RADIATION SHIELDING AND SAFETY CONSIDERATIONS FOR THE NAL 200 MeV LINAC

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ABSTRACT

The basic philosophy of tolerable beam losses and hadron shielding requirements that guides the design of all radiation shielding at NAL is described.

Also, data is presented to aid in estimating remanent exposure rates and shield thickness requirements. Penetrations to the linac enclosure, beam dumps and radiation safety interlock philosophy are presented, too.

Introduction

The NAL Linac is the newest of a long series of drift tube linear accelerators. As considerable experience and sophistication has been brought to its design, we expect few and small undesired beam losses.

An important consideration which comes from experience at other accelerators as well as from simple arguments is that there is a direct relationship between the thickness of the shield needed to protect personnel outside the enclosure during accelerator operation and the residual radioactivity after shutdown. This residual activity makes maintenance of the accelerator more difficult. Therefore, our general approach to radiation control in accelerator design has been to decrease beam losses rather than to increase the shielding thickness. Thus, we will always be able to maintain the accelerator conveniently. It is our firm intention that if there is undesired beam loss at some point, we will operate the accelerator at an intensity low enough to maintain tolerable residual exposure rates until the causes of the beam loss are understood and removed. Hence, we have designed the shielding for the whole accelerator on the basis of these expected beam losses.

At the same time, we have attempted to provide a safety factor by providing space for local shielding within the accelerator housings around beam loss points. There is also provision in the design of the housings for additional external shielding should that be necessary. However, in some locations where it would be prohibitively expensive to add shielding later on, a slight excess of shielding thickness was built in from the start.

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This approach expresses a willingness to proceed carefully while trying to avoid over-design (such as over-shielding) and always leaving room for corrective measures should the initial designs prove to be inadequate. The philosophy is that the savings on the whole NAL project by avoiding over-design will more than offset the extra expenses that necessary additional work may cost later on in some problem situations.

At a time when NAL was not yet officially in existence, good shielding calculations were becoming available for line sources of neutrons due to proton losses on copper through K. O'Brien[1] of the AEC Health and Safety Laboratory (New York Operations Office). Later, other calculations became available and they all added up to a harmonious picture of realistic tolerable proton beam losses, remanent exposure rates and beam loss detector designs.

Expected Beam Losses as Used in the Radiation Calculations

In order to be conservative in the design of the shielding walls of the linac where it would be nearly impossible to add bulk later on, it was assumed that the proton beam losses would be uniform along the linac and amount to 1.0% of the maximum possible linac current capability. The 1.0% loss for the full linac was obtained as follows:

Between tanks 1 & 2 (E_p = 10 MeV)	2%	- to occur on graphite scrapers, so it will produce no neutrons
Between tanks 2 & 3 (E_p = 37 MeV)	0.5%	- local shielding will be provided
Between other tanks	0.01%	- per junction, total of 0.06%.

With the local shielding one might take a total estimated loss of 0.1% as a basis for the design of the shielding walls. We chose 1% as a safe basis, thus incorporating a safety factor of 10.

The design and maximum expected proton currents are summarized in Table I below.

Table I

	Design Values	Maximum Values
Peak Current (mA)	50-75	100
Pulse Width (μsec)	30	100
Repetition Rate (Hz)	14-15/(3.2-4.0)	15
Average Current (A)	$5.25\text{-}10.5 \times 10^{-6}$	1.5×10^{-4}
Proton Current (sec^{-1})	$3.3\text{-}6.6 \times 10^{13}$	9.4×10^{14}

The length of the linac is 138 meters. Hence, the assumed uniform loss of 1% of the beam leads to the following loss rates (dI/dℓ),

Design: $2.4\text{-}4.8 \times 10^7$ p/cm-sec

Maximum: 6.8×10^8 p/cm-sec

The larger figure is used throughout the calculations, giving an additional safety factor of 14 to 28 in the expected mode of operation.

Exposure Rates from Remanent Radioactivity

The control of the maximum tolerable current losses is made in order to limit the remanent exposure rate due to induced radioactivity.

The significance of the maximum and expected beam loss rates upon the remanent exposure rate may be examined with the help of two calculations. One of the calculations was made at two energies with great care by R. G. Alsmiller[2], and the other one was a simpler one made for many combinations of proton energy, geometry, and irradiation times by P. J. Gollon[3]. These results presented on Table II are in good agreement. As it can be seen, no problems are expected from remanent exposure during normal maintenance work.

Table II

Exposure rates at 30 cm from the linac tanks resulting from current loss rates of 6.8×10^8 and 4.8×10^7 p cm^{-1} sec^{-1}.

