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RADIATION HAZARDS OF A HIGH INTENSITY PROTON LINEAR ACCELERATOR

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Linear accelerators have been traditionally associated with high intensity beams. Now that there are a number of proton linacs with average currents of the order of hundreds of microamperes contemplated, a review of some of the problems associated with these high intensities seems pertinent. In the various injector applications, the average currents will be somewhat lower, while the peak currents will remain high, and some of the remarks on the loss of a single pulse will be applicable.

In Fig. 1 is shown a schematic diagram of the mechanism for the production of radiation hazards by protons of the order of 1 GeV (after the reactor particle genealogy diagram by E. P. Blizard), setting forth the origin of the three major problems associated with accelerators: shielding, radiation damage and activation.

The high energy nucleons and pions and their derivatives from the "target" nucleus are indicated as "useful beams" (from the meson factory point of view). Those that are not separated from the primary beam and used experimentally will next interact with a nucleus in some nearby object. The high energy particles result from the intranuclear cascade process, of the sort theoretically treated

by Metropolis[1,2] et al, and more recently, by Bertini.[3] The high energy neutrons produced in successive cascades transport most of the energy through the shielding because charged particles have a finite range, usually somewhat less than the mean free path for an inelastic event (of the order of 100 gm/cm^2 for nucleons). If the primary energy is in excess of about 10 GeV, some of the high energy pions may decay before stopping or interacting, and produce a flux of fast muons which constitute the most serious shielding problem. However, at any energy for which proton linacs have been seriously considered, high energy neutrons control the shielding.

The highly excited residual nuclei from cascade events decay by evaporation of neutrons and various light nuclei, with an average energy of between 5 and 10 MeV, and a maximum energy which is rarely above 30 MeV. This process has been treated theoretically by Dostrovsky, et al.[4] The evaporation particles cause most of the radiation damage, and again, it is principally the neutrons which are responsible. However, some of the charged evaporation particles can initiate secondary reactions leading to neutrons. Another possible source of evaporation particles is the first interaction of the high energy particles. In addition, some of the "cascade" particles are of low energy and augment the evaporation spectrum, to the extent of perhaps 10% at 1 GeV. The lower energy cascade and the evaporation particles are almost isotropic.

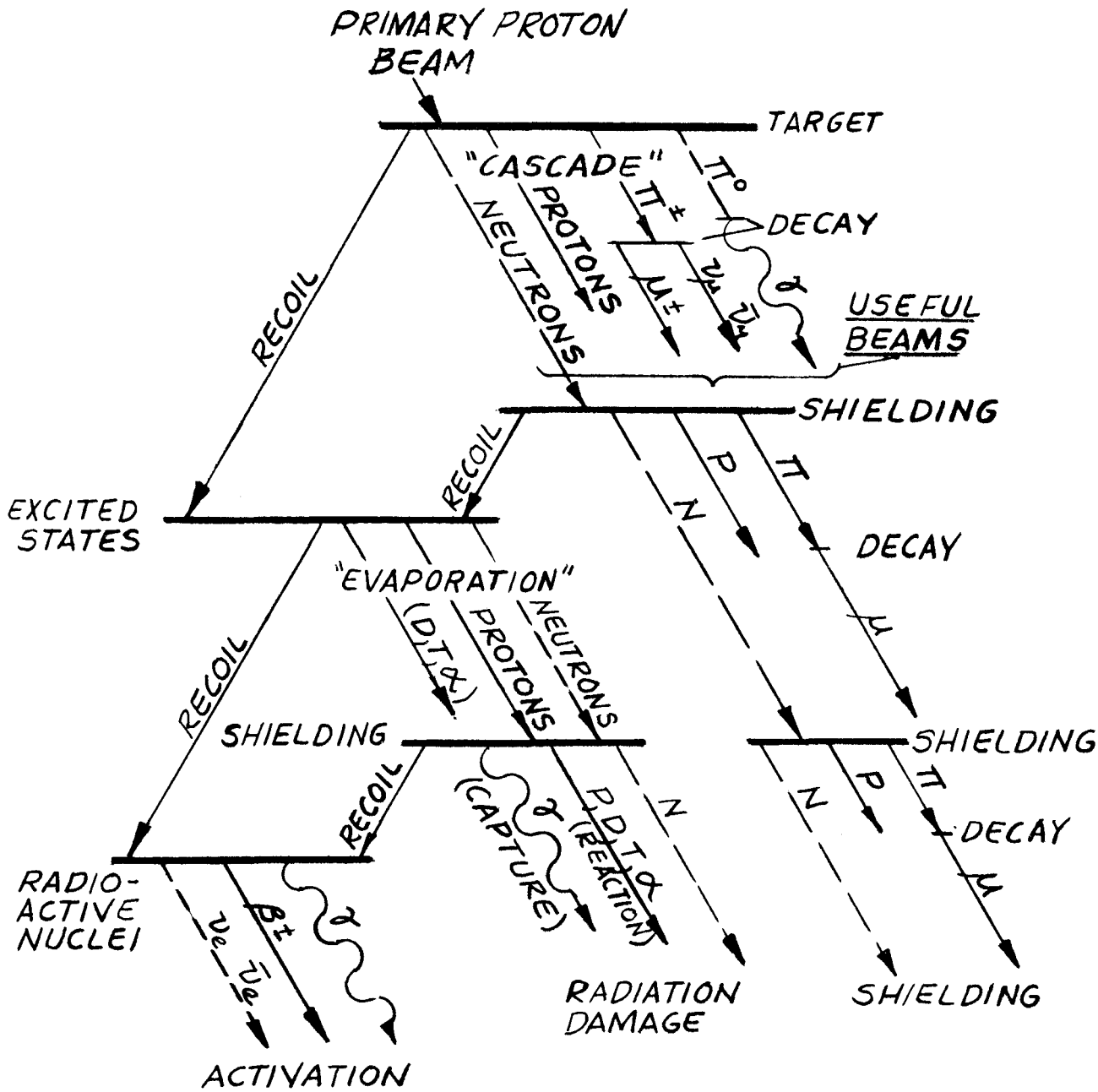

FIG 1. SCHEMATIC MECHANISM OF SECONDARY PARTICLE PRODUCTION FROM PROTONS OF ABOUT 1 GEV K.E.

