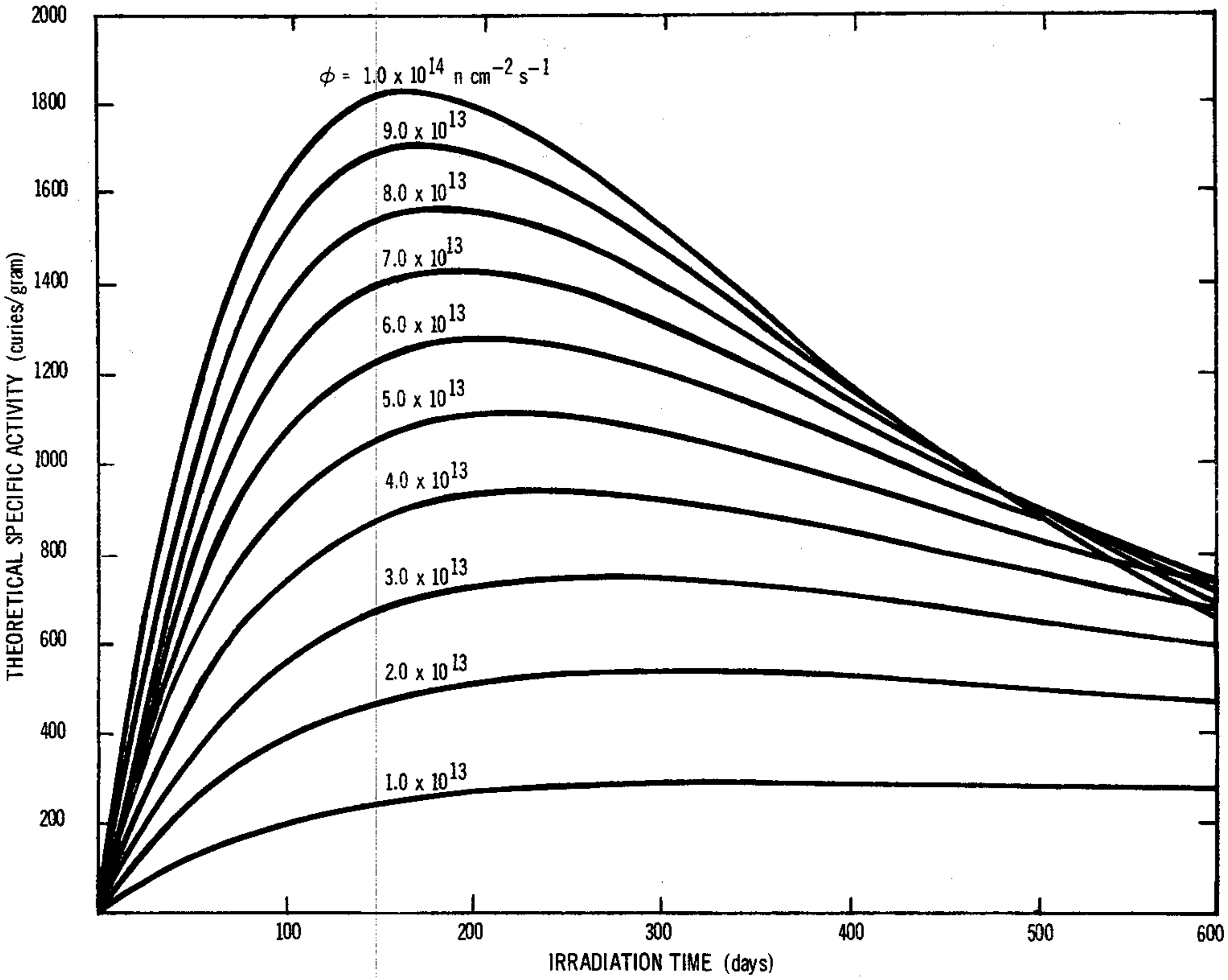

FIGURE 1. THEORETICAL ACTIVATION OF IRIDIUM-192 FOR A GIVEN THERMAL FLUX AND NO FLUX DEPRESSION