Proton Energy	Exposure Rate (mR/hr)		
	P. J. Gollon[3]	R. G. Alsmiller[2]	
MeV Cooling Time:	8 hr	8 hr	1 hr
38	1.3/ .1	-------	-------
50	1.5/ .1	2.4/ .2	4.4/ .3
100	6.7/ .4	-------	-------
150	24/1.7	-------	-------
200	46/3.3	51/3.7	68/4.8

The systematic variation of the residual exposure with proton energy, geometry, and irradiation and cooling times may be seen in the following figures.

Figure 1 shows that the gamma ray exposure rate per proton lost is a sharply increasing function of proton energy. There are altogether ten curves: one for each of 5 cooling times and two shielding conditions. The $0 g/cm^2$ corresponds to the lack of shielding from activity that might be induced on the front face of a drift tube; the $40 g/cm^2$ corresponds to shielding from activity induced inside the bore of the drift tube.

Figure 2 shows the same data replotted with cooling time as the independent variable. It can be seen from the shape of the curves that for low proton energies the linac will cool down by a factor of 2 between 8 hours and 3 days after shutdown, after which its activity will remain rather constant in time. At higher proton energies the cooling will occur much less rapidly so that there would be little point in waiting more than one shift after shutdown before performing maintenance.

The above comments pertain to equilibrium conditions which will exist after the linac has been operating for several years. For shorter irradiation times the long-lived activity will not have reached equilibrium and hence it will not contribute as much to the gamma exposure rate. This is shown on Figure 3. There, the decay of the exposure rate produced by the bombardment of copper with 66 MeV protons for periods upwards of 1 day is presented for various irradiation times. It can be seen that the effects of beam losses which last only a few days disappear in a few days. Thus, for purposes of accelerator testing, experimenting, or diagnosis it will be possible to incur short-term losses much higher than the normal ones without seriously affecting the remanent exposure rates.

Design of Lateral Shield

The calculations have been carried out using K. O'Brien's results. The dose rate outside a thick shield is given by Mr. O'Brien as

$$I = k(dI/d\ell)/2\pi R$$

where k is a constant chosen for each proton energy, shielding material, and depth is the shield, $dI/d\ell$ is the loss above, and R is the transverse distance from the beam line to the observation point. Mr. O'Brien has given[1] tables of the constant k, which we have parameterized for computation[4].

The linac wall between the equipment gallery and the linac tunnel itself is made of ordinary concrete with a density of 2.3 g/cm^3. For the berm over the linac tunnel, the soil was compacted to a density of 1.9 g/cm^3 with a water content of 15%. The calculated dose rate one foot inside the linac gallery is shown on Figure 4. Curves for the dose rate at the side and top of the berm are similar.

Figure 5 gives the calculated required wall thickness as a function of distance along the linac. Walls of solid concrete, soil plus concrete, and the actual wall thickness is shown. The extra wall thickness near the 200 MeV beam switchyard was chosen to allow the operation of beam diagnostic equipment with total beam loss for short periods of time.

For architectural reasons the soil thickness of the berm is everywhere the same and equal to 11.5 ft. Hence, the dose rate at the 200 MeV end would be approximately equal to 0.15 mrem/h at maximum design intensity. In practice, we expect at least a factor of 10 below this number, or about 0.02 mrem/h.

Linac Beam Dumps

Two low power 200 MeV beam dumps have been designed for the linac. Their function is to permit operation of the linac for tune-up and improvements at the same time that workers are occupying the booster enclosure.

The nominal design beam power of the linac is 2.3 kW. The maximum beam power expected (in the same sense as in Sec. 4.1) is 30 kW. In order to avoid construction of a water-cooled dump, it was decided to limit the beam power capacity of the dumps to 3 kW. We do not plan to operate the linac at high power levels without injecting the beam into the booster. Should it be necessary at a later time to test the linac at higher power levels, either of the two dumps can be easily removed and replaced by a water-cooled dump.

The size of the dumps designed for the linac is dictated by thermal considerations. Figure 6 is a cross-section view of the dumps. The main body is a solid cylindrical steel casting which is embedded in a heavy concrete block, as shown in the drawing. To reduce the density of energy deposition, the surface that the beam strikes is oblique rather than normal to the beam direction, as shown in the figure.

An estimate has been made of the concentrations of radionuclides leaving the site in water via the aquifer at the 690 ft. elevation. Table III gives the data used in this estimate.

Table III

Ground-Water Data and Assumptions

Max. vertical ground-water velocity	8 ft/yr
Max. horizontal water velocity in aquifer	13 ft/day
Aquifer elevation	690 ft above msℓ
Beam dump elevation	740 ft above msℓ
Neutron mean-free path in soil, L	80 g/cm^2
Solubility fraction	0.1

In this model, the beam dump was taken to be a sphere of radius R. All the radionuclides are created in a disc of diameter and height of 2(R + 3L). While vertically traversing this disc at 8 ft/yr, the activity reaches a maximum, then decays during the additional time needed to reach the site boundary. The dilution is calculated assuming the aquifer to be only 1 cm thick; this gives a large over-estimation of the concentration. We find an activation time of 2.06 years, a decay time of 8.69 years, and a volume of water leaving the site of 5.45×10^7 cm^3/yr. Table IV lists the calculated concentrations of various radionuclides and compares them with the maximum permissible concentrations given in the AEC Manual.

