SLAC
TN-62-70
H. DeStaebler
October, 1962

AVERAGE RADIATION LEVELS INSIDE THE ACCELERATOR HOUSING WHEN THE MACHINE IS OFF

I. SUMMARY

When beam electrons hit the machine, some of the copper becomes radioactive, and some of the radiation scatters out of the machine and makes the concrete of the tunnel radioactive. Figures 3 and 4 show the calculated activity from the copper and from the concrete under a variety of assumptions and approximations. In summary, the radiation level as a function of time after the beam is turned off is roughly

Time (hr)	Calculated Radiation Level mrem/hr
0.1	1,000
1	350
10	200-250
50	35-50

for an assumed beam loss is 3% of 2.4 Mw (60 μa at 40 Bev, or 120 μa at 20 Bev) distributed uniformly over 10,000 ft. For reference, radiation worker tolerance is 0.75 mrem/hr.

We consider (n, γ) and (γ, n) reactions in ordinary concrete. The principal reaction is Na^{23} (n, γ) Na^{24}, $T_{\frac{1}{2}} = 15$ hr, and the cross section is fairly well known. In copper we consider γ induced reactions leading to daughter nuclides down through manganese (4p, 2 - 11n). The principal activities are $Cu^{65}(\gamma, n)Cu^{64}$, $T_{\frac{1}{2}} = 13$ hr, and $Cu^{63}(\gamma, n)Cu^{62}$, $T_{\frac{1}{2}} = 10$ min, where the cross

sections are well known. After a waiting time of a few days the activities from Co^{58}, $T_{\frac{1}{2}} = 70$ days, and Co^{60}, $T_{\frac{1}{2}} = 5$ years, become important; these cross sections are not well known. We briefly consider reactions induced by high energy neutrons, and estimate that they do not dominate the photon induced reactions, and that they may in fact be comparable.

We briefly consider the question of shielding.

It is difficult to assess the errors and uncertainties. Figure 5 shows how the radiation level scales with different assumptions about beam loss. There will probably be some localized regions in the tunnel where the levels will be ~ 100 times those shown in Figs. 3 and 4. As mentioned above, the Na^{24}, Cu^{64}, and Cu^{62} activities are rather definite. The cobalt activities are less definite. The neutron induced activities can only raise the radiation levels, but we guess that this will be by a factor of less than 2.

II. GENERAL REMARKS

If radioactive nuclei with mean life τ are made at a constant rate R for a time T, the number remaining at a time t after the end of the radiation is

$$n(t) = R\tau(1 - e^{-T/\tau})\, e^{-t/\tau} \tag{1}$$

The number decaying per unit time (the activity) is

$$-\frac{dn}{dt} = R(1 - e^{-T/\tau})\, e^{-t/\tau} \tag{2}$$

R is called the saturation activity or the steady-state activity, and is the maximum possible activity. R is proportional to the amount of electron beam power absorbed (current times energy--usually in Mev/sec), to the abundance of the parent nuclide, and to the cross section for the particular reaction integrated over the energy spectrum of the inducing reaction.

When a radioactive nucleus decays it usually emits a β^+ or a β^- and various γ rays. The β^+ are usually quickly absorbed in the material itself. We only consider the penetrating γ rays and treat each β^+ like two 0.51 Mev γ rays because of the annihilation.

To convert a photon flux to rem we use the conversion factor[1] 4.6×10^{-10} rem/Mev-cm^{-2}. This actually depends somewhat on γ energy, but it is fairly constant for γ energies from 0.2 to 2.0 Mev, which covers most of the range of interest. A more convenient factor is

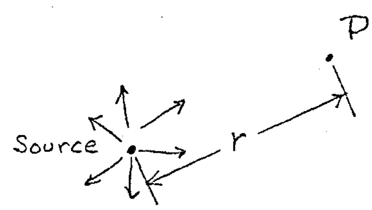
$$F = 3.6 \times 10^6 \times 4.6 \times 10^{-10} = 1.66 \times 10^{-3} \frac{\text{mrem/hr}}{\text{Mev/cm}^2\text{sec}} .$$

In this preliminary note we neglect detailed shielding which depends markedly on γ energy except that we neglect nuclear γ rays less than 0.2 Mev because of the strong absorption. To get the biological effect of the decay of a particular nucleus we define the total energy as

$$E_\gamma(\text{Mev}) \equiv 1.02 \times \text{number of } \beta^+ + \Sigma \text{ (energy of all nuclear } \gamma \text{ rays above 0.2 Mev).}$$

We consider three different geometries. For a point, isotropic source, the flux a distance r from the source is

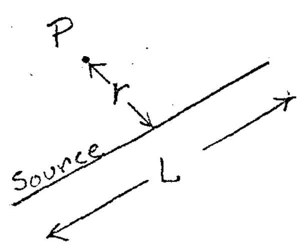
$$\varphi = \frac{Q}{4\pi r^2} \qquad (3)$$



In our case Q is the total activity.

For an isotropic line source of length L and total strength Q, the flux at a distance r is approximately ($r \gg L$; neglect end effects).

$$\varphi = \frac{Q}{2\pi r L} \qquad (4)$$

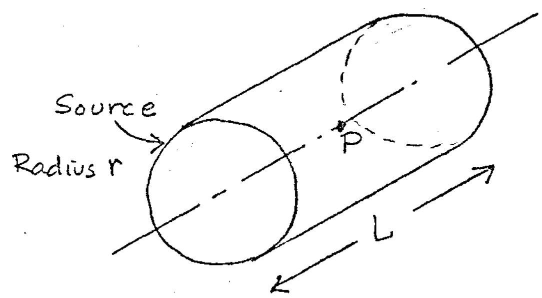


where the total source Q is distributed uniformly along L. This is the so-called directional flux, and is the flux through an area element coaxial about the source. The omni-directional flux is the total path length of the radiation across a small sphere divided by the volume of the sphere--it is the flux through a unit area which is always perpendicular to the direction of motion of the particles. For a point source the two fluxes are the same. For a line source the omni-directional flux is

$$\varphi = \frac{Q}{4rL} \tag{5}$$

For a source which is uniformly spread over a cylindrical shell of radius r and length L, the omni-directional flux on the axis is the same as for the line source case

$$\varphi = \frac{Q}{4rL} \tag{6}$$



This case is useful for radioactivity in the walls of the tunnel where the omni-directional flux is more appropriate than the directional flux.

III. INDUCED ACTIVITY IN CONCRETE

We consider two kinds of reactions leading to induced activity in concrete: γ induced giant resonance reactions, and neutron capture reactions. A typical composition of ordinary concrete is[2]

Element	Weight %
H	1
O	53
Si	34
Al	3.4
Fe	1.4
Ca	4.4
Mg	0.2
C	0.1
Na	1.6
K	1.3

We assume that 5% of the beam energy absorbed in the machine scatters out,[4] and that this 5% is carried by photons with energies near the giant resonance. The latter assumption is extreme and leads to an overestimate of the activity. We also assume that the effective average path length of these photons in the concrete is one radiation length. The saturation activity from a particular reaction is

$$R = \left(\frac{W}{k_o}\right)\left(gh\,\frac{N_o}{A}\right) X_o \,\frac{\int \sigma dk}{\Delta k} \qquad (7)$$

We make the approximation that k_o and Δk are independent of the parent nuclide.

W Total electromagnetic power scattered out of machine. We assume that 3% of the final beam power (2.4 Mw) is absorbed, and that of this 5% scatters out. (See M-263)[4]

$W = 5\% \times 3\% \times 40 \times 10^3 \text{ Mev} \times 3.75 \times 10^{14} (e/s)$

$= 2.25 \times 10^{16}$ Mev/sec

k_o	Energy of giant resonance (20 Mev)
g	Weight % of parent element in ordinary concrete
h	Atomic abundance of parent nuclide in parent element
N_o	Avogardro's number
A	Atomic weight of parent element
X_o	Radiation length in concrete (28 gcm^{-2})
$\int\sigma dk$	Ingegrated giant resonance cross section
Δk	Width of giant resonance (10 Mev)

Then

$$R = \frac{2.25 \times 10^{16} \times 10^{-2} \times 6 \times 10^{23} \; 28 \times 10^{-27}}{20 \qquad \times \qquad 10} \; \frac{gh\int\sigma dk}{A}$$

$$= 1.89 \times 10^{10} \; (sec^{-1}) \; \frac{gh\int\sigma dk}{A}$$

$$= 0.51 \text{ curies } \frac{gh\int\sigma dk}{A}$$

with these units

$\int\sigma dk$	Mev - mb
g	%
h	Fraction

The saturation radiation level at the center of the tunnel is approximately

$$D(0) = \frac{RFE_\gamma}{4rL} \qquad (8)$$

where

R Activity

F Conversion factor [e.g., 1.66×10^{-3} (mrem/hr)/(Mev/cm^2-sec), or 6.17×10^{7} (mrem/hr) (curie-Mev/cm^2)]

E_γ Total γ energy (Mev)

r Effective radius of tunnel (5 ft)

L Distance over which beam is absorbed (10^4 ft).