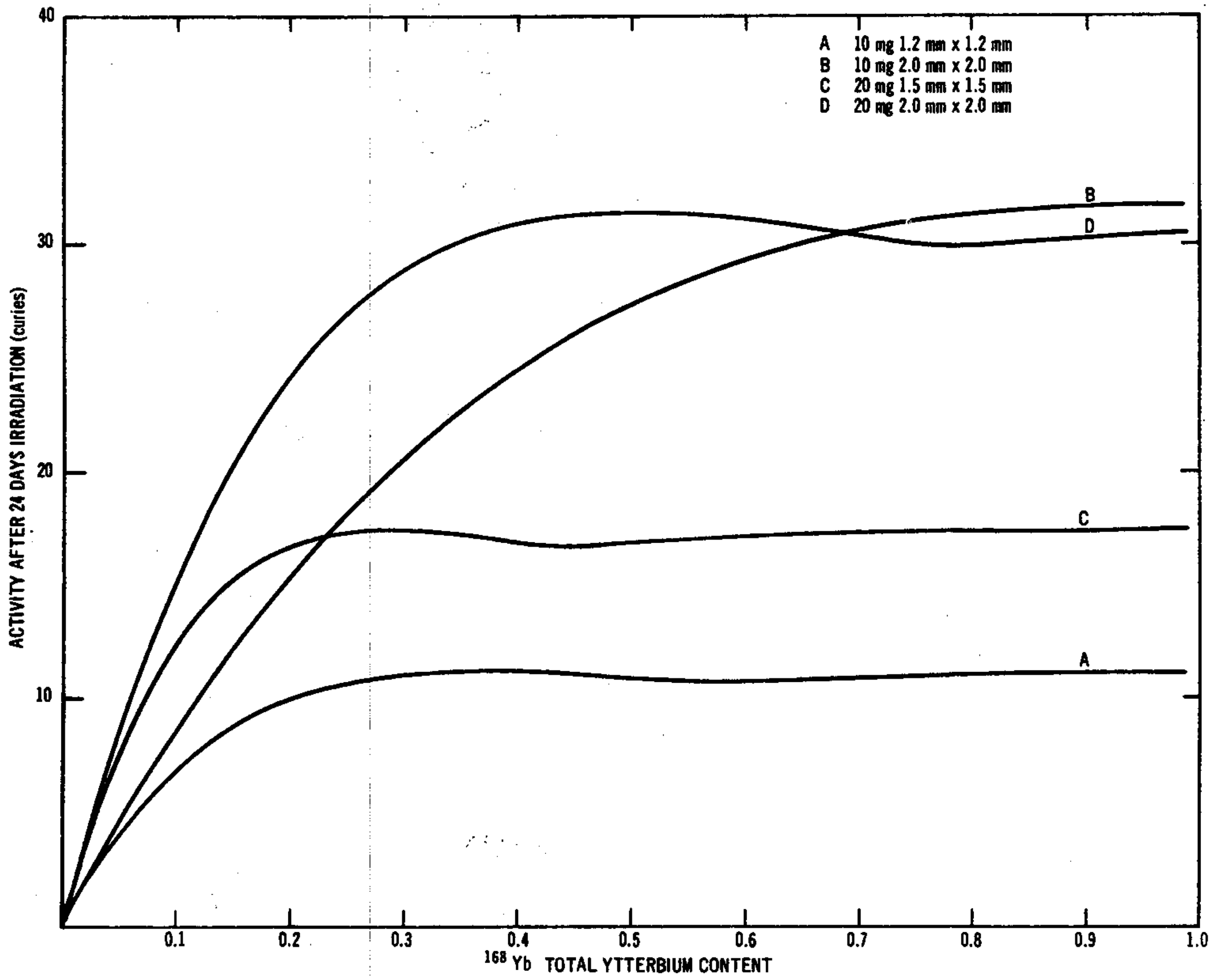

FIGURE 2. DEPENDENCE OF ACTIVATION ON TARGET ENRICHMENT