Table IV

Nuclide	Expected Concentration (p Ci/mℓ)	MPC (p Ci/mℓ)	Safety Factor
^{55}Fe	5.9×10^{-3}	267	4.5×10^4
^{22}Na	1.5×10^{-3}	13	8.7×10^3
^{3}H	6.7×10^{-3}	1000	1.5×10^5
^{39}Ar	0.40×10^{-3}	----	---------
^{14}C	1.1×10^{-4}	267	2.4×10^6
^{41}Ca	0.38×10^{-4}	----	---------

There are apparently no problems of radionuclides arising from the linac beam dump.

Accesses and Penetrations

All personnel accesses and penetrations for control cables, utilities, RF power, etc., are possible sources of neutron leakage. Hence, as potential hazards they were carefully studied.

There are four personnel entrances:

(i) Temporary entrance at about the 20 MeV point. This will be sealed after installation of the second tank.

(ii) 92 MeV entrance. An air-cushion concrete door is located here. The door is as thick as the fixed wall (in units of g/cm^2).

(iii) 200 MeV entrance. The four-legged labyrinth at this entrance has a calculated attenuation factor of approximately 4×10^{-7}.[5]

(iv) Low energy entrance. There could be back-scattering of neutrons giving a dose rate of approximately 0.5 rem/hr at the pre-accelerating column which is not an occupational area. This dose rate corresponds to the maximum beam loss rate (6.8×10^8 p/cm-sec), which includes a safety factor of an order of magnitude. If this back-streaming should prove troublesome, a wall of solid concrete blocks will be built at approximately the middle of the first tank.

There are also twenty seven, 30 inch penetrations of the gallery tunnel wall for power, utility, and control connections. These penetrations will be partly filled with cables and pipes. Should the neutron flux through them be objectionable, the voids in the penetrations will be filled and they will be locally shielded.

Shielding of "Hot Spots"

In the beam switchyard area there will be point losses that may be of the order of 1% in such places as the septum magnet following the fast electrostatic kicker. In places like this, local lead or steel shields will be built with walls about twelve inches thick. The best local shield may turn out to be a steel core with one or two inches of lead on the outside.

Personnel Protections Against Inadvertent Entry to the Linac Enclosure

The interlock system for all personnel access will consist of two safety loops. One loop will be a simple hardwire system. The other one will be a logical one with location information. Each access door will be connected by independent switches to each loop. Each loop will independently interlock two or more critical devices. Hence, turning off of the beam can be accomplished by either loop in at least two different ways.

In order to simplify the "search and secure" missions after short beam interruptions during periods of operation, the linac enclosure is partitioned by light beams. If the light beams are not interrupted, then no searching is needed beyond the light beam. The light beam interlocks may be crossed by using safety-key "by-passes".

Conclusion

The NAL linac has had its permanent shield and accesses designed to provide adequate personnel protection outside the linac enclosure during operations for the expected beam losses. The expected beam losses will cause remanent exposure rates that will permit maintenance and other work with only minor occupancy time limitations. Hence, it may be said that at this time the ion source and linac technologies match to the point of permitting operations about 10^{14} p/sec. The other radiation safety problems and solutions are not different from those at all other accelerators.

References

1. K. O'Brien, Transverse Shielding Calculations for the Components of a 1/2 TeV Proton Synchrotron, HASL-199 (August 1968).
2. R. G. Alsmiller - to be published.
3. P. J. Gollon, Radioactivation of the NAL Linac by Proton Beam Losses. . ., NAL Report TM-210 (February 1970).
4. M. Awschalom, Linac Shielding. . ., NAL Report TM-236 (May 1970).
5. P. J. Gollon, R. A. Carrigan, Jr., Design of Personnel and Vehicle Access Labyrinths, NAL Report TM-239 (May 1970).