The radioactive nuclei left from primary and higher order reactions are the activation. This is increased by the capture of thermal neutrons, which are created by evaporation neutrons moderated in and reflected from the walls of the enclosure. Thermal and low energy evaporation neutrons diffuse through apertures in the shielding and create local shielding problems.

Shielding

Much of the information about shielding for the planned Yale proton linac has been previously presented.[5] An independent estimate of the concrete thickness required around a 100 μA meson factory yielded 35 ft,[6] while we find that about 45 ft is a better thickness to use in the forward direction. The difference is partly caused by the expected tenfold increase in beam intensity (which requires 5 ft more) and also by the use of a somewhat lower value for permissible high energy neutron fluxes.

It is only the higher energy neutrons which are difficult to shield, as can be seen from a curve of the half-intensity thickness versus neutron energy, which is essentially flat at energies above 250 MeV.[6] Our neutron flux values were derived from some of the unpublished data of Metropolis, *et al*[7] which yielded an energy spectrum in each angular interval. These values were further adjusted to include the lower energy neutrons produced by an 800 MeV proton "stopping" in copper, weighting the neutron multiplicity at any energy by the probability of survival

to that energy. The thickness of concrete in each direction was then obtained by an iterative calculation so that the dose rate was 2.5 mrem/hr at the surface of the shield. This provided the contour of an "idealized concrete shield", which is shown as a function of angle in Fig. 2.

There is a superposed plot of the yield per solid angle of the sum of all neutrons above 240 MeV (in arbitrary units).[7] The similarity of the curves indicates that an elaborate calculation is unnecessary if one knows the required thickness in one direction and the angular distribution of high energy neutrons. The idealized shield is imagined to be around a point source of neutrons. On replacement of ordinary concrete by some denser material thickness adjustment must be made to compensate for the inverse square variation. No correction was made for secondary scattering of neutrons within the shield.

The above detailed calculation of the shielding is somewhat different from the practice usually followed at a new accelerator installation: when in doubt, simply add a few more feet of shielding. There are two reasons for not doing this in our case. We wish to bring out short-lived particles through the side walls of the target area and minimize the beam path. This is why iron is used to replace concrete in one place. Also, additional shielding over the face of a large structure adds quite substantially to the cost. The calculated shielding thickness presented in Fig. 2 is for a completely stopped beam. Actually, a separate target room will be used and

the beam stopped in a special enclosure. The high energy neutron production will be reduced by a factor of about ten in the target room and the lateral shielding can thus be reduced by 5 ft from these values.

The high energy neutron skyshine has not been examined in any detail, but there is some evidence that it falls off faster than r^{-1}.(6)

So far, only the shielding for the beam use and disposal areas have been considered. The shielding around the linear accelerator can be much lighter, because we protect against steady-state beam loss. If a single (2 msec) beam pulse should begin to be lost, neutron detectors located near the accelerator axis will respond and disable the beam at the ion source, presumably within 100 μsec. Other beam spill detectors will be connected to the disabling signal, and the accelerator should at most lose one 2 μsec pulse. The shielding along the length of the accelerator is sufficiently thick so that personnel standing opposite the point at which a complete pulse is lost will receive no more than a few millirem. More recent considerations suggest that the losses will almost never be concentrated at one point and that less shielding may be needed.

Permissible Fluxes

There is some uncertainty about the relation of high energy neutron flux to dose rate. Recently Gibson(8) at ORNL and Neary at Rutherford(9) have re-evaluated the