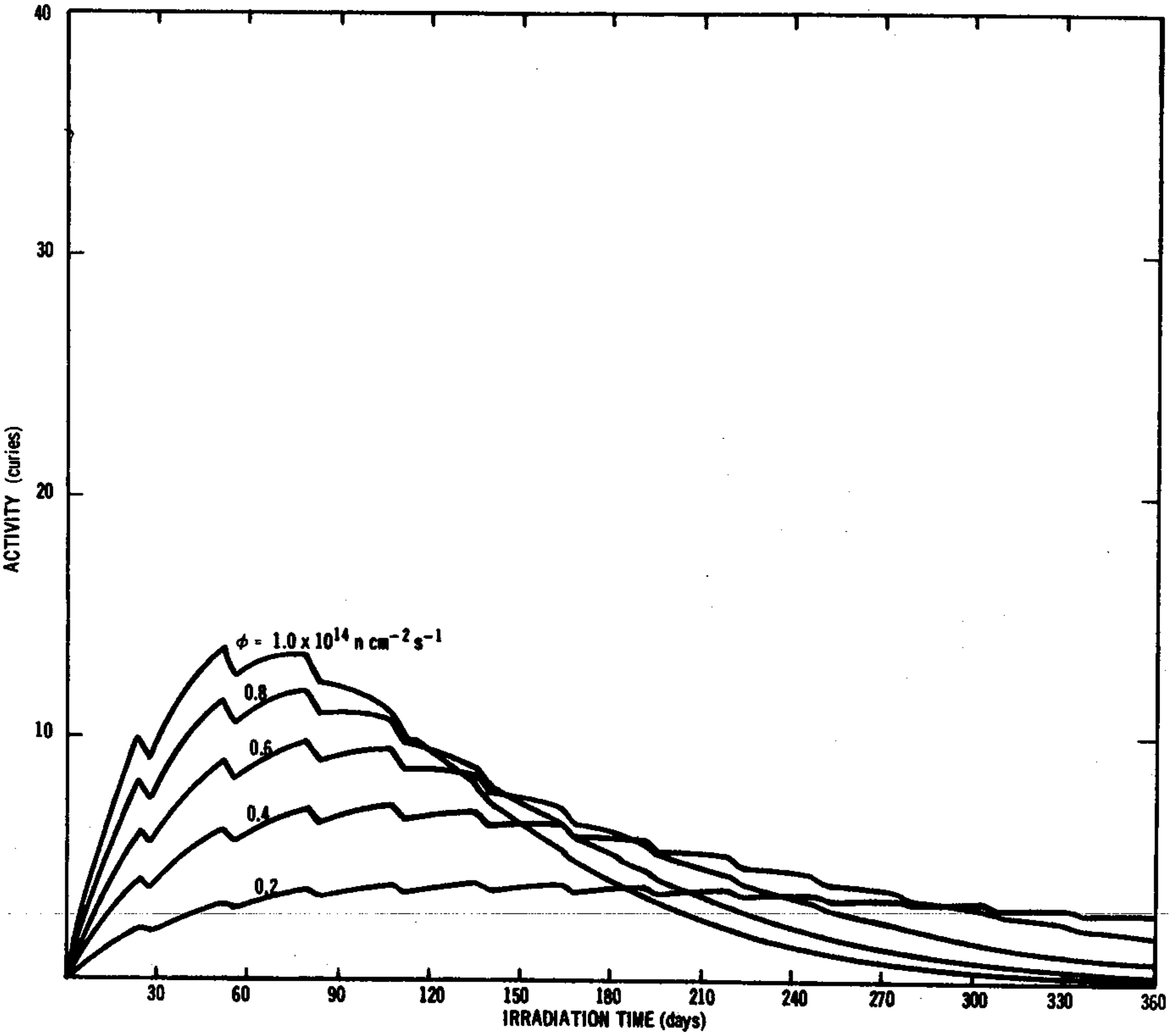

FIGURE 3. ACTIVATION OF A 10mg, 1.2mm×1.2mm Yb_2O_3 TARGET (20% ^{168}Yb ENRICHED)