The more serious daughter nuclides are listed in Table I with some of their properties and the product RE_γ. The sodium activities dominate: Na^{24} at short times, and Na^{22} at long times. The resulting activities as a function of time are shown in Fig. 3 and 4, where from Eq. (1)

$$D(t) = D(0)(1 - e^{-T/\tau})\, e^{-t/\tau} \qquad (15)$$

For the neutron capture we assume that every giant resonance neutron made in the machine is thermalized in the wall and is eventually captured. We assume that the fraction captured by a particular nuclide is proportional to the atomic abundance of the particular species and to the thermal capture cross section. Thus 5% of the neutrons are captured on Na even though the atomic abundance is only 1.2%.[2] The important effect here is not that Na has a large σ_{capt}, but that oxygen which is most abundant has a very small σ_{capt}. The saturation activity is

$$R = GQ \qquad (9)$$

G Fraction of neutrons captured on Na(5%)

Q Rate of creation of giant resonance neutrons. For a power absorption of 3% of 2.4 Mw, $Q = 8.4 \times 10^{13}$ n/sec.[4]

TABLE I

INDUCED ACTIVITIES IN CONCRETE

Reaction	Mean[3] Life τ (hr)	Radiation ($+ \rightarrow \beta^+$, γ Energy in Mev)	E_γ[3] (Mev)	Abundance Element in Concrete g (wt %)	Parent Isotopic Abundance h	$\int \sigma dk$ (ref. 9) (Mev-mb)	Saturation Activity times E_γ RE_γ (curie-Mev)
$Fe^{54}(\gamma,n)Fe^{53}$	0.21	.4, +	1.13	1.4	.06	440	0.40
$C^{12}(\gamma,c)C^{11}$	0.49	+	1.02	0.1	.99	40	0.17
$Na^{23}(\gamma,n)Na^{22}$	3.3×10^4	1.3, +	2.30	1.6	1.0	100	8.2
$K^{39}(\gamma,n)K^{38}$	0.19	2.3, +	3.18	1.3	.93	240	12.0
$Na^{23}(n,\gamma)Na^{24}$	22	1.4, 2.7	4.12				470

Then

$$R = \frac{8.4 \times 10^{13}}{20} = 4.2 \times 10^{12} \text{ disintegration/sec}$$

$$= 114 \text{ curies total in the tunnel}$$

Each Na^{24} decay gives two γ, 1.37 Mev and 2.75 Mev, so $E_\gamma = 4.12$ Mev. The radiation level is

$$D = \frac{R}{4rL} \ F \ E_\gamma \qquad (10)$$

where we take $r = 5$ ft and $L = 10^4$ ft as before.

$$D(0) = \frac{4.2 \times 10^{12} \quad 1.66 \times 10^{-3} \quad 4.12}{4 \quad 1.5 \times 10^2 \quad 3 \times 10^5}$$

$$= 160 \text{ mrem/hr}$$

This is summarized in Table I.

We have neglected absorption of the γ in the concrete. The slowing down length for fast neutrons in concrete is about 10 cm (Ref. 2) which is about 1 interaction length (good geometry) for the γ from Na^{22}, so there might be a factor of 2 attenuation.

We compare this calculation with an experiment done at OAK Ridge in which a block of ordinary concrete (3 ft square and 1 ft thick) was irradiated for 20 hr with neutrons from the Tower Shielding Facility, and the resulting Na^{24} activity was measured.[11] First we estimate the neutron flux. The fast neutron dose rate at the top of the block was 2.9×10^5 erg/g.hr. We convert this to flux using 3.5×10^{-8} rem/n cm^{-2} and RBE $\approx$ 7 for fast neutrons.[5] Then

$$\varphi_{neut} = \frac{2.9 \times 10^5 \text{ (erg/g.hr)}}{3.5 \times 10^{-8} \text{ (rem/n cm}^{-2}\text{)} 1/7 \text{(rad/rem)} 100 \text{(erg/g.rad)}}$$

$$= 5.8 \times 10^{11} \text{ n/cm}^2 \text{ hr.}$$

At 5 ft from the concrete block the radiation level was about 100 mr/hr at the end of irradiation. Using our values of F and E_γ this corresponds to

$$\frac{100 \text{ mr/hr}}{4.6 \times 10^{-7} \text{ (mrem/Mev cm}^{-2}\text{) } 4.12 \text{ Mev}} = 5.3 \times 10^7/\text{cm}^2 \text{ hr.}$$

disintegrations per hour which send their γ rays through 1 cm^2 of the detector. Since the concrete only subtends about $(1/4\pi)(1.5/5)^2 = 1/186$ of a sphere at the counter the number of disintegrations/cm^2 hr at the block is

$$186 \times 5.3 \times 10^7 = 10^{10} \text{ dis/cm}^2 \text{ hr.}$$

To make a comparison with our calculation we should adjust the ORNL activity to correspond to saturation by dividing by

$$(1 - e^{-T/\tau}) = 1 - \exp(-20/22) = 0.60.$$

The number of disintegrations/neutron is

$$\frac{1.67 \times 10^{10} \text{ dis/cm}^2 \text{ hr}}{5.8 \times 10^{11} \text{ n/cm}^2 \text{ hr}} = \frac{1}{35}$$

We assumed 1/20, i.e., 5% of the neutrons are captured on Na. In view of the approximations - no attenuation correction, uncertain neutron flux, neutron albedo, geometrical corrections - this seems like good agreement.

IV. INDUCED ACTIVITY IN COPPER

A. Photon Reactions

In the copper the differential photon track length (Approximation A) arising from the absorption of an electron of energy E_o is

$$\frac{dN}{dk} = 0.57 \frac{E_o}{k^2} X_o \ .$$

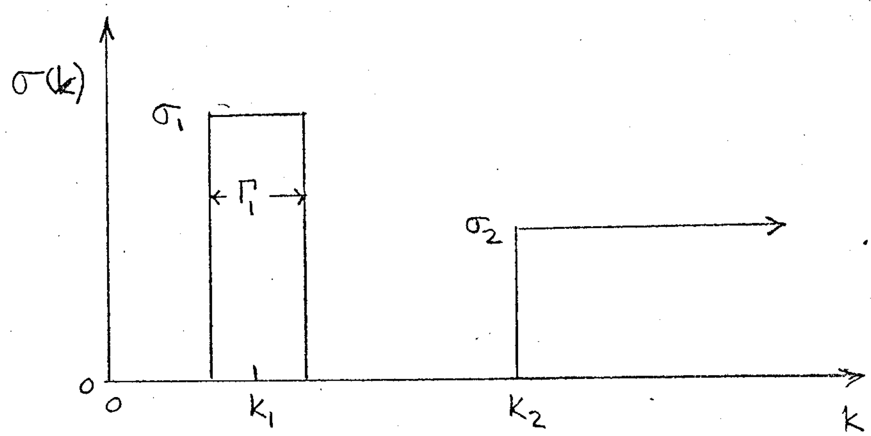
For the absorption of a current (fI), we have

$$\begin{aligned} R &= fI \int \left(0.57 \frac{E_o dk}{h^2} X_o\right) g \frac{N_o}{A} \sigma(k) \\ &= 0.51 \ f \ (IE_o) \ g \frac{X_o N_o}{A} \int_0^{E_o} \frac{\sigma(k) dk}{k^2} \end{aligned} \qquad (11)$$

IE_o	Total beam power (2.4 Mw)
f	Fraction of total beam power absorbed (3%)
X_o	Radiation length (13 g cm^{-2} in copper)
g	Atomic abundance of parent nuclide in parent element
N_o	Avogardro's number
A	Atomic weight (63.54 for copper)
$\sigma(k)$	Cross section leading from the parent nuclide to a particular daughter nuclide as a function of photon energy.

The integral over k extends up to high energies, but very few cross sections have been measured above a few hundred Mev. For reactions in which one or two nucleons are emitted there is a peak in the cross section around $k = 20$ Mev (giant resonance). When 5-10 nucleons are emitted, the cross section is small at low energies (the typical binding energy is 8 Mev for single nucleons) and some show a marked rise around a few hundred Mev, probably as a result of meson processes. At MIT copper was irradiated with 320 Mev thin target bremsstrahlung and analyzed radiochemically.[6] We inquire whether we can scale these results to high energy, thick target bremsstrahlung.

Assume that σ looks like this.