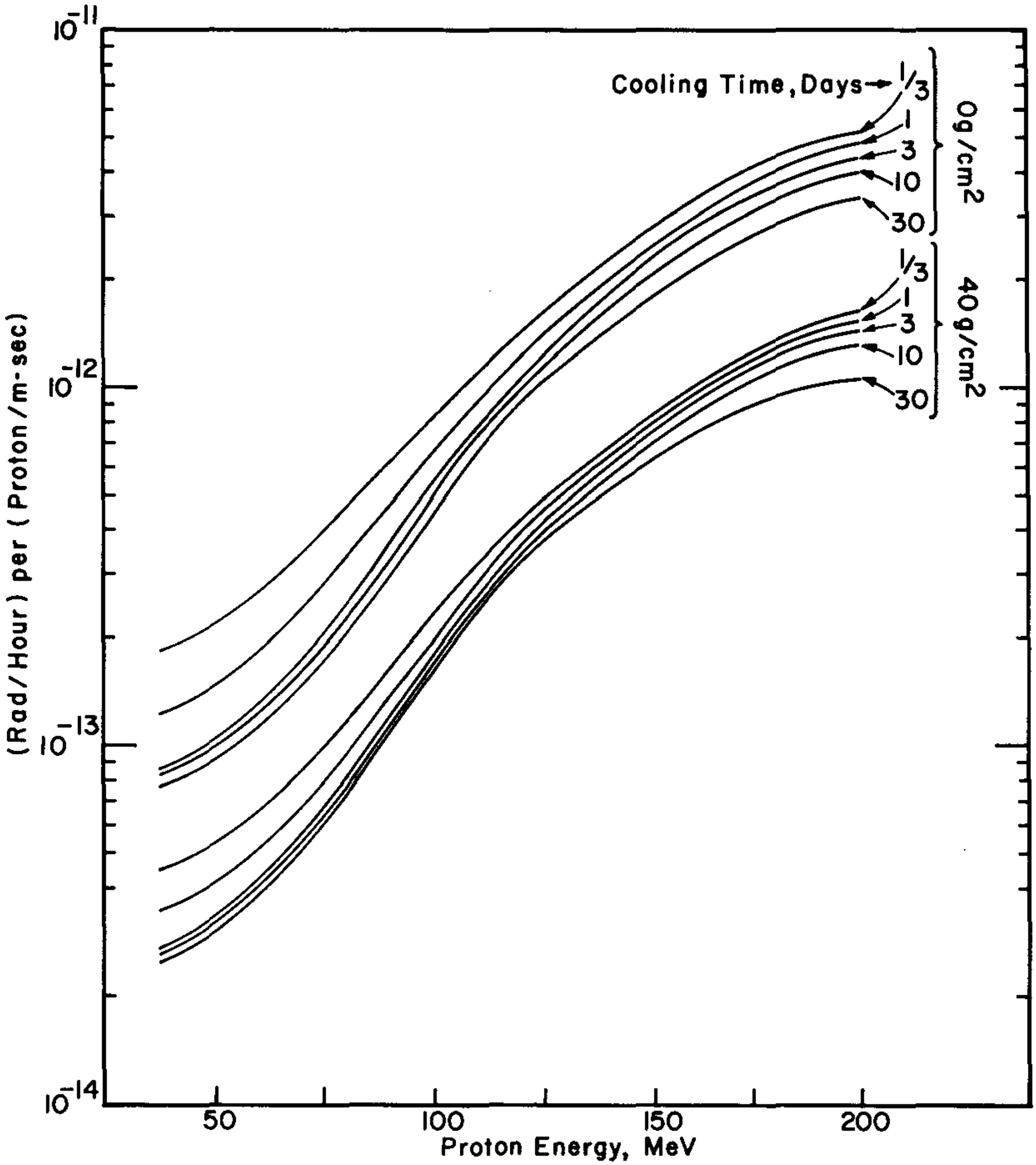

Fig. 1. Remanent exposure rates to personnel inside a linac tank (30 cm from beam-line) after an infinitely long irradiation time and a uniform "line" loss of 1 proton/meter-second. The 0 g/cm^2 shielding corresponds to the lack of shielding from activity induced on the front face of a drift tube. The 40 g/cm^2 corresponds to shielding by the full drift-tube thickness of activity induced in the drift-tube bore In this figure the proton energy is the independent variable and cooling time is a parameter.