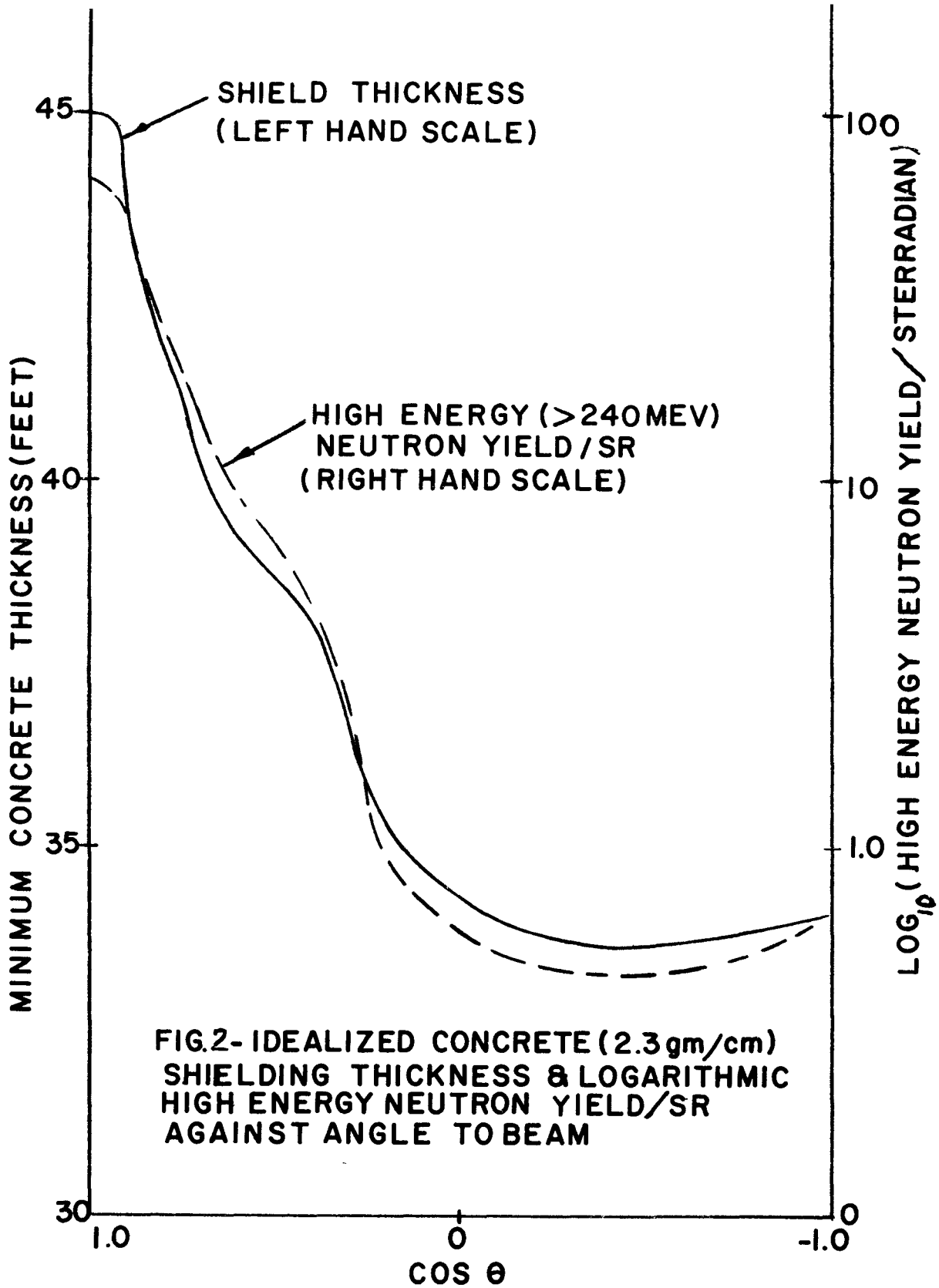

FIG.2- IDEALIZED CONCRETE (2.3 gm/cm) SHIELDING THICKNESS & LOGARITHMIC HIGH ENERGY NEUTRON YIELD/SR AGAINST ANGLE TO BEAM

permissible high energy fluxes, including the effects of spallation events in tissue. Neary includes the cascade particles coming out of the shield, and therefore his "permissible neutron flux" (which drops to about 1 cm^{-2} sec^{-1}) at 1000 MeV uses the neutron flux as an index of the total dose, caused by neutrons plus their associated equilibrium fluxes of fast protons, pions and muons. Neary's values have been used in calculating the shielding.

There are at present, no high energy neutron counters of the kind needed for a rapid and accurate determination of fluxes, and some developmental work should be initiated on this problem.

Radiation Damage

The radiation resistance decreases in the sequence: metals, inorganic materials, organic materials and semiconductor devices. Many of the studies on this subject have been done with either the fission spectrum from a reactor - the "fast" spectrum - or with the so-called "pile" spectrum, which includes a large component of thermal neutrons. These two spectra are sometimes not differentiated in the literature. Neither spectrum closely resembles the evaporation spectrum, but the more energetic evaporation neutrons penetrate the material and, after a few collisions, come to resemble the fission spectrum.

Metals and inorganics have their properties changed by the production of point Frenkel defects within the microcrystalline structure. These are caused when an atom

receives more than the displacement energy (10 to 30 eV) from a collision.[10] Particles of kinetic energies down to a few kilovolts can do this, but charged particles tend to give up less energy in nuclear collisions (Rutherford scattering reduces the average recoil energy of the struck nucleus) and lose most of their energy by electron collisions. Thus while a fission neutron of average energy $\sim$ 1.5 MeV can cause about 1000 displacements, a proton of the same energy produces about 4.[11] Thermal neutrons generally cannot create Frenkel defects. Evaporation neutrons each produce a few high energy charged particles in the process of slowing down to an average energy comparable to that of fission neutrons, and thus can roughly be compared to them in metals and inorganics.

When semi-conductors are considered, the lower displacement energy (in some instances so low as to be well into the thermal neutron distribution) and the reduction of the lifetime of minority carrier by charged particles (through the production of new energy levels) make them very sensitive to all kinds of radiation.[12]

Organics are damaged by breaking of their molecular bonds. Charged particles are at least as effective for this as neutrons. It is more appropriate to measure an organic radiation dosage in "rads" that is, in the density of energy deposited, as is done in the case of biological organisms.

Metals and inorganics (to some degree) show greatly enhanced radiation effects when irradiated at temperatures below about 40°K. The changes can sometimes be partially or totally annealed by raising the temperature.[10] There is, however, often some hysteresis in the radiation-annealing cycle. Dimensional changes of 1 or 2% are sometimes observed in typical metals (Cu, Al, Fe) irradiated with 10^{20} neutrons/cm^2 at liquid hydrogen temperatures. This indicates that some care should be taken with the use of cryogenic devices around a very high intensity neutron source. It also suggests that there might be some obstacles to the development of a practical cryogenic accelerator.

The radiation sensitivities in Fig. 3 are taken only from experimental studies at room temperatures.[13-22]* Almost all the data on organics relates to their lifetime as insulators, although there is one report of a rubber gasket failure indicated. Organics are to be related to the right-hand scale (megarads) and the others to the left-hand scale (neutrons/cm^2) and the scales are very roughly comparable to each other (i.e., 1 rad $\sim$ 10^8 n/cm^2).[21] The lethal dose for humans has been plotted to give an idea of the relative magnitude.

This simple method of presentation cannot present all the parameters. One might note the case of concrete, in which the lateral breaking strength decrease (loss of tensile strength, in effect) seems to relate more closely

* References shown on Fig. 3.