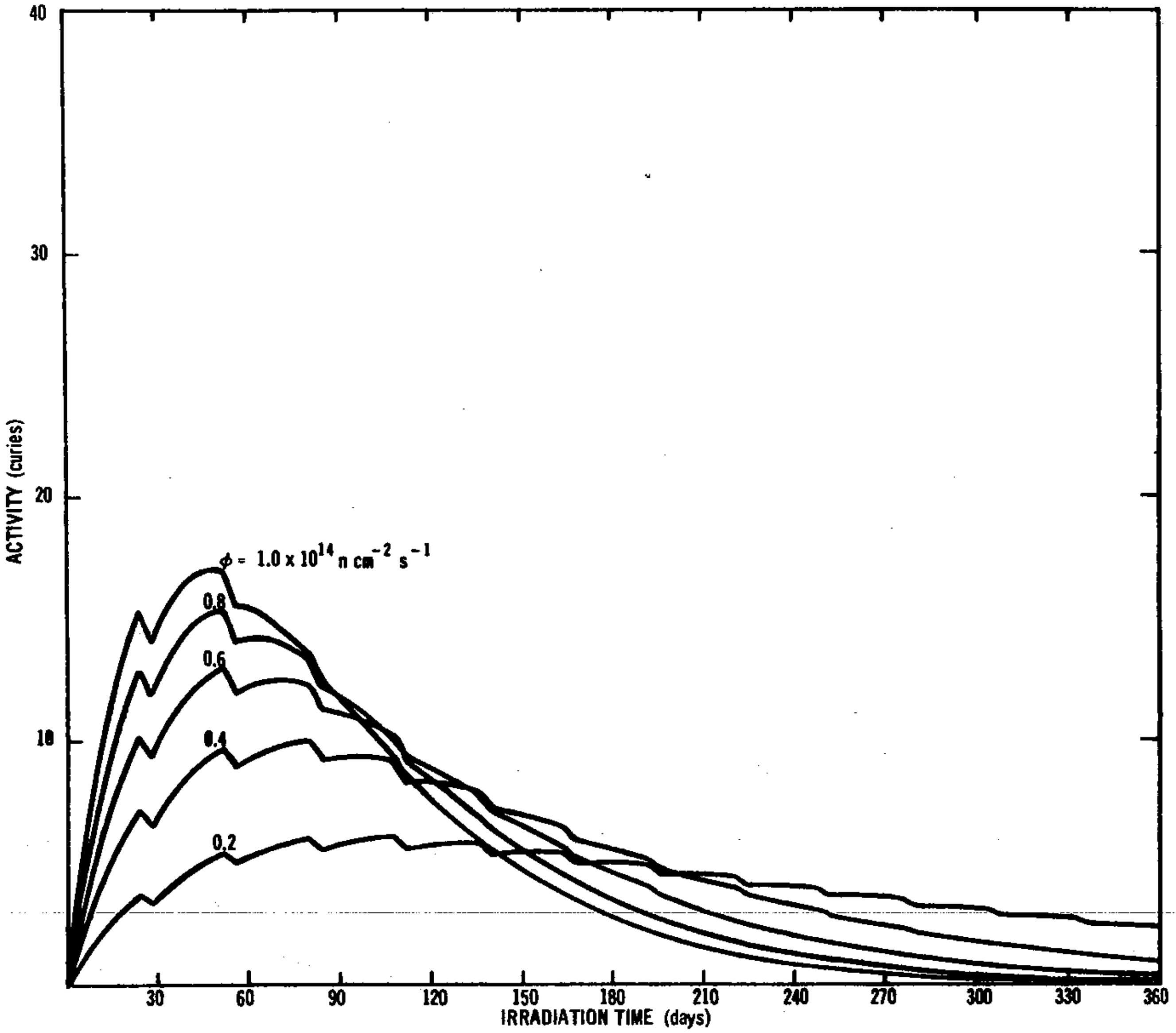

FIGURE 4. ACTIVATION OF A 10mg, 2.0mm×2.0mm DILUTED Yb_2O_3 TARGET (20% ^{168}Yb ENRICHED)