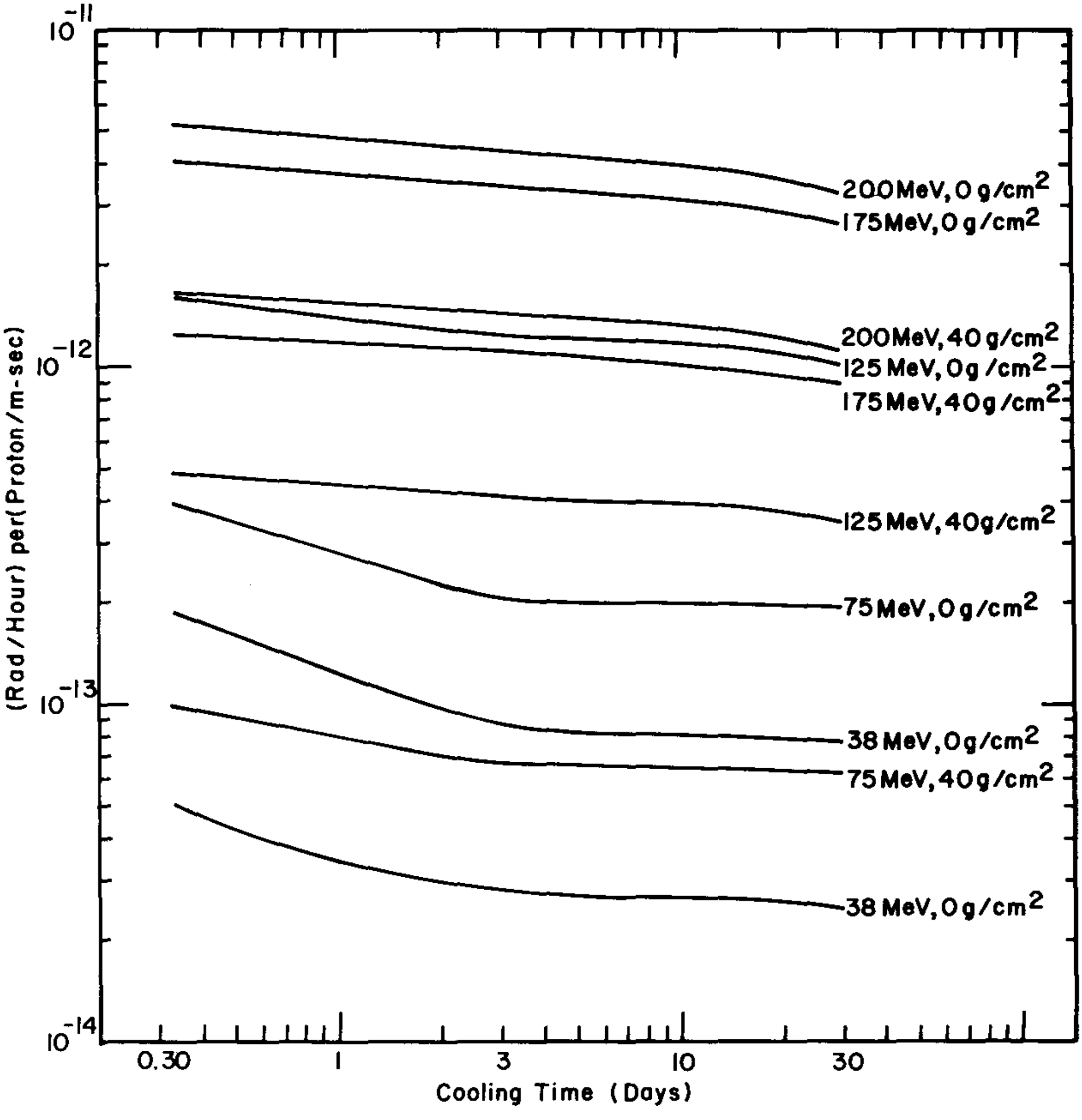

Fig. 2. Remanent exposure rate to personnel as a function of cooling time for various proton energies and shielding thicknesses. The assumptions of Fig. 1 concerning geometry and proton loss apply here also.