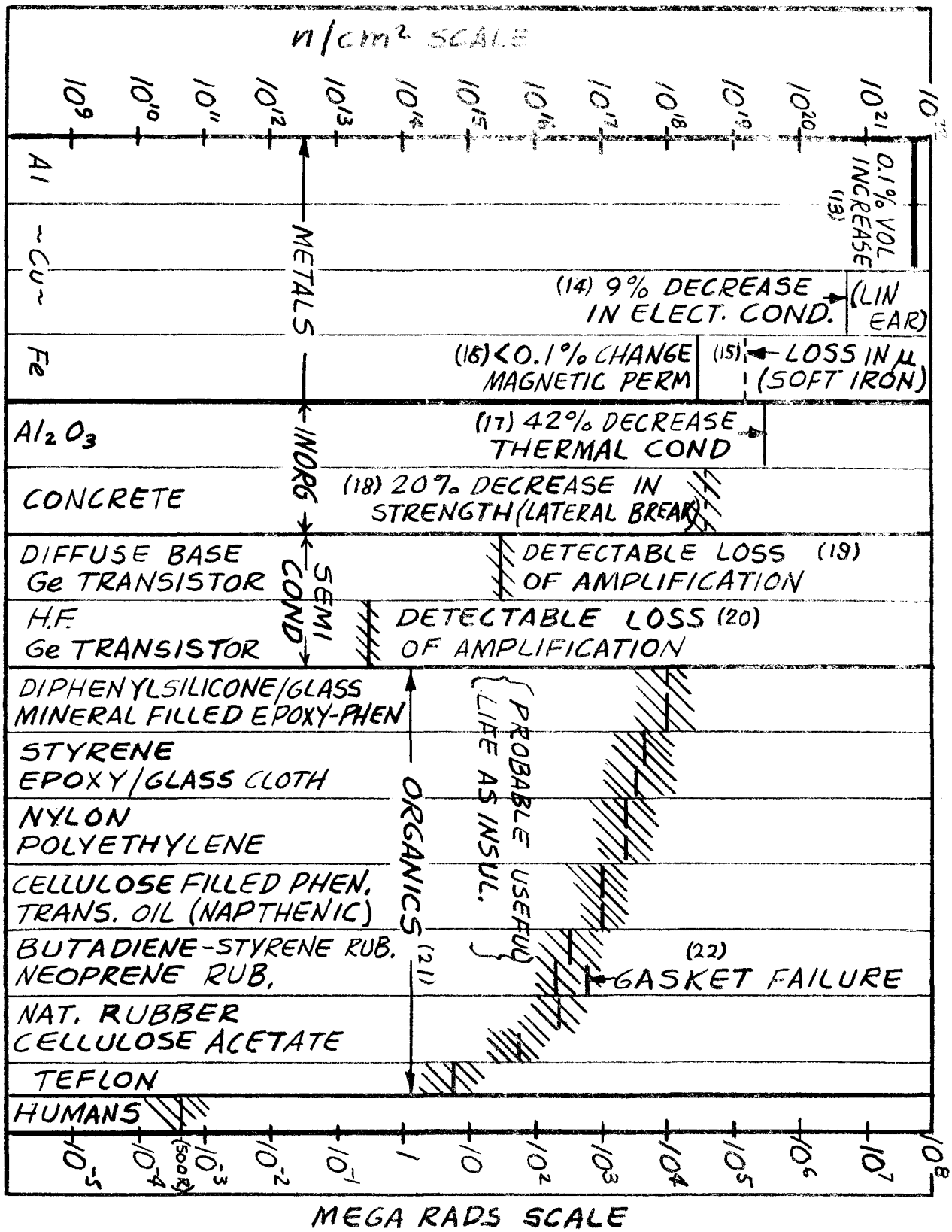

FIG 3 - RADIATION DAMAGE IN VARIOUS MAT'LS (ROOM TEMP)

to dose rate than to integrated dose, because it is the resulting thermal stresses that weaken the concrete.[18] There are reports of concrete structures surviving without undue damage above 10^{20} n/cm^2, for low dose rate.[23]

The most important radiation damage problems to be considered in linear accelerator design seem to be these:

Length Increase: A copper cavity may change its linear dimensions by ~ 3×10^{-4} after receiving 10^{22} neutrons, and thus change its frequency. Tuning devices would accommodate this.

Conductivity: The conductivity, and thus cavity shunt impedance, decreases linearly with neutron irradiation. This problem can be solved by making provision for additional input power and more cooling.

Permeability: Focussing magnet iron may lose permeability (no good data exists on this -- the point shown is for 3.5% Si steel) and this requires provision for more current.

Resistivity: Insulation of organic magnet windings may deteriorate.

Elasticity: Organic vacuum gaskets may polymerize, and metal gaskets harden.

General: Associated electronic equipment - pulse transformers, insulators, semi-conductor devices - may become unreliable or fail altogether.

Activation

There are two general categories of activation. One comes from the high energy events directly, and might result

in the production of active isotopes of atomic number 5 or 6 less than the target nucleus and of an atomic weight 10 to 15 lower. The second type results from simpler reactions induced by the evaporated particles, and by capture of the thermal neutrons produced by neutron moderation in the walls of the enclosure.

Not very much can be done about the direct interactions because copper (in the accelerator) and brass, aluminum, stainless steel or iron (in the target area) will usually be the intercepting material. The secondary beam forming targets can be of some particularly inactivable material (e.g., carbon) and it is presently proposed to stop the beam in water. Direct activation has been studied by Barbier, who exposed a number of small samples inside the CERN synchrocyclotron.[24] The exposure time was more than a year, thus permitting long-lived activities to build up. The samples received a mixture of radiations.