The yield is

$$Y_i = \int_0^{E_m} \sigma_i(k) \frac{dN}{dk} dk \tag{12}$$

For the thin target

$$\frac{dN}{dk} \sim \frac{1}{k}, \quad 0 < k < E_o \approx 320 \text{ Mev}$$

and for the thick target

$$\frac{dN}{dk} \sim \frac{1}{k^2}, \quad 0 < k < E_o \sim 20 \text{ Bev}$$

We want the relative yields (Y_2/Y_1) for the two spectra. We have approximately

	Y_1	Y_2	Y_2/Y_1
Thin	$\frac{\sigma_1\Gamma_1}{k_1}$	$\sigma_2 \, \ln(E_o/k_2)$	$\frac{\sigma_2}{\sigma_1} \frac{\ln(E_o/k_2)}{\Gamma_1/k_1}$
Thick	$\frac{\sigma_1\Gamma_1}{k_1^2}$	$\sigma_2 \frac{E_m - k_2}{E_m k_2}$	$\frac{\sigma_2}{\sigma_1} \frac{E_m - k_2}{E_m k_2} \frac{k_1^2}{\Gamma_1}$

$$\frac{(Y_2/Y_1)_{\text{thick}}}{(Y_2/Y_1)_{\text{thin}}} \approx \left[\frac{E_m - k_2}{E_m k_2} \; \frac{k_1^2}{\Gamma_1}\right]\left[\frac{k_1}{\Gamma_1} \ln\,(E_o/k_2)\right]^{-1} \qquad (13)$$

$$\approx \left(\frac{E_m - k_2}{E_m k_2}\right) \frac{k_1}{\ln\,(E_o/k_2)}$$

We evaluate this roughly for

$$E_m \gg k_2$$

$$k_2 \approx 200 \text{ Mev}$$

$$k_1 \approx 20 \text{ Mev}$$

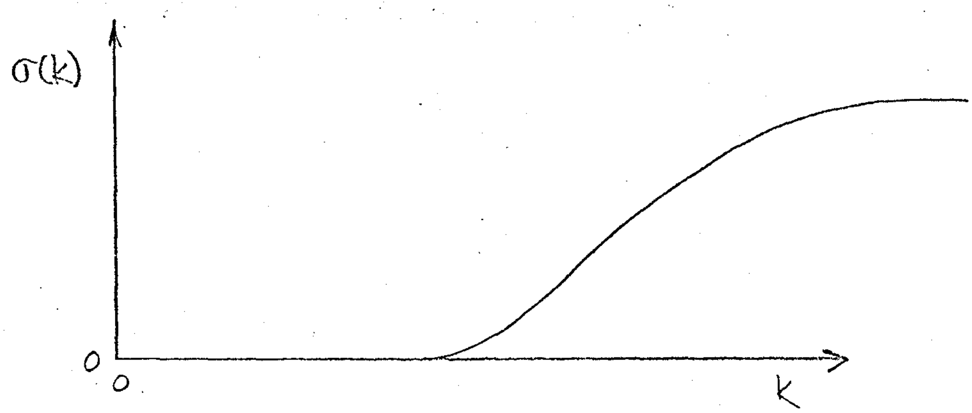
$$E_o \approx 320 \text{ Mev}$$

$$\frac{(Y_2/Y_1)_{tk}}{(Y_2/Y_1)_{tn}} \approx \frac{k_1}{k_2} \; \frac{1}{\ln(E_o/k_2)} = \frac{20}{200} \; \frac{1}{\ln 1.6} \approx \frac{1}{10}$$

We assume that we can scale the yields at high energy using

$$(Y_2)_{\text{thick}} = G \left[(Y_1)_{\text{thick}} \; (Y_2/Y_1)_{\substack{\text{thin} \\ \text{expt.}}}\right] \qquad (14)$$

where $(Y_1)_{\text{thick}}$ is fairly well calculable, and $G \approx 1/10$ in the rough calculations above. In the following computation we take $G = 1$ because k_2 could be smaller than our reasonable value of 200 Mev, and if the high energy cross section actually goes like this



and 320 Mev is not yet up on the plateau, we could underestimate the yields at high energies. This approach is uncertain, but in our present view it tends to be conservative (over-estimate the radiation level in the tunnel).

Now we find the saturation activities of various nuclides in the machine. We normalize all of these yields against the reaction Cu^{63} (γ,n) Cu^{62} as measured by Berman and Brown with a separated Cu^{63} target.[7] (The natural abundance of Cu^{63} is 69%, and the other 31% is Cu^{65}.) They found $\int \sigma dk = 550$ Mev-mb with the peak at 17 Mev. From Eq. (11)

$$R = 0.57\ (3\%)(3.75 \times 10^{14}\ \text{e/s}\quad 4 \times 10^{4}\ \text{Mev})\ (69\%)(13\ \text{g cm}^{-2})$$

$$\times \frac{6 \times 10^{23}}{63.54}\ \frac{550 \times 10^{-27}}{17^{2}}$$

$$R = 4.13 \times 10^{13}\ \text{disintegrations/sec}$$

$$= 1120\ \text{curies total in the machine}$$

Just to get a feeling for the magnitudes involved we calculate the radiation level 3 ft from the machine assuming that this activity is uniformly distributed along the full 10,000 ft. From Eq. (8) with $E_\gamma = 1.1$ Mev

$$D(0) = \frac{4.13 \times 10^{13} \quad 1.66 \times 10^{-3} \quad 1.1}{4 \quad 90 \quad 3 \times 10^5}$$