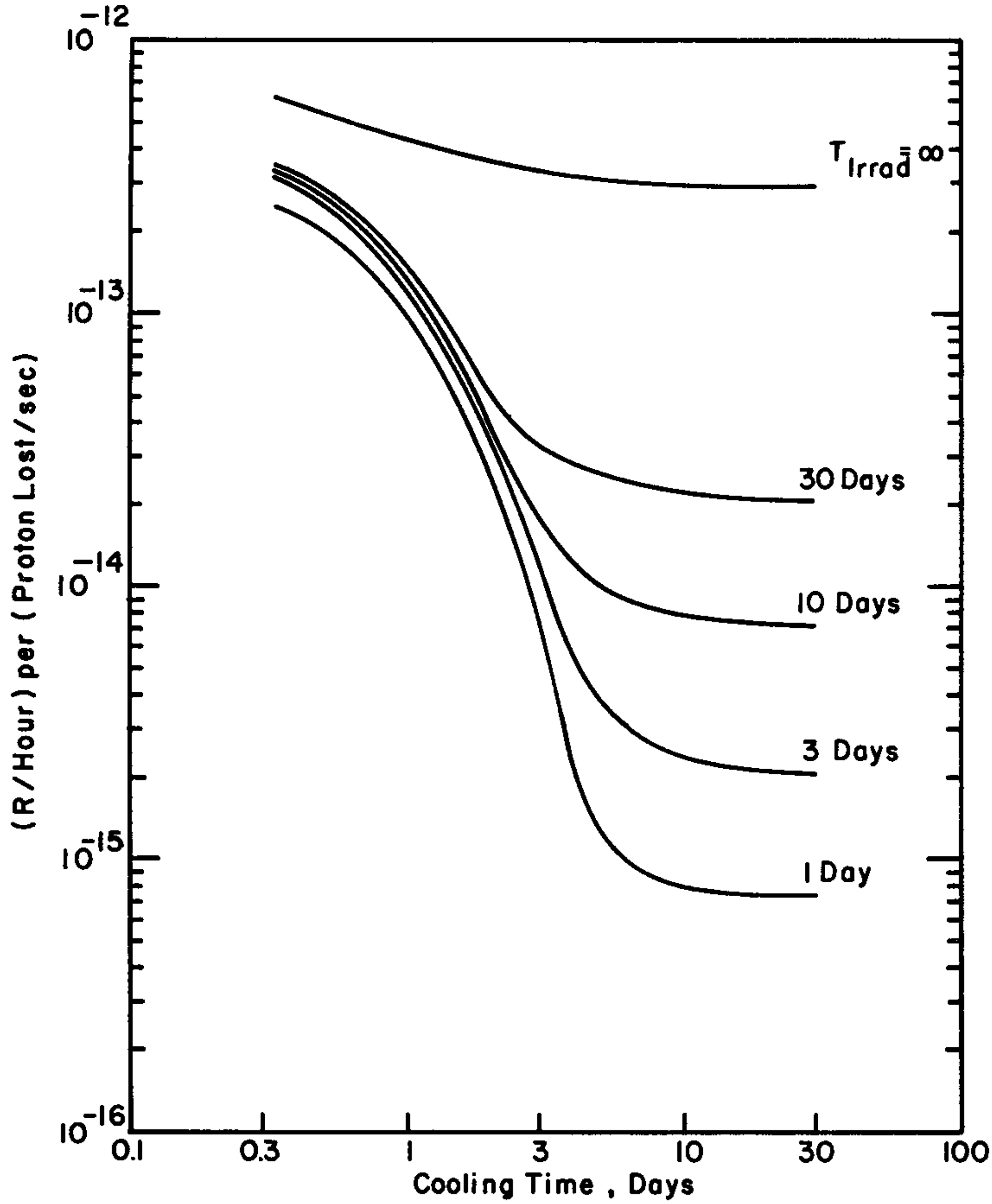

Fig. 3. Remanent exposure rate to personnel inside a linac tank for various irradiation and cooling times resulting from a single large "point" loss of 66-MeV protons. A shielding thickness of 0 g/cm^2 is used.