The curves of activity of several important materials is shown in Fig. 4, plotted in counts/sec-gram against time in days. The activities are long-lived. Thin foils directly bombarded by protons for a few hours in the Nevis Cyclotron showed a much more rapid decay during the first day and very little long-lived activity. Three materials (Al, Cu, Fe) have been extrapolated backward in time according to the calculations of the ORNL group.[25] Unfortunately, one cannot perform a direct normalization because the original flux is unknown.[26] High energy neutron-induced activities follow essentially the same decay curves.

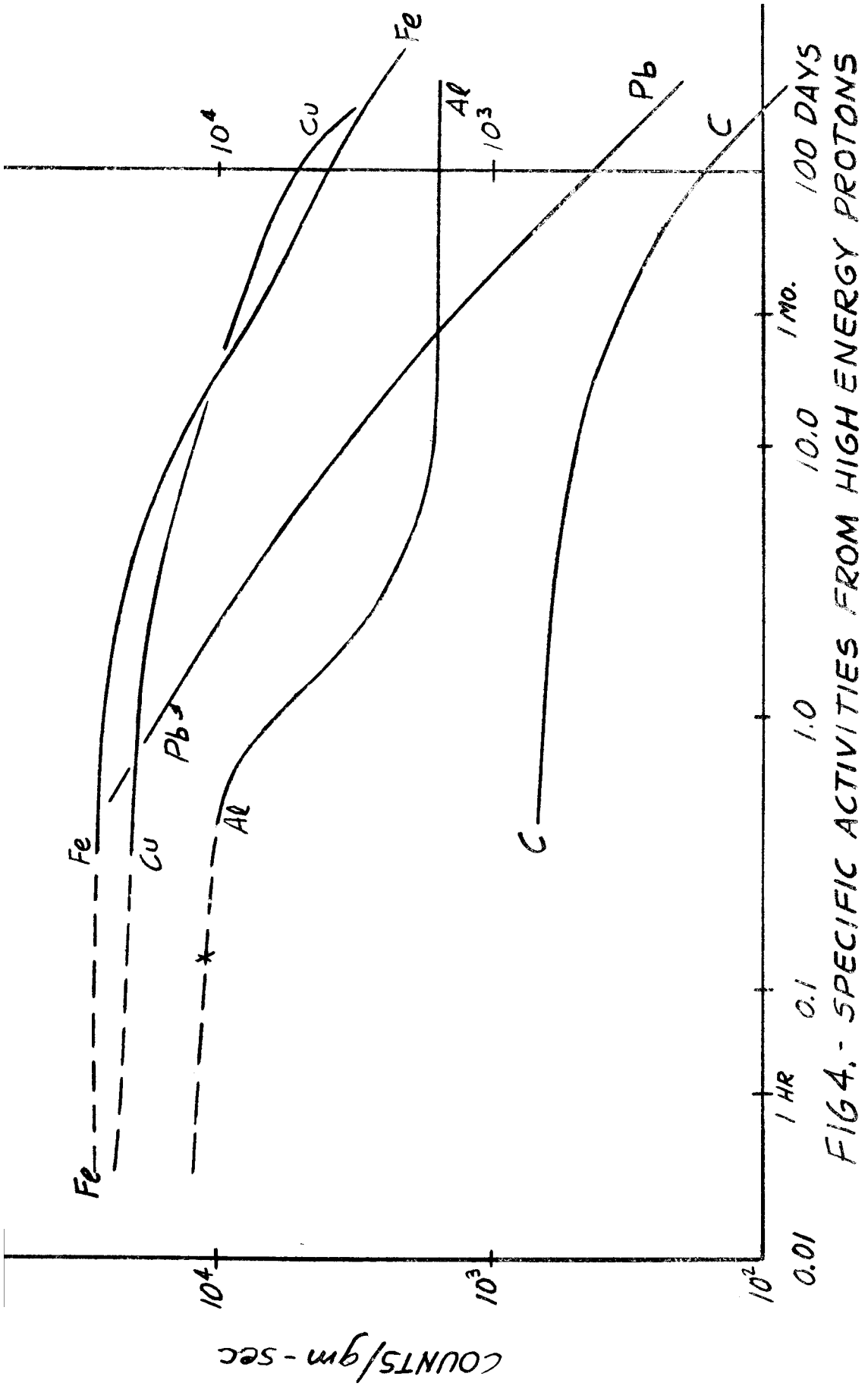

FIG 4. - SPECIFIC ACTIVITIES FROM HIGH ENERGY PROTONS

Where usable, carbon or SiO_2 (not shown, but between C and Al) seem to be the most satisfactory solids to allow the beam to strike.(27)

The secondary activation, over which one might have hoped to have some control, has been mostly studied in reactors. Certain activation calculations can be performed on the assumption of a typical evaporation spectrum and the published cross sections. The latter are, at present, not as complete as one would like. Table I lists a number of those that are likely to be important.(28-29) The concrete aggregate assumed here is granitic. A limestone aggregate reduces the Al content by almost an order of magnitude, but increases the Ca content correspondingly.(30)

Evaporation Neutron Yield

The number of evaporation neutrons produced per stopped proton can be calculated by numerical integration from the values of Dostrovsky(4) (and from other parameters). Fig. 5 shows the yield in copper per stopped proton as a function of the proton range. It is linear up to 300 g/cm^2 (a range for 700 MeV protons) and then falls off but because of cascade augmentation, I use the linear extrapolation: yield = 10^{-2} neutrons/g/cm^2 range per stopped proton.(31)

In the target and beam stopping rooms, light elements will be inserted in the beam, and the targets will produce fewer evaporation neutrons per stopped proton, but also have a somewhat shorter range. Therefore, the values shown in Fig. 5 are used as a fairly good approximation.

Table II gives some pertinent information about neutron production from a single 2 millisecond proton pulse which contains 2×10^{14} protons, at various energies.