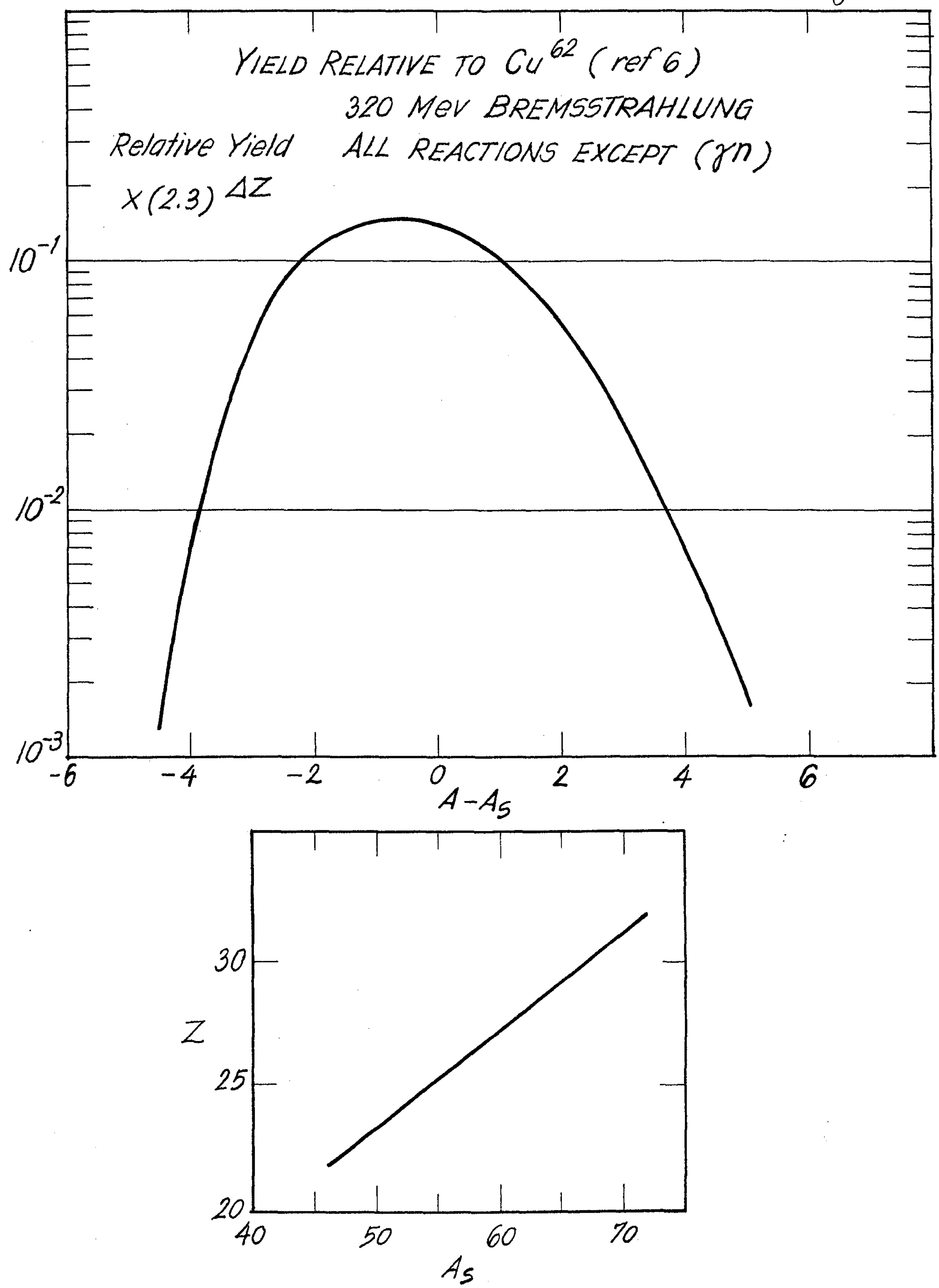
$$= 690 \text{ mrem/hr}$$

We find the other activities by scaling according to the MIT yields relative to Cu^{62} with $G = 1$. The MIT group demonstrated some systematics in the yields which make it possible to estimate the yields of nuclides which were not actually detected by them. In the table those inferred yields are enclosed in parantheses. Fig. 1 shows the empirical, approximate, saturation yield curve relative to Cu^{62} derived from the MIT results. It is accurate within a factor of about 1.5, if more than a few nucleons are emitted. To produce this "universal" curve, the yields are multiplied by $(2.3)^{\Delta Z}$ where ΔZ is the change in nuclear charge; A is the mass number of the daughter nuclide, and A_s is the mass number of the center of the stable valley at the Z of the daughter nuclide. We do not calculate the yields of all possible nuclides; we pick out those which are most troublesome for radioactivity which means they must have individual γ energies greater than 0.2 Mev (absorption increases rapidly at low energies) and half lives between about 10 min and 5 years. Table II lists these nuclides down through manganese. Fig. 2 shows the time dependence of the saturation activity times the total γ energy (RE_γ).

The radiation level depends on the duration of the irradiation, T, (see Eq. (2)) as well as on the geometry. We calculate the radiation level at 3 ft from the machine for $T = 10^2$ and 10^4 hr, assuming that 3% of 2.4 Mw is absorbed uniformly over 10,000 ft. To get the total radiation level as a function of time, we make the sum

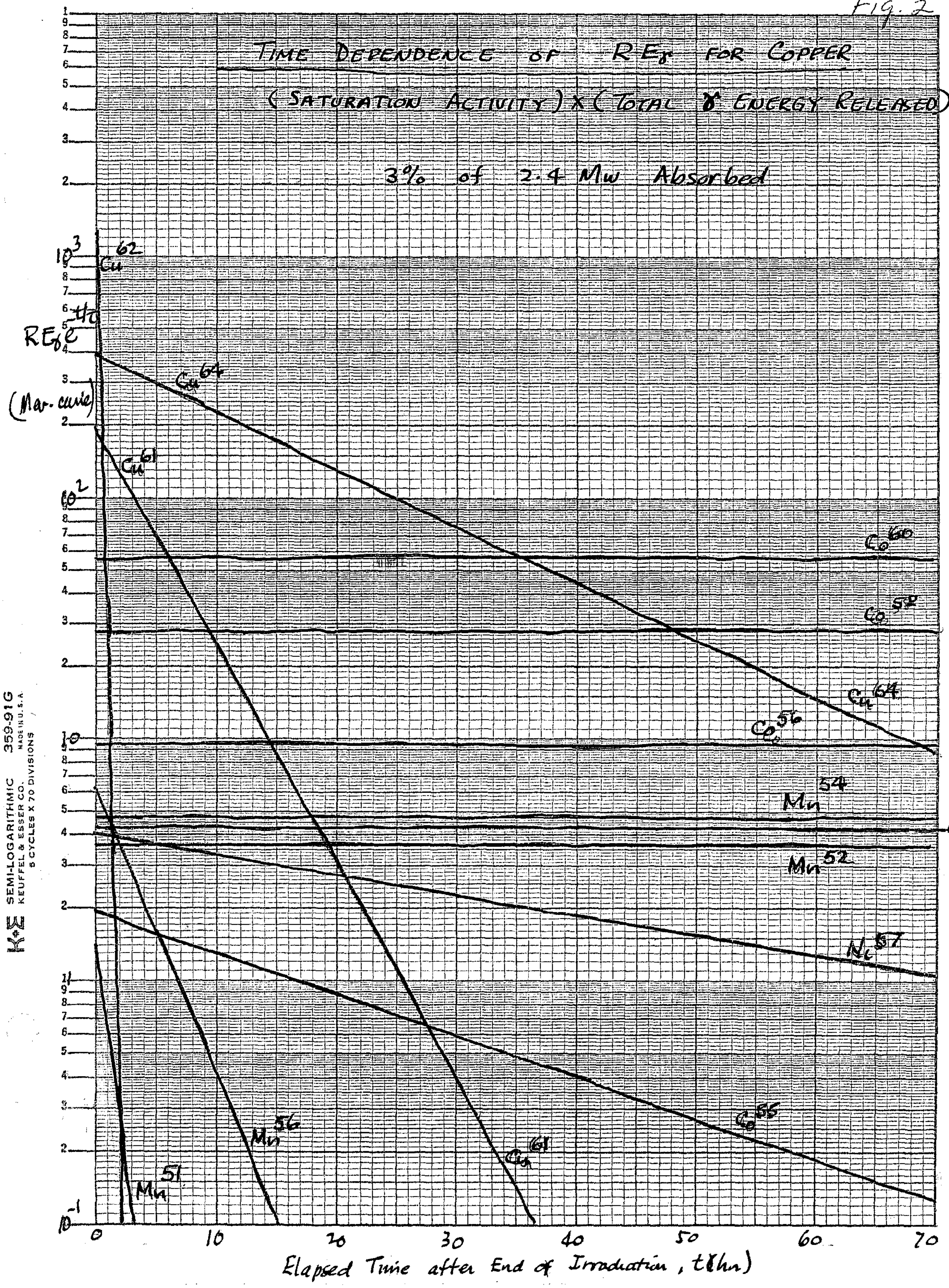
$$D(t) = \frac{F}{4rL} \sum_i (RE_\gamma)_i \, (1 - e^{-T/\tau_i}) \, e^{-t/\tau_i} \qquad (15)$$

Fig. 1



YIELD RELATIVE TO Cu^{62} (ref 6)
320 Mev BREMSSTRAHLUNG
ALL REACTIONS EXCEPT (γn)
Relative Yield
x(2.3)$^{\Delta Z}$
10^{-1}
10^{-2}
10^{-3}
-6
-4
-2
0
2
4
6
A-A$_S$
30
25
20
Z
40
50
60
70
A$_S$

Fig. 2



TIME DEPENDENCE OF REγ FOR COPPER
(SATURATION ACTIVITY) x (TOTAL γ ENERGY RELEASED)
3% of 2.4 Mw Absorbed
REγ e^-t/τ
(Max. curie)
Cu62
Cu64
Cu61
Co60
Co58
Co56
Mn54
Fe59
Mn52
Ni57
Co55
Mn56
Mn51
10^3
10^2
10
1
10^-1
0
10
20
30
40
50
60
70
Elapsed Time after End of Irradiation, t (hr)
K+E SEMI-LOGARITHMIC 359-91G
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

TABLE II

PHOTON INDUCED ACTIVITIES IN COPPER

Daughter Nuclide Element	A	Mean Life[3] τ (hr)	Radiation ($+ \rightarrow \beta^+$, γ energy in Mev)	E_γ[3] (Mev)	Yield Relative[6,*] to Cu^{62}	RE_γ (Energy)×(Activity)** (Mev-curies)
Cu	64	18.4	+, -	.60	.58	390
	62	0.23	~ 2% γ, +	1.10	1.00	1230
	61	4.8	~ 10% γ, +	0.94	.18	190
Ni	57	52	1.4,1.9,+	1.99	1.8×10^{-3}	4.0
Co	60	6.6×10^{4}	1.17,1.33	2.51	(2.0×10^{-2})	56
	58	2.8×10^{2}	.80, +	0.94	(2.7×10^{-2})	28
	56	2.7×10^{3}	.89,others,+	0.70	(1.2×10^{-2})	9.4
	55	26	many, +	2.02	8.5×10^{-4}	1.9
Fe	59	1.56×10^{3}	1.1,1.3	1.29	(3.0×10^{-3})	4.3
Mn	56	3.7	.8,2.8	1.80	3.0×10^{-3}	6.1
	54	1.0×10^{4}	.8	.84	(5.0×10^{-3})	4.7
	52	2.0×10^{2}	1.4,+	2.45	1.3×10^{-3}	3.6
	51	1.1	+	1.02	(1.2×10^{-3})	1.4

* Parentheses indicate that yield is inferred not measured.

** For a power absorption of 3% of 2.4 Mw.

r Distance from machine (3 ft)

L Distance over which power is absorbed (10^4 ft)

This is shown in Fig. 3 for $\tau = 10^2$ hr ($\approx$ 1 week) and in Fig. 4 for $\tau = 10^4$ hr ($\approx$ 1 year). The concrete activities are also shown (for $r = 5$ ft).