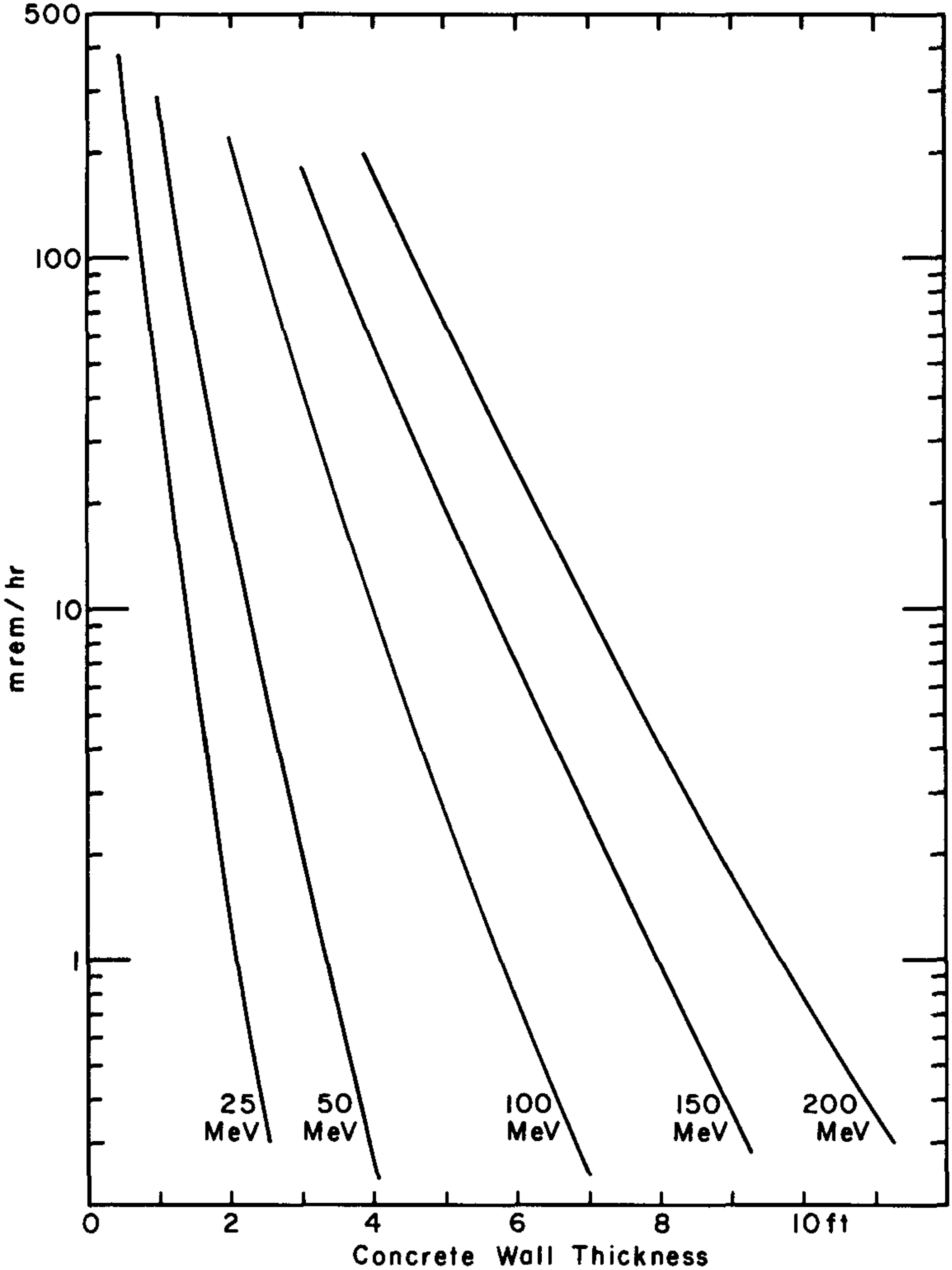

Fig. 4. Dose rate in the linac gallery at one foot from the wall. Current loss is 6.8×10^8 p/cm sec. Ordinary concrete of density equal to 2.3 g/cm^3