TABLE I - ACTIVATION DATA IN A FEW COMMON MATERIALS

Material	Proportion by Weight	Possible Reactions	Threshold	Effective Cross Section (mb)	Half Life	Product Radiation (MeV)
Copper						
Cu^{63}	~ 70%	$Cu^{63}(n,2n)Cu^{62}$	11.5 MeV	500	10 m	0.51 (β^+ annih.)
		$Cu^{63}(n,\gamma)Cu^{64}$	0 (thermal)	4,500		0.51 (β^+ annih.)
Cu^{65}	~ 30%	$Cu^{65}(n,2n)Cu^{64}$	10.1 MeV	500	12.8 m	1.34
		$Cu^{65}(n,\gamma)Cu^{66}$	0 (thermal)	2,300	5.1 m	1.04, 0.83
Iron						
Fe^{54}	~ 6%	$Fe^{54}(n,\gamma)Fe^{55}$	0 (thermal)	2,500	2.7 y	(EC x-rays)
Fe^{56}	~ 92%	$Fe^{56}(n,p)Mn^{56}$	5.0 MeV	40	2.6 h	3.00, 2.65, 0.85
Fe^{57}	~ 2%					
Fe^{58}	~ 1%	$Fe^{58}(n,\gamma)Fe^{59}$	0 (thermal)	1,000	46 d	1.30, 1.10
Aluminum						
Al^{27}	100%	$Al^{27}(n,\alpha)Na^{24}$	6.0 MeV	30	15.0 h	2.75, 1.37
		$Al^{27}(n,\gamma)Al^{28}$	0 (thermal)	230	2.30 m	1.78
		$Al^{27}(n,p)Mg^{27}$	3.0 MeV	50	9.45 m	1.01, 0.84
Concrete (Grantic Aggregate)						
O^{16}	50%	$O^{16}(n,p)N^{16}$	11.5 MeV	20	7.4 s	8.9 to 1.76
Si^{28}	28%	$Si^{28}(n,p)Al^{28}$	4.2 MeV	500	2.30 m	1.78
Ca^{40}	3.7%	$Ca^{40}(n,\gamma)Ca^{41}$	0 (thermal)	200	1.1×10^5 y	(EC x-rays)
Al	4.5%	See above				
Fe	1.2%					
Others	QSP 100 percent					

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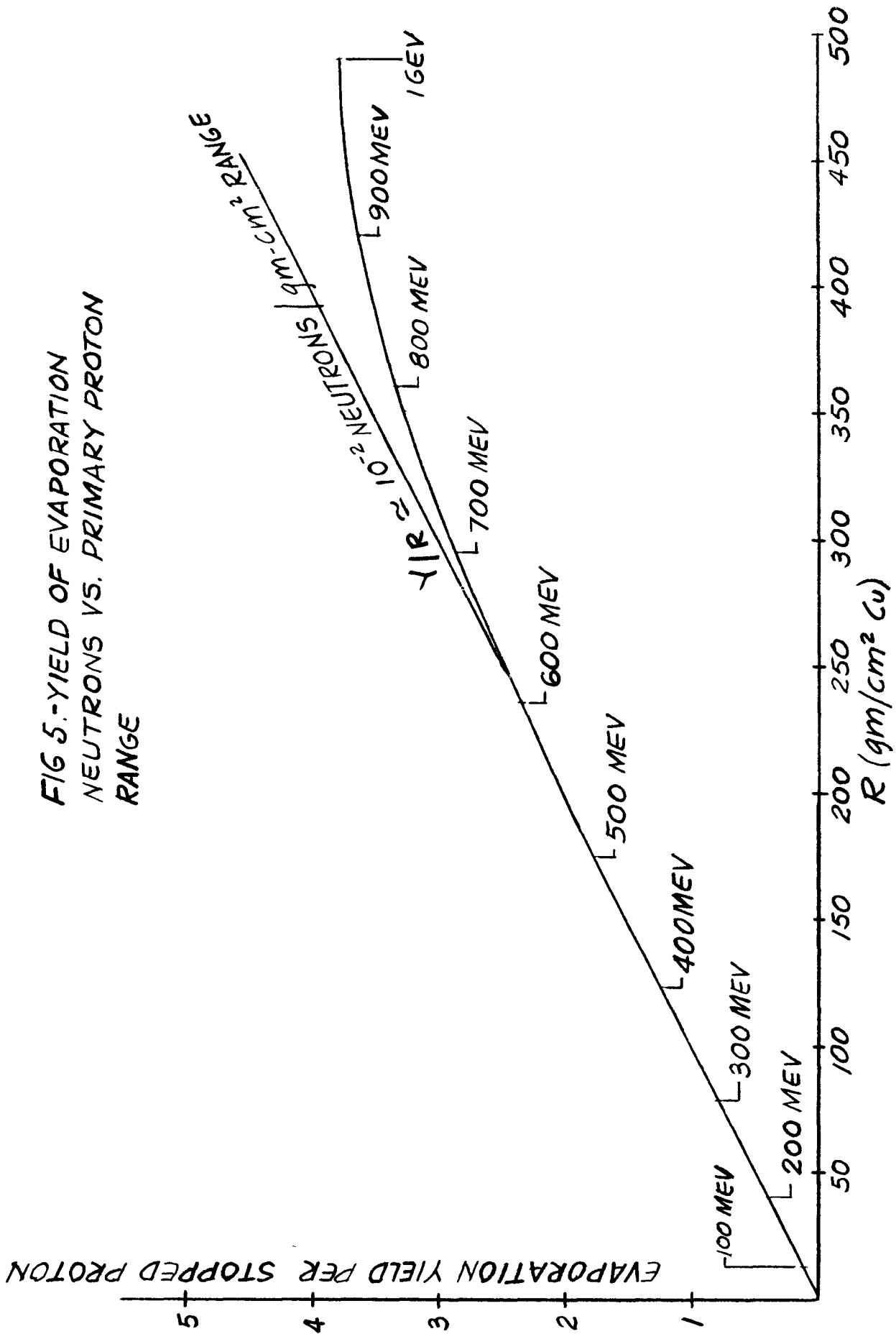