The radiation levels are proportional to the absorbed power, and to the inverse of the distance over which the power is absorbed (as long as $r \lesssim L$)

$$D \sim \frac{f(IE_o)}{L}$$

In Fig. 5 we show the factor, α, by which the levels should be increased for different f and L.

$$\alpha = \left(\frac{f}{3\%}\right)\left(\frac{10^4 \text{ ft}}{L}\right) \tag{16}$$

An interesting case arises if much of the beam is absorbed regularly at the same place for a short time each day. Suppose that half way down the machine the full beam is absorbed over a distance of 10 ft (almost a point) for 5 minutes each day (1/3% of the time) for one year (8766 hr $\approx 10^4$ hr). Then the time behavior of the radiation level near this hot spot would be similar to that shown in Fig. 4, but the level would be higher by the following factor

$$\left(\frac{1/3\%}{3\%}\right)\left(\frac{.5\ E_o}{E_o}\right)\left(\frac{10^4}{10}\right) \approx 50.$$

Right after the machine is turned off the radiation level near this point would be around 50 rem/hr.

Fig. 3

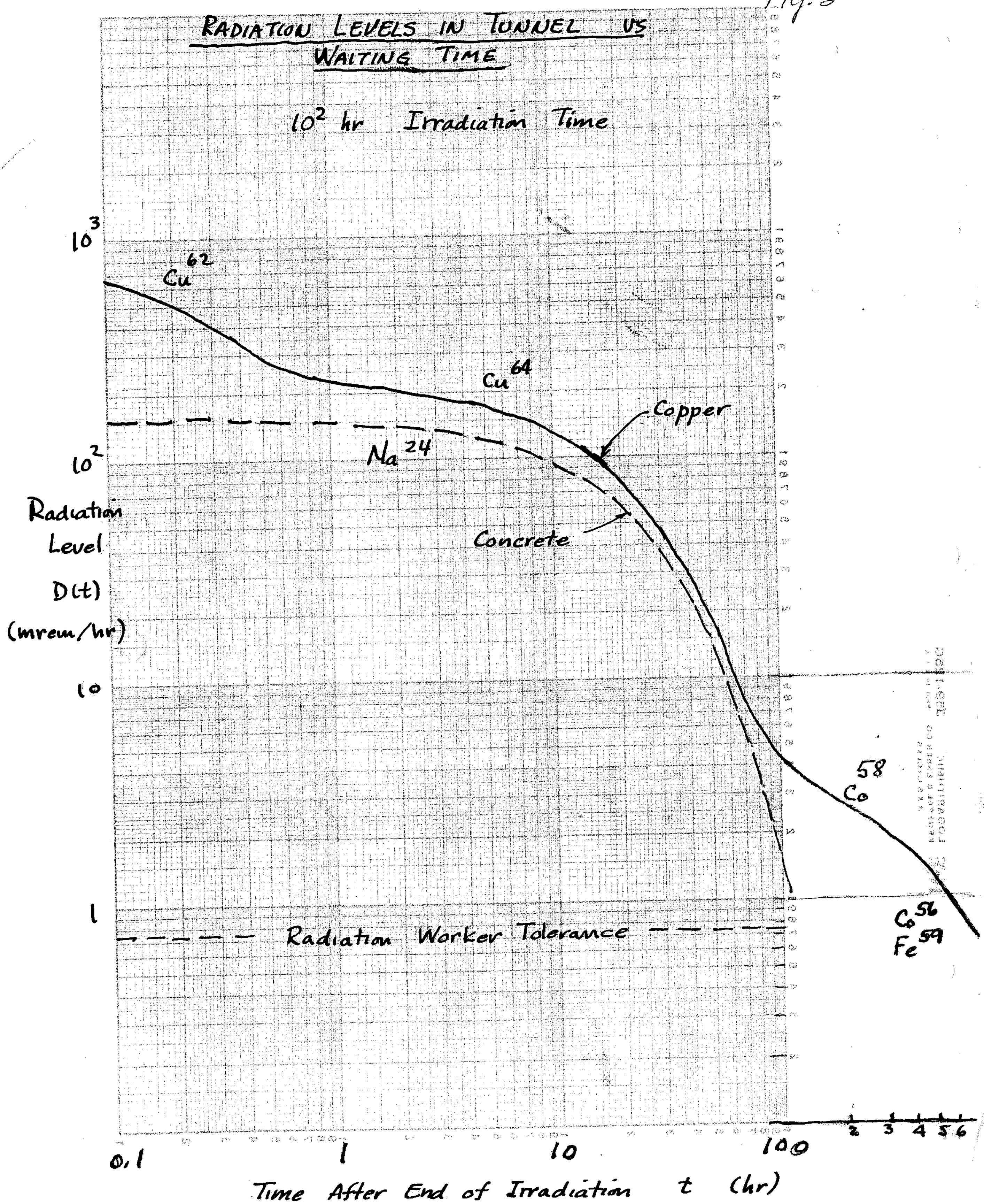

RADIATION LEVELS IN TUNNEL VS WAITING TIME
10^2 hr Irradiation Time
10^3
10^2
10
1
Radiation Level D(t) (mrem/hr)
Cu^{62}
Cu^{64}
Copper
Na^{24}
Concrete
Co^{58}
Co^{56}
Fe^{59}
Radiation Worker Tolerance
0.1
1
10
100
2
3
4
5
6
Time After End of Irradiation t (hr)