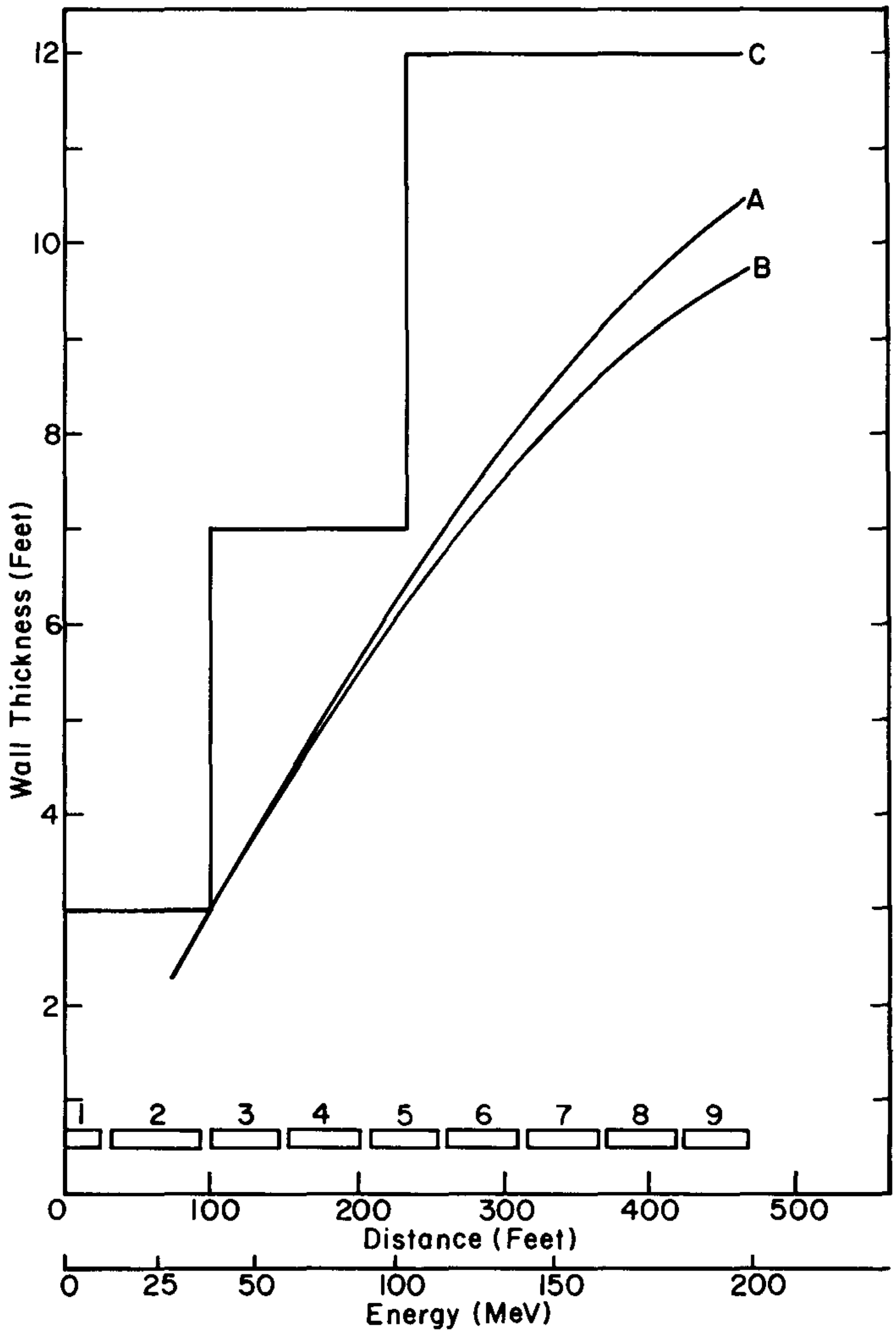

Fig. 5. Required concrete wall thickness as a function of distance along the linac. The origin is at the entrance to the first tank. The beam losses are assumed to be uniform and equal to 6.8×10^8 p/cm per sec. The dose equivalent rate one foot from the wall in the linac gallery is 1 mrem/hr.

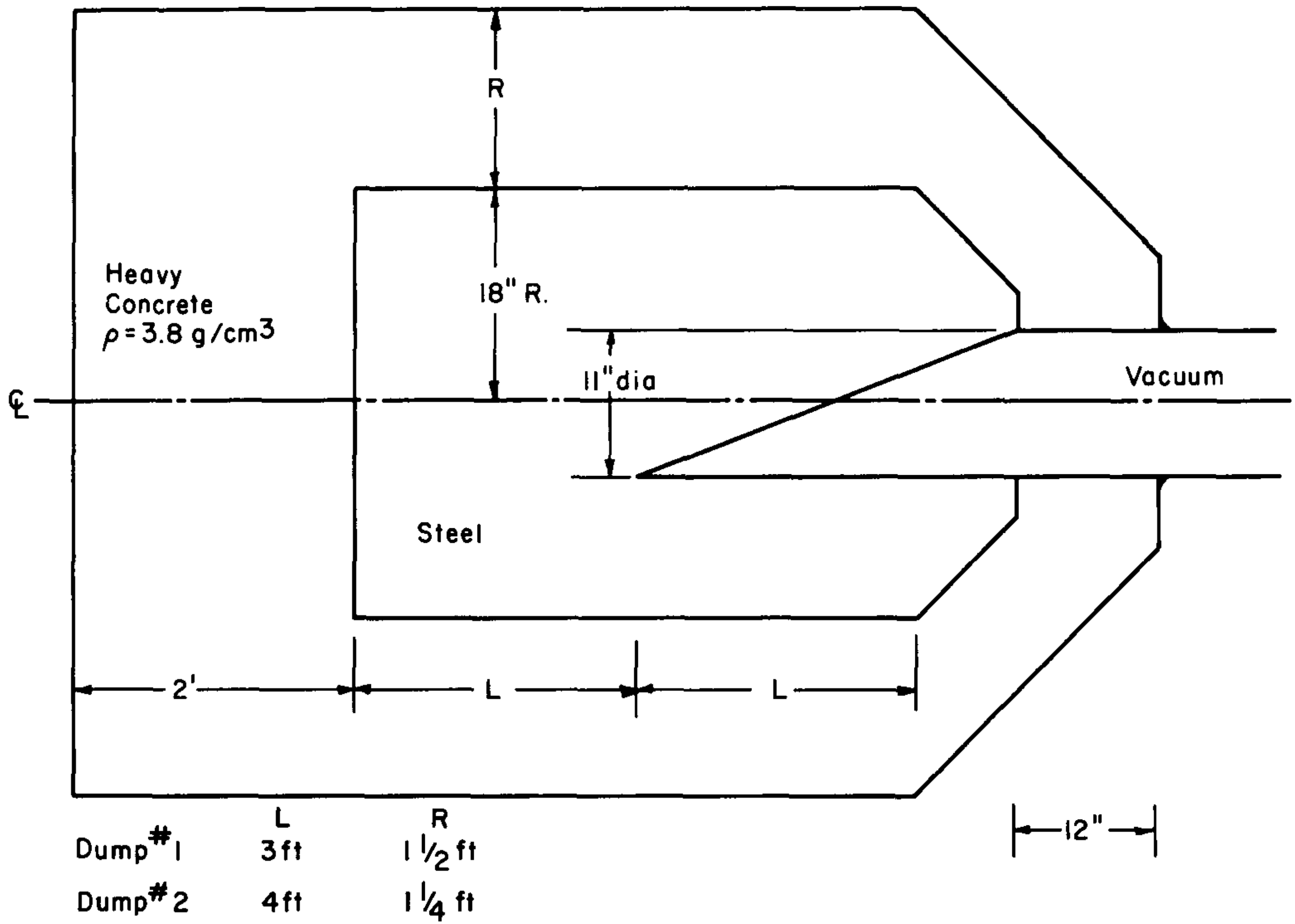

Fig. 6. Cross section of a beam dump. Power rating 3 kW. The slant in the steel is made to help spread the beam energy over a large volume.