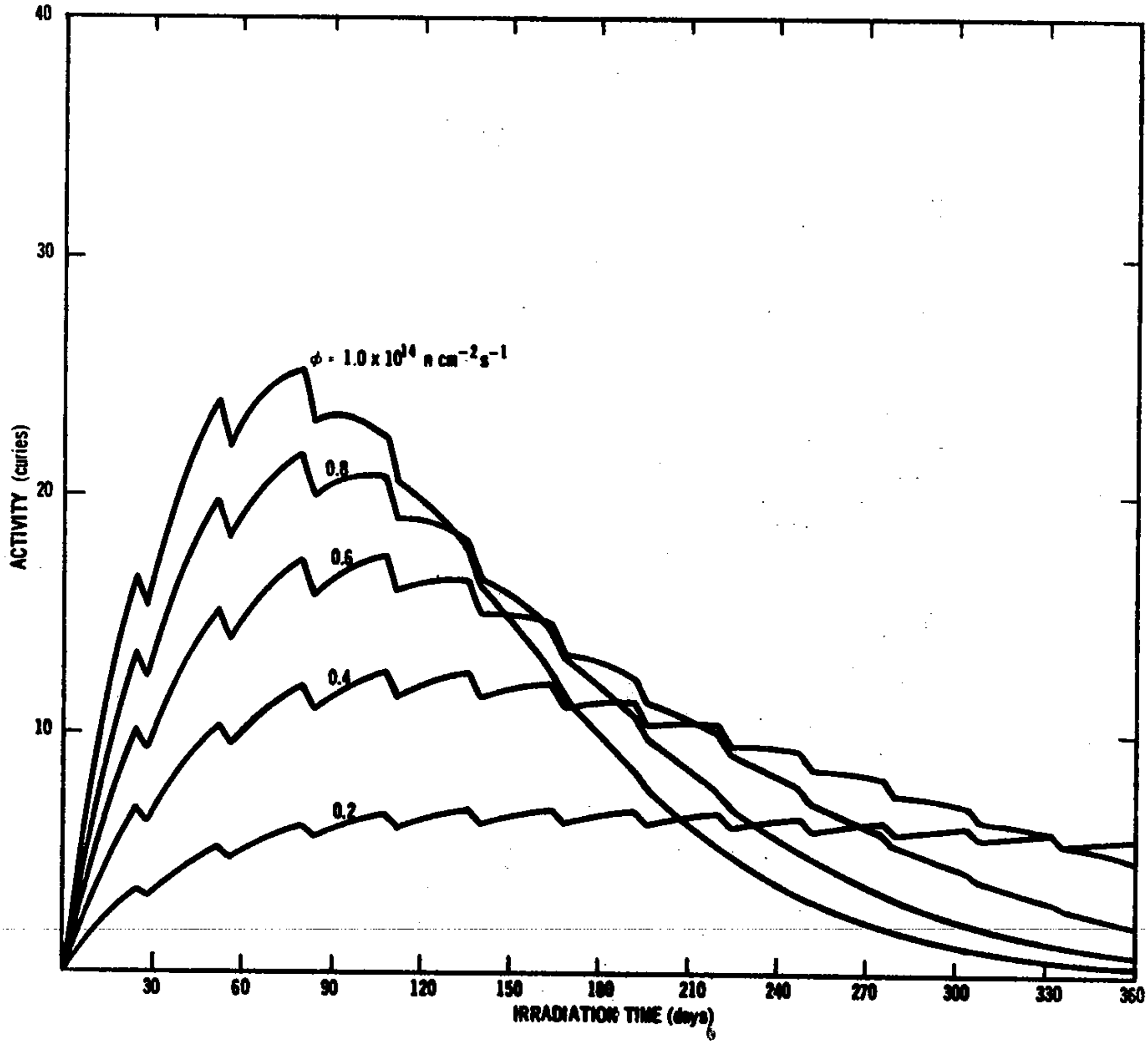

FIGURE 5. ACTIVATION OF A 20mg, 1.5mm×1.5mm Yb_2O_3 TARGET (20% ^{168}Yb ENRICHED)