Fig. 4

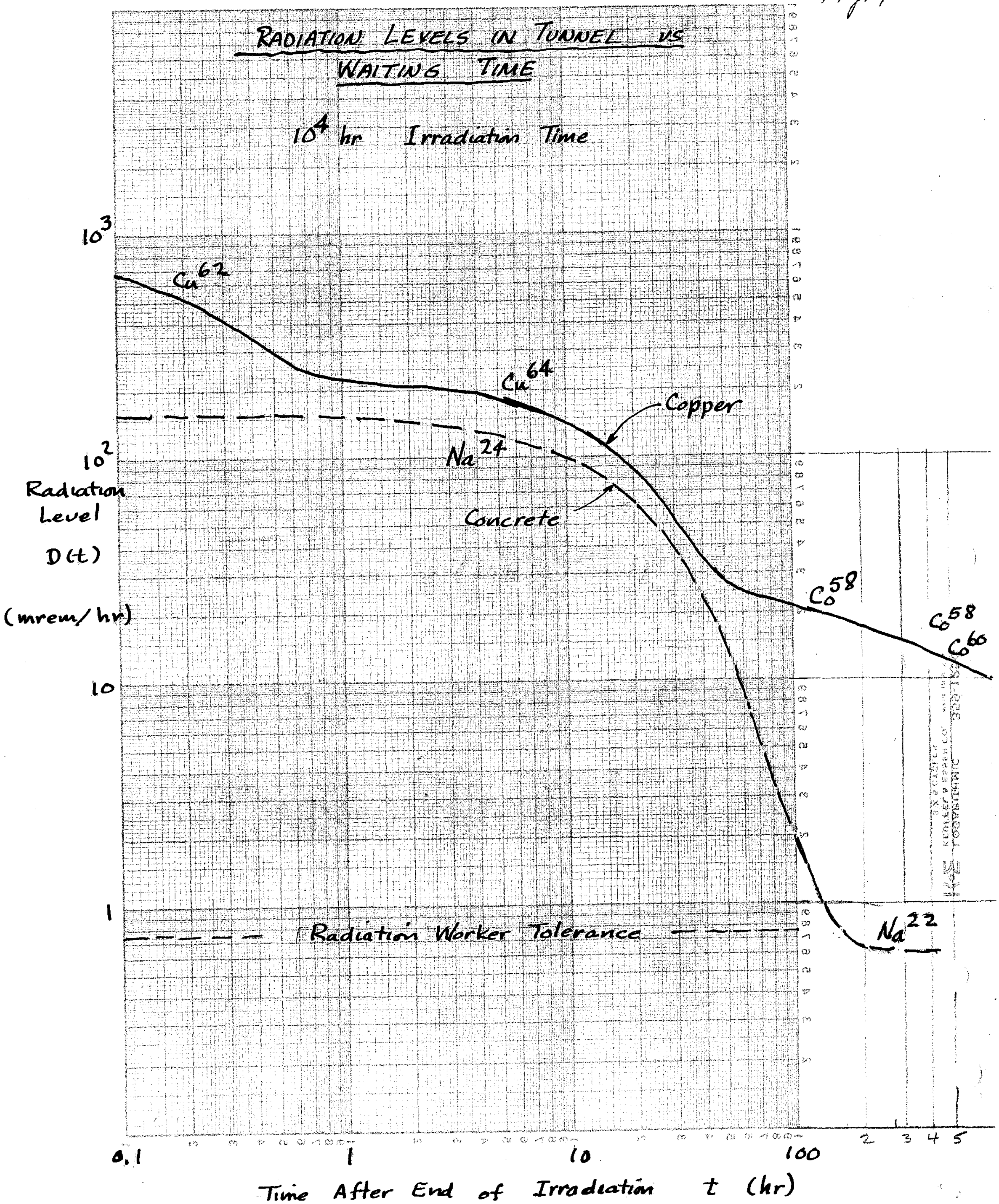
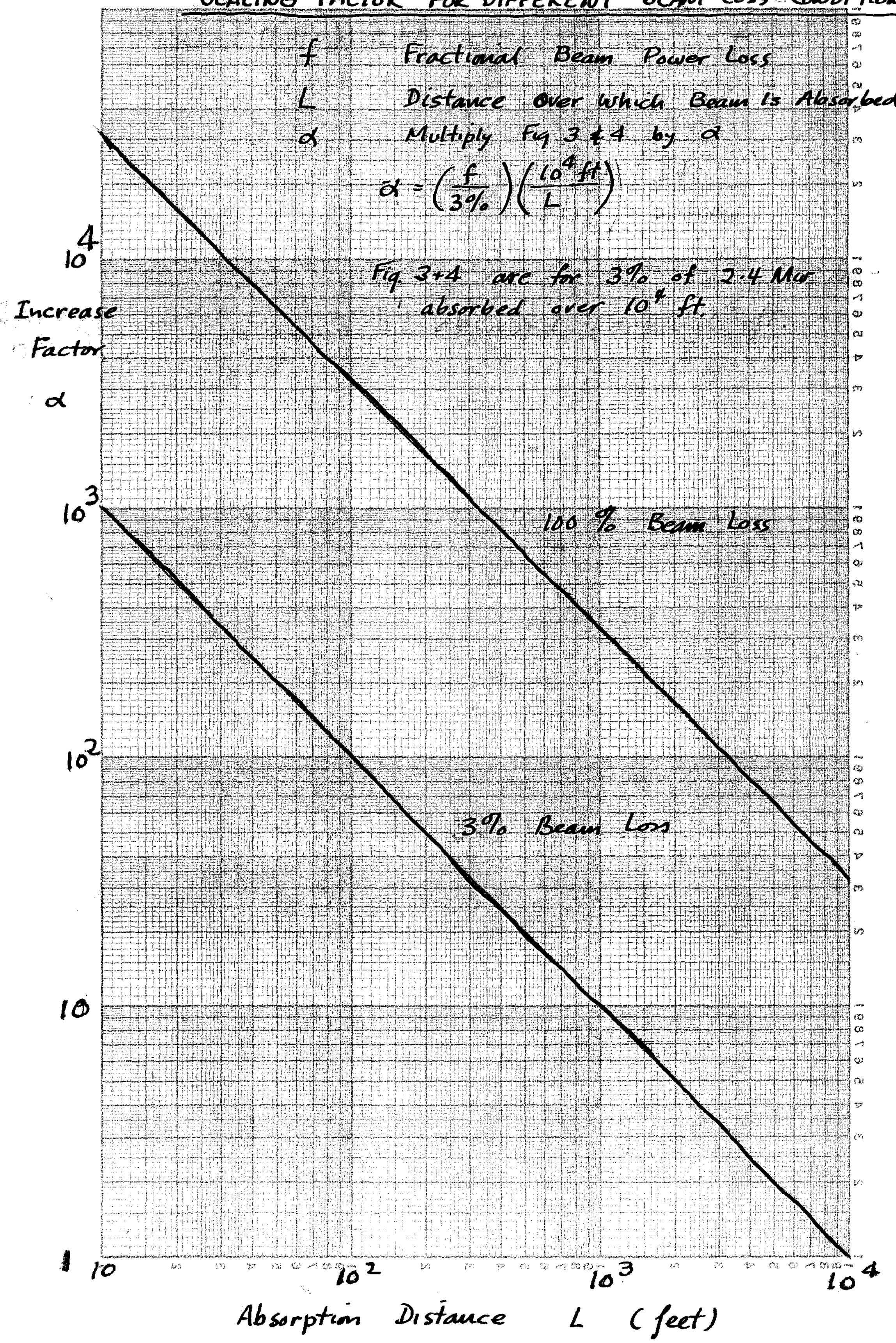

RADIATION LEVELS IN TUNNEL vs
WAITING TIME
10^4 hr Irradiation Time
10^3
10^2
10
1
Radiation Level
D(t)
(mrem/hr)
Cu^62
Cu^64
Copper
Na^24
Concrete
Co^58
Co^58
Co^60
Radiation Worker Tolerance
Na^22
0.1
1
10
100
2
3
4
5
Time After End of Irradiation t (hr)

Fig. 5

SCALING FACTOR FOR DIFFERENT BEAM LOSS CONDITIONS



B. Nuclear Reactions

Each γ induced nuclear reaction can leave behind a radioactive nucleus; it also gives rise to some nuclear particles (n,p,π) which may in turn make nuclear interactions, and more radioactive nuclei. Are these secondary interactions significant sources of activity?

The spectra of nuclear particles and the cross sections are fairly well known, but the effective path length in the copper is poorly known--this is the nuclear analog of the differential photon track length.

For neutrons the differential energy spectrum at low energies comes from boil-off neutrons from giant resonance reactions and is approximately (T is now kinetic energy)

$$\frac{dN}{dT} = \frac{T}{\tau^2} e^{-T/\tau} , \quad \tau \approx 1 \text{ Mev}$$

$$\int_0^\infty \frac{dN}{dT} dT = 1 .$$

These neutrons are approximately isotropic. This distribution drops exponentially, but above about 5 Mev we expect the actual spectrum to drop only somewhat faster than about $1/T^2$ because the γ spectrum drops like $1/k^2$. At higher neutron energies the angular distribution becomes more forward peaked.

We make some rough calculations to get an idea of the magnitude of the activities induced by neutrons.

To get the neutron spectrum we join a $1/T^2$ spectrum to the boil-off spectrum at T_o

$$\frac{dN}{dT} = B \left(\frac{T_o}{T}\right)^2 \tag{17}$$

$$(T_o/\tau^2)\, e^{-T_o/\tau} \equiv B$$

For $T_o = 5$ Mev and $\tau = 1.2$ Mev

$$B\, T_o^{\,2} = 1.35 \qquad \text{(n-Mev)}$$

So for the higher energies

$$\frac{dN}{dT} = \frac{1.35}{T^2}\,, \qquad \left(\frac{\text{high energy n}}{\text{giant resonance reaction - Mev}}\right)$$

The total rate of giant resonance reactions is

$$R' = f(IE_o)\,\frac{N_o}{A}\,X_o\;\frac{\int \sigma dk}{k_o^{\,2}} \tag{11}$$

We take $k_o = 20$ Mev and $\int \sigma dk = 900$ Mev-mb which yield

$$R' = (3\%)(3.75 \times 10^{14}\; 4 \times 10^4)\;\frac{6 \times 10^{23}}{63.54}\;\frac{13 \times 900 \times 10^{-27}}{(20)^2}$$

$$= 1.2 \times 10^{14} \quad \text{sec}^{-1}$$

The total neutron differential spectrum is (n/Mev-sec)

$$\frac{dN}{dT} = \frac{1.35 \times 1.2 \times 10^{14}}{T^2} = \frac{1.7 \times 10^{14}}{T^2}\,, \quad T \text{ in Mev.}$$

The integral spectrum is (n/sec)

$$N(T_1) = \int_{T_1}^{\infty} \frac{dN}{dT}\,dT \tag{18}$$

$$= \frac{1.7 \times 10^{14}}{T_1}\,, \quad T_1 \text{ in Mev}$$

At low energies where there are most neutrons we expect simple reactions. We list some approximate cross sections and thresholds for reactions on natural copper (I found no evidence pertaining to n,α).[8]

Reaction	Threshold Energy, T_2 (Mev)	Cross Section (barn)
Total		2.5
(n, p)	6	0.05
(n, 2n)	12	0.7 .