FIG 5.-YIELD OF EVAPORATION NEUTRONS VS. PRIMARY PROTON RANGE

TABLE II

Evaporation Neutrons Produced per 2 x 10^{14} Protons "Stopped" in Cu

E_p (MeV)	R (g/cm^2)	Neutrons/ pulse	Flux at 1 m (n/cm^2) (point source)	R/λin
50	3.5	7.0×10^{12}	5.6×10^{7}	~0.02
100	12.0	2.4×10^{13}	1.9×10^{8}	~0.08
200	40	7.8×10^{13}	6.2×10^{8}	0.31
400	122	2.4×10^{14}	1.9×10^{9}	0.95
600	235	4.7×10^{14}	3.7×10^{9}	1.8
800	360	7.2×10^{14}	5.7×10^{9}	2.8
1000	590	1.1×10^{15}	8.6×10^{9}	4.5

The fourth column of Table II gives representative integrated fluxes at an average distance of one meter. The next column gives the range divided by the mean free path for inelastic events.

Without precise normalization for direct activation, one can make a very rough estimate of the ratio of the number of directly activated nuclei to the number indirectly activated (by evaporation neutrons) by the relation:

$$\frac{N_p}{N_n} \sim (1-e^{-R/\lambda in})$$

which is of the order of 0.5 over the region of interest.

Estimate of the Hazards

A rough order of magnitude estimate of the neutron fluxes and activation in four "environments" -- the drift tube section, iris loaded section, target room, and beam stop room can be made on the basis of either single pulse or continuous loss.

I assume that either type of single pulse loss is spread over a distance of 1 m in the drift tube section, and over 5 m in the iris loaded section. In these two environments, the evaporation neutron fluxes are evaluated at radii appropriate to the radiation sensitive components. Activation magnitudes in either structure are estimated by assuming an "activation efficiency", (the probability that the evaporation neutrons will not escape from the tank) on the basis of a total mean free path in Cu and Fe of the order of 30 g/cm^2. These efficiencies are roughly, 90% and 40% for the drift tube and iris-loaded structures. Dose rates from the accelerator are calculated on the assumption that the short-lived copper activities given in Table I are the primary source of activity. This is adequate for single pulse loss, but may be in error for steady state loss. When self-attenuation in the structure is included, the dose rate is obtained from the gamma flux $\varphi_\gamma(E_\gamma)$ by the approximate relation

$$D_\gamma(r/hr) \simeq 2 \times 10^{-6} E_\gamma(MeV)\ \varphi_\gamma\ (photons/cm^2\text{-}sec)$$

assuming an appropriate distance from the beam center line in both environments. Table III gives the values of the

TABLE III

RADIATION HAZARDS IN FOUR 800 MeV PROTON LINAC ENVIRONMENTS

Environment and Energy	Beam Loss	Neutron Fluxes/cm^2	At Distance	Activ. Eff.	Iso-tope	Dose Rate	At Distance	Estimated Total Dose Rate
Drift Tube Section								
0.75 to 100 MeV	2×10^{14}	10^{11} to	1 cm	93%	Cu^{63}	0.40 to	2m	10 mr/hr
0.75 to 200 MeV	2×10^{14}	5×10^{12}			Cu^{64}	5 mr/hr		
Iris-Loaded Section								
100 to 430 MeV	2×10^{14}	5×10^{11} to	2 cm	40%	Cu^{63}	0.1 to	1m	5 to
200 to 800 MeV	2×10^{14}	4×10^{13}			Cu^{64}	10 r/hr		10 r/hr
Transition 200 MeV	6×10^{12}	3×10^{8}/sec	2 cm	40%	Cu^{63} Cu^{64}	1.7 r/hr	1m	0.5 to 5 r/hr*
Target Room								
430 to 800 MeV	2×10^{14}	10^{12} to 4×10^{13}	2 cm	~10%	Cu?	0.5 r/hr	1m	5 to
800 MeV	6×10^{15}	5×10^{9}/sec	1 m	Magnet	Mn^{56}	0.3 r/hr	1m	20 r/hr*
		2×10^{9}/sec	Therm	Walls	Na^{24}	1.5 r/hr	3m	
Beam Stop Room		6×10^{10}/sec	2.5 m	Walls	Na^{24}	90 r/hr	2.5m	>100*
800 MeV	6×10^{15}	3×10^{11}/sec	1 m					r/hr
		3×10^{10}/sec	Therm					

* Probably higher as long-lived activities build up.

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neutron fluxes and activation dose rates. A series of 2 to 4 targets of 10-30 g/cm^2 is assumed in the target room and a water tank as a final target in the beam stop room. In the latter two environments, an independent estimate of the ambient thermal flux is shown.

Conclusions and Recommendations

The following remarks are applicable to the proton linac under consideration by Yale. The assumed distance of beam loss (1m and 5m) for the values in Table III should be particularly noted; if the losses are eventually found to occur over a shorter distance, the neutron fluxes will be more intense, although the dose rates will not change by very much.

Drift Tube Section: Single pulse losses create no major difficulty with respect to radiation damage, and organic vacuum seals and magnet insulation can probably be used. The former will take of the order of 10^4 lost pulses and the latter, at least 10^5, if epoxy/glasscloth or another resistant material is used. Radiation hazards to personnel are trivial, partly because of the self-shielding of the tank and drift tubes. Ordinary good engineering design practice should suffice, except that semi-conductor devices cannot be used near the beam axis.