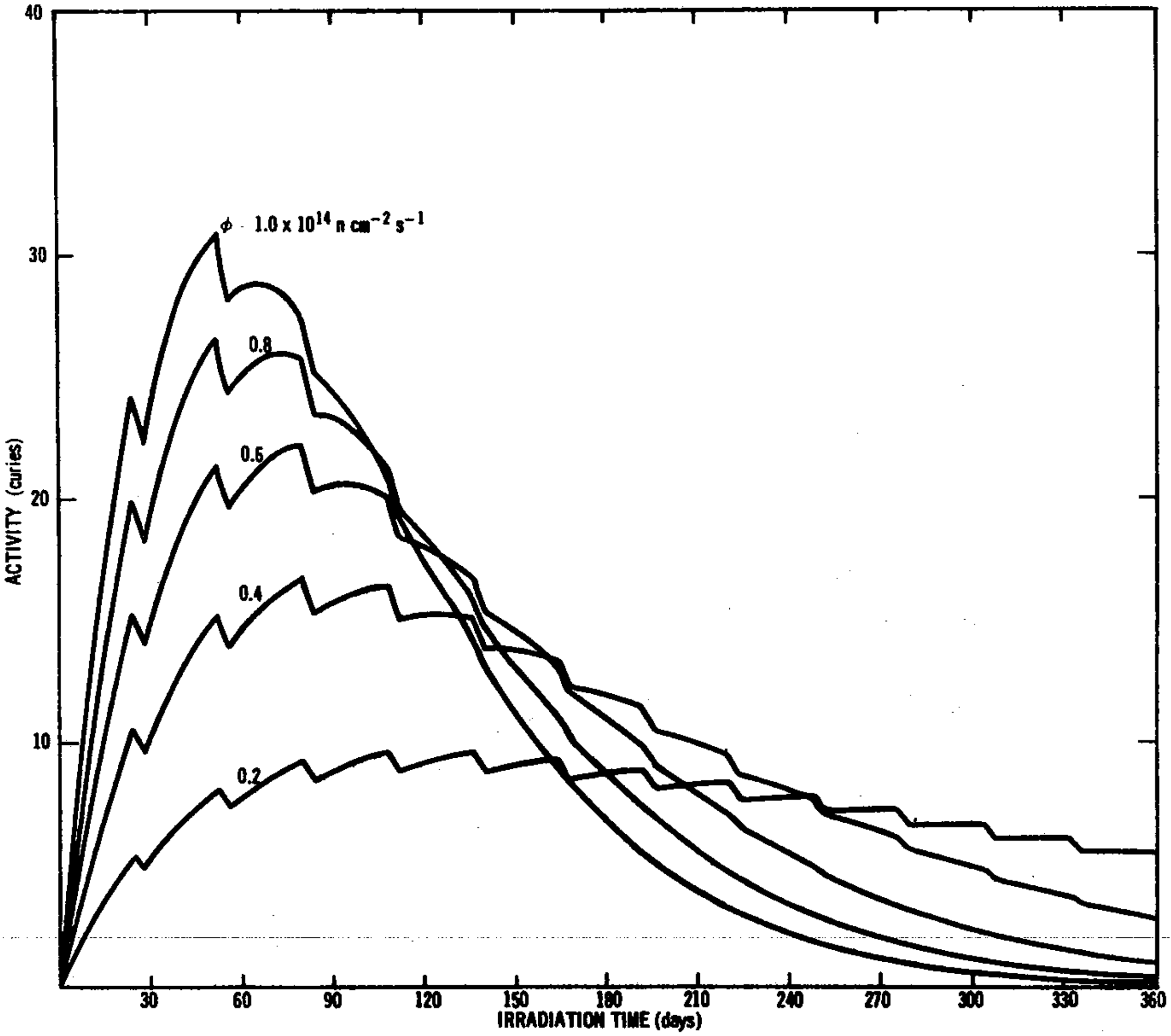

FIGURE 6. ACTIVATION OF A 20mg, 2.0mm×2.0mm DILUTED Yb_2O_3 TARGET (20% ^{168}Yb ENRICHED)