(Note that the $n,2n$ reactions give the same end products as the γ,n). Instead of estimating the path length, we assume that the probability that a neutron makes a particular reaction is σ/σ_{tot}. Then the saturation activity arising from a particular reaction is

$$R = \int_{T_2}^{\infty} \frac{\sigma(T)}{\sigma_{tot}} \frac{dN}{dT} dT \approx \left(\frac{\sigma}{\sigma_{tot}}\right) N(T_2) \tag{19}$$

$$R = \left(\frac{\sigma}{\sigma_{tot}}\right) \frac{1.7 \times 10^{14}}{T_2} \quad sec^{-1}, \quad T_2 \text{ in Mev.}$$

In Table III we show the yields of various daughter nuclides calculated with the assumption that the cross sections for Cu^{65} and Cu^{63} are the same. For instance for $Cu^{63}(\gamma, 2n)\, Cu^{62}$

$$R = \frac{0.7}{2.5} (69\%) \frac{1.7 \times 10^{14}}{12} = 2.7 \times 10^{12} \quad sec^{-1}$$

$$= 73 \text{ curies}$$

TABLE III

ACTIVITY IN COPPER INDUCED BY NEUTRONS

Reaction	Mean Life τ (hr)	Radiation ($+ \to \beta^+$, γ energy in Mev)	E_γ (Mev)	(Energy)(Activity) RE_γ (Curies-Mev)	$\frac{(RE_\gamma)\gamma}{(RE_\gamma)n}$
$Cu^{65}(n,2n)Cu^{64}$	18.4	+, -	0.60	20	20
$(n,p)Ni^{65}$	3.7	1.1,1.4	0.59	2.8	
$(n,\alpha)Co^{62}$	0.34	$\gtrsim 1.2$	≈ 1.3		
$Cu^{63}(n,2n)Cu^{62}$	0.23	~ 2% γ, +	1.10	80	15
$(n,p)Ni^{63}$	$\sim 10^6$	0	0.0	0	
$(n,\alpha)Co^{60}$	6.6×10^4	1.17,1.33	2.51		

For Cu^{64} and Cu^{62} the (γ,n) reactions dominate. The Ni^{65} is completely swamped by the Cu^{61} (See Table II) and is negligible. For the (n,α) reactions, the Co^{62} has a short life time and would have to have a very large cross section to be serious.

At higher energies more complex reactions can occur. To get an idea of the yield we take a hypothetical case in which $(g\sigma/\sigma_{tot}) = 1/10$, $T_2 = 100$ Mev and $E_\gamma = 1.0$ Mev. Then $RE_\gamma = 4.6$ curies-Mev. This is comparable with the calculated γ yields. However, the complex γ yieldx are uncertain.

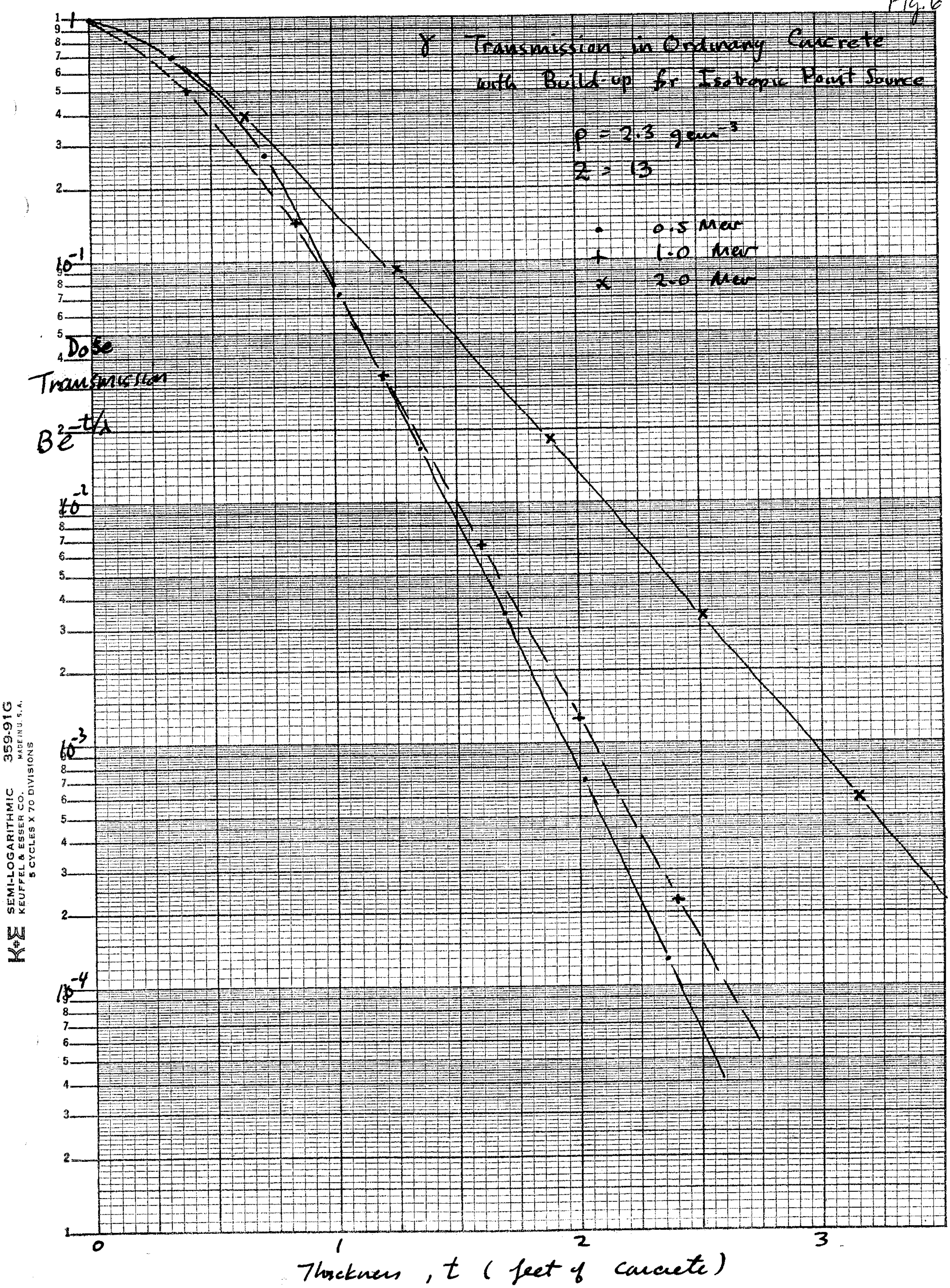
We conclude that the activities from interactions induced by nuclear particles are probably less than or comparable with those from γ induced reactions, but that they do not dominate.

V. SHIELDING

Figs. 6, 7, and 8 show the attenuation of photons of 0.5, 1, and 2 Mev in concrete, copper, and lead. For concrete we use the photon cross sections for aluminum.[10] The attenuation includes dose build-up factors, B, for point, isotopic source.[2] For concrete we use the dose build-up factor in water, and for copper that in iron. For densities (g cm^{-3}) we use 2.3 for concrete, 8.9 for copper, and 11.3 for lead. We summarize the mass absorption coefficients[10] (μ in cm^2/g), and the absorption mean free paths used.

Material	Quantity	Photon Energy (Mev)		
		0.5	1.0	2.0
Aluminum	μ	.0845	.0608	.0452
Concrete	λ (ft)	.169	.200	.315
Copper	μ	.0792	.0561	.0398
	λ (in)	.560	.788	1.39
Lead	μ	.166	.0720	.0451
	λ (in)	.210	.484	.772

Fig. 6


γ Transmission in Ordinary Concrete
with Build-up for Isotropic Point Source
ρ = 2.3 gcm⁻³
Z = 13
• 0.5 Mev
+ 1.0 Mev
x 2.0 Mev
Dose Transmission
Be^{-t/λ}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
Thickness, t (feet of concrete)
SEMI-LOGARITHMIC 359-91G
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