Iris Loaded Section: Single pulse losses create neutron fluxes about an order of magnitude higher than in the drift tube section. Near the high energy end, the use of organic gaskets is questionable.. This is particularly

true if steady state beam loss is likely at the drift tube to iris transition point.. If an assumed 1 μA is lost for a year the gaskets will have received of the order of 10^{16} n/cm^2 and be on the point of failure. The magnet insulation is somewhat less marginal. If replacement becomes necessary, they are more accessible than in the drift tube section. It is thus uncertain if there would be any economic advantage in using inorganic insulation on these. Semiconductor electronics should be kept out of this environment (at least, a distance of 2 m from the machine). The personnel hazard from activation is serious, largely because of the reduced self-shielding of the iris-loaded structure. The dose rates would be hazardous for a period of a few hours after a pulse loss. I would recommend that additional shielding be placed between the accelerator and the personnel access aisle, to facilitate prompt servicing of components.

Target Room: The neutron fluxes here are above $10^9 n/cm^2 sec$. It is clear that no organics should be used, either as vacuum seals, or as insulators in this room, and semi-conductors are absolutely excluded. Activation has now become a major hazard. Special precautions can be taken: iron can be protected from thermal neutron capture by a few mils of cadmium plating. For higher energy neutrons an effective technique might be to surround the magnet with thick pieces of some material like carbon which has only short-lived activities and would shield against the longer-lived activities underneath. Nothing can be done about the short-lived activities in the concrete walls.

As long-lived activities build up, the entire lining of the target room will probably have to be replaced and pro - vision has been made for this.

Beam Stop Room: Neutron fluxes and activation are sufficiently intense so that even resistant components will require occasional replacement. For example, the walls will receive about 2×10^{18} n/cm^2 in the course of a year, and some local damage is probable. Remote handling equipment and the exclusion of all unnecessary materials are required. Possibly some reduction in the fluxes and gamma ray hazards calculated here can be achieved by care- ful design of the stopping target, but the primary safety precaution will be isolation of the area.

QUESTION: I believe youranalysis is based on steady state radiation damage data. I wonder how that applies if you have a large ratio of thermal spikes introduced by this beam structure?

KNOWLES: This is based on steady state radiation damage data and it isn't completely applicable. However, it is the low energy neutrons which do most of the radiation damage - the high energy neutrons will tend to go right through an organic material. They also aren't well moder- ated in most metals. Unfortunately the information is not uniform -- they sometimes report the pile spectrum, and sometimes the fast fission spectrum. There is also a little data for 14 MeV neutrons. The evaporation spec- trum is not like the fission spectrum. It is peaked at a few MeV and zero at 20 or 30 MeV. The fission spectrum

normally has a peak at about 1.5 MeV. The sort of spectrum I would like to use for measurements has its peak higher. The data is not very good, but it is all we have just now.

QUESTION: Is there experimental work underway here at Yale?

KNOWLES: There is work by the SLAC group, but I haven't seen their data yet. We are hoping to do some parasitic runs using the best fast neutron spectrum possible out of the Yale Electron Linac.

QUESTION: Are you going to do radiation damage studies?

KNOWLES: I'm going to do activation first, because I think it is more of an immediate concern. And I think that radiation damage studies are too hard to do in a limited time.

HUBBARD: Is there any hope of undoing the radiation damage?

KNOWLES: I don't know very much about annealing the damage produced at higher temperatures in metals. Once you have damaged an organic it will tend to re-polymerize and it just falls to pieces. This might not apply in the case of a gasket. If a gasket has received 10^{17} n/cm^2, it might mean the vacuum will hold until you have to take that particular section off and then you find it's lost its elasticity and won't reseal. As to metals, it depends upon the metal and the property. I believe that inorganics can also be annealed to some degree. I don't think that there are really any careful bulk studies. Most of the work deals with microcrystalline structure and things like this.

FEATHERSTONE: I might mention that even in the very low beam currents at the University of Michigan linear accelerator, we get regular damage to gaskets that are located where they see some portion of scattered proton flux; of course, this is a direct beam, but in our case, despite our best efforts to shield them from the beam, the gaskets on the isolation valves at the ends of the cavities have a working life of the order of a year.

KNOWLES: The CERN synchrocyclotron has a teflon insulator on the dee stem and this is replaced regularly once a year, because it begins to show mechanical failure. This replacement is a routine matter, because they had one that failed after a year and a half. In their case, I'm not sure what radiation is causing it. It could be neutrons, but they have a strong residual gamma radiation field of the order of 1 to 2 r/hr outside of the tank. I think that it is an iron activity. This is what Boom, Toth and Zucker found in the 184-inch synchrocyclotron at Berkeley. They reported that a really long-lived activity was built up from the impurities in steel, cobalt, manganese, etc. I didn't include any manganese in Table I, but it has several very long-lived activities. Also, I ignored the thermals that come back from the walls, although they can make a substantial contribution to the activation.

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(26) Information received from Dr. R. S. Livingston since the conference indicated that additional data now permits the curves of Fig. 4 to be normalized.

(27) An erroneous statement about the specific volumetric activity of aluminum was made at the conference, which was called to my attention by Dr. A. Galonsky. Aluminum is almost an order of magnitude lower than Cu or Fe on an activity per unit volume basis.

(28) D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, 2nd ed., BNL-325.

(29) See Ref. 21, p. 334, for thermal neutron cross sections.

(30) Gladys White Goldstein, X-ray Attenuation Coefficients, N. B. S. Report 1003 (U. S. Government Printing Office, Washington 25, D. C.).

(31) Very few of the protons actually "stop." As indicated in Table II, only about $e^{-1.8} \approx 17\%$ of a pulse of 600 MeV protons escape inelastic collisions and come to rest.