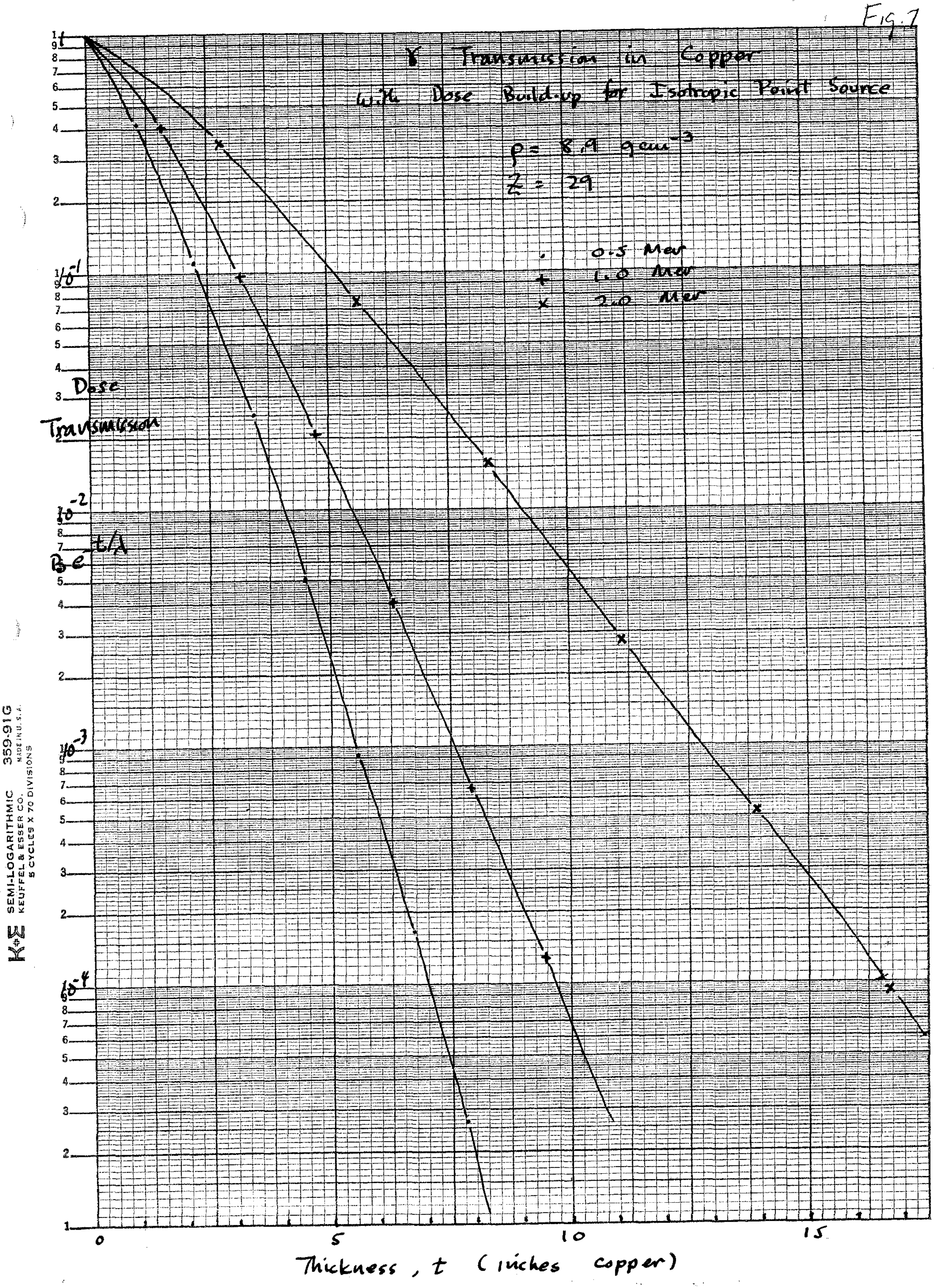
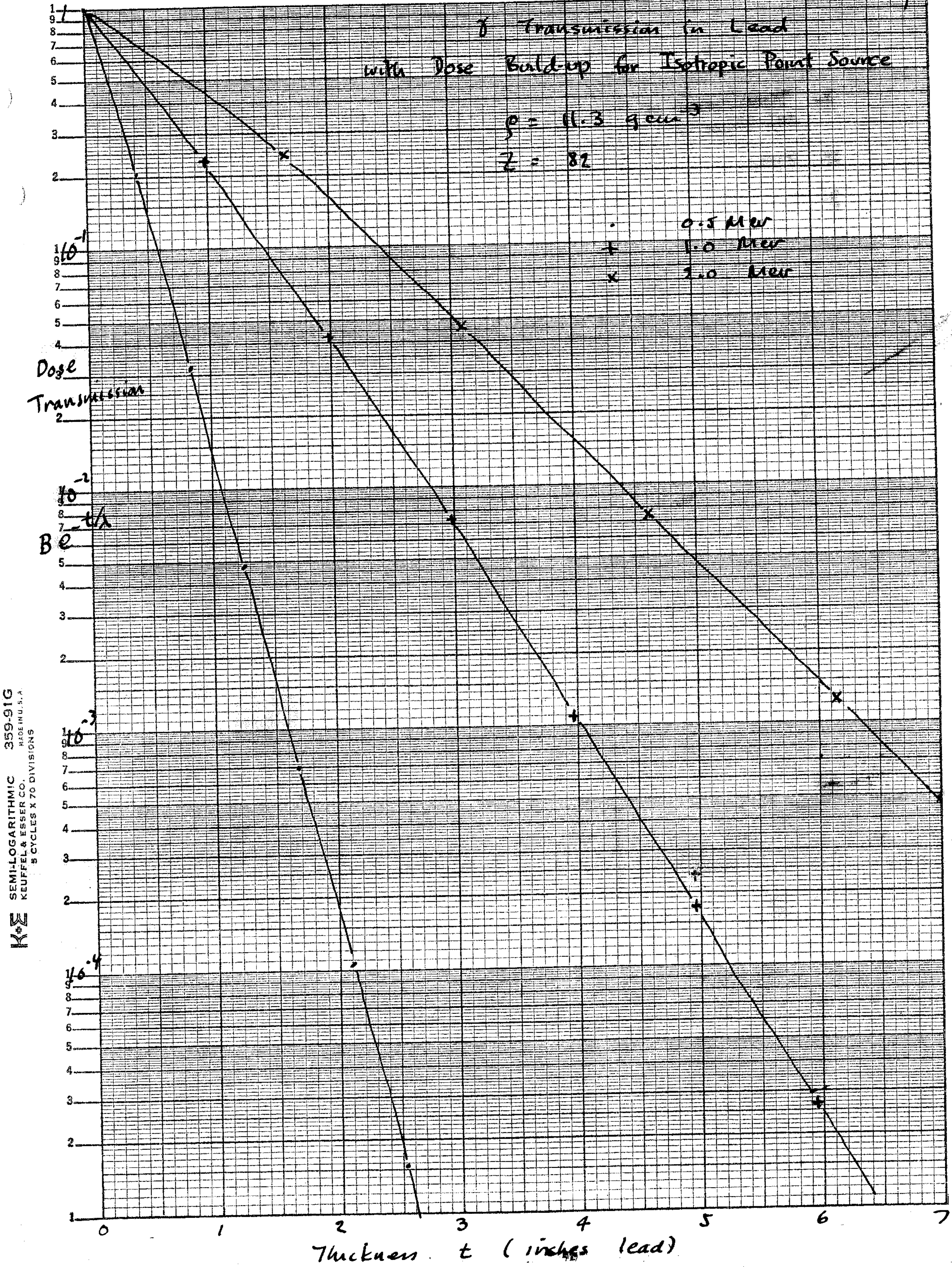


Fig. 7
γ Transmission in Copper
with Dose Build-up for Isotropic Point Source
ρ = 8.9 gcm⁻³
Z = 29
· 0.5 Mev
+ 1.0 Mev
x 2.0 Mev
Dose Transmission
Be^{-t/λ}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
Thickness, t (inches copper)
SEMI-LOGARITHMIC 359-91G
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

Fig. 8


γ Transmission in Lead
with Dose Build-up for Isotropic Point Source
ρ = 11.3 g cm⁻³
Z = 82
· 0.5 Mev
+ 1.0 Mev
x 2.0 Mev
Dose Transmission
$Be^{-t/\lambda}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Thickness t (inches lead)
K+E SEMI-LOGARITHMIC 359-91G
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

REFERENCES

1. "Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays," NBS Handbook 75, p. 79.

2. Price, Horton, and Spinney, Radiation Shielding (Pergamon, London, 1957).

3. D. Strominger, J. M. Hollander and G. T. Seaborg, Rev. Mod. Phys. 30 585 (1958).

4. H. DeStaebler, "Radiation Levels Inside the Project M Accelerator Tunnel," M-263, SLAC, May, 1961.

5. "Protection Against Neutron Radiation Up to 30 Mev," NBS Handbook 63.

6. Debs, Eisinger, Fairhall, Halpern, and Richter, Phys. Rev. 97, 1325 (1955).

7. A. I. Berman and K. L. Brown, Phys. Rev. 96, 83 (1954).

8. R. J. Howerton, "Semi-Empirical Neutron Cross-Sections," Part II, Vol. I, UCRL-5351, University of California, Livermore, Calif., November, 1958. D. J. Hughes and R. B. Schwartz, "Neutron Cross Sections Supplement No. 1" BNL-325, Brookhaven National Laboratory, Upton, New York, January, 1957.

9. For example, for approximate values see L. S. Edwards and F. A. MacMillian, Phys. Rev. 87, 377 (1952).

9.

10. J. H. Atkinson and B. H. Willis, "High-Energy Particle Data, Vol. II" UCRL-2426(rev), University of California, Berkeley, Calif., June, 1957.

11. F. J. Muckenthaler, W. R. Champion, J. L. Hall, and V. R. Cain in "Applied Nuclear Physics Division Annual Progress Report," ORNL-2389, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October, 1957.