R.P Note No. 71
Shield Walls in IB1 for Loma Linda Accelerator
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I. Introduction

This note describes an analysis of the shielding requirements for the Loma Linda accelerator installation in IB1. The dose estimates are based on the results given in SAIC report 87/1072 [1]. Other useful information relevant to these calculations is given in Fermilab TM-1354 by Awschalom [2] as well as the extensive references in those two papers. Shielding of the "experiment/dump" area in the parking lot will be addressed in a separate note.

II. Review of SAIC Calculations

Calculations of the dose attenuation in concrete (ρ=2.3 gm/cm^3) for neutrons produced by protons striking a thick iron target are described in [1]. Those calculations proceeded in two steps. First, primary neutron spectra were calculated for several angular bins relative to the incident proton beam direction. The program HETC was used to generate these spectra. Then, to avoid having to do three-dimensional neutron transport calculations, a series of one-dimensional calculations (with spherically symmetric geometry) were done with the transport code ANISN. Each calculation used as input the primary spectra computed with HETC for a single angular bin. The result, when folded with the dose-equivalent response function for neutrons, is a dose equivalent attenuation curve for that angular bin.

The SAIC attenuation curves for three incident proton energies (150, 200, 250 MeV) and 6 angular bins are shown in figures 1 through 6. Note that the actual quantities plotted are the doses multiplied by R^2, where R is the depth in the shield. Calculated doses are not given for shielding thicknesses less than 100 cm since the SAIC calculations did not follow primary neutrons with energies below 20 MeV. For shields substantially less than one meter in thickness these neutrons may contribute significantly to the dose. Extrapolations of the dose to shield thicknesses much less than one meter could result in an underestimate of the true dose.

III. Parametrization of SAIC Results

To simplify further calculations it is useful to parameterize the SAIC results with some analytic expressions. Over the angular range 10 to 120 degrees the SAIC results can be described by expressions of the form

$$R^2 \cdot \text{Dose}\ (\theta,i) = A_i(\theta) \cdot 10^{B_i(\theta)\ R} \qquad (1)$$

where R is the depth into the shield along the direction of interest, θ is the angle relative to the incident beam direction, and i is an index denoting the incident proton energy. The derivation of this parameterization is given in the Appendix.

For cases where the distance, D, along the direction of interest from the loss point to the start of the shield is non-zero, the dose is then given by

$$\mathrm{Dose}(\theta,i) = \frac{A_i(\theta)\ 10^{B_i(\theta)\ R}}{(R+D)^2} \qquad (2)$$

There are two basic shielding geometries to consider for the IB1 case. These are shown in figures 7a and 7b. First consider the side wall case. I assume an incident proton beam striking a loss point a distance, S, from the wall and producing neutrons at some angle, θ. I assume that the dose measured immediately outside the shield wall at angle θ is determined by the attenuation curve value for that angle and energy, and for a shield thickness, R(θ), given by R=T/sin(θ) , where T is the transverse shield wall thickness. In this case there are two competing effects that determine the maximum dose outside the shield. As the angle decreases the dose for fixed shield depth increases. However, the effective shield thickness also increases with decreasing angle, providing increased attenuation. This causes the dose to reach a maximum at some angle forward of 90^0.

On the other hand, the end wall case will result in a dose maximum at 0^0 (i.e. along the beam direction). The relevant shield thickness, R, is given by T/cos(θ) in this case.

IV. Results

A. Normal Running

The analytic expressions for the dose attenuation were incorporated into spreadsheets to allow quick calculations for a variety of shielding thicknesses, angles, and energies. Tables 1 through 4 display some results. Based on these results, it is proposed that a 1.5 foot thick, 6 foot high concrete wall be installed in IB1 on the west side of the accelerator. This will result in a total shield thickness of at least 2.5 feet for elevations less than 2 feet above beam elevation. The additional 1 foot of shielding comes from the existing concrete wall that is already part of the IB1 building. The remainder of the concrete shield wall (north, south, east) surrounding the accelerator is proposed to be 3 feet thick and 9 feet high (see figure 8). The most likely loss points are considered to be the septum in the east straight section and the extraction Lambertson in the north straight section. Losses are expected to be less in the west and south straight sections. Note that injection losses do not present a shielding problem since the injection energy is 2 MeV, below the neutron production threshold for most materials (Fe, Al, Cu, etc.)

The calculations for the side wall geometry show that the maximum dose rate will be at an angle of about 55^{o}. The dose rate will be about 6.6 mrem per hour for a 2.5 foot thick shield and 3.5 mrem per hour for a 3 foot thick shield for a beam loss of 2.5×10^{8} p/sec at 250 MeV in a straight section of the accelerator that is 3 feet away from the shield wall. The loss rate for normal operation is assumed to be 1% of a maximum intensity of 5×10^{10} protons per 2 seconds.

Calculations for the end wall geometry show that dose rates outside the west wall due to the same loss on the extraction Lambertson will be 2 mrem per hour at an angle of 35^{o}. Angles less than 35^{o} intercept the steel of the downstream bending magnets. This will provide substantially more shielding. These smaller angles also will have additional shielding provided by the concrete in the experiment/dump area (see figure 8).

A 1% beam loss on the septum in the east straight section is calculated to produce dose rates of about 10 mrem per hour immediately outside the north wall near the northeast corner (end wall geometry). This is at an angle of about 12^{o}. Angles less than this are additionally shielded by the steel of the downstream dipoles.

B. Accident Conditions

Scaling from the results in the previous section, the continuous loss of full intensity beam would result in dose rates 100 times higher for the same loss points and locations outside the shielding. Thus, accident dose rates outside the east wall might be as high as 350 mrem per hour for the worst case assumption of 5×10^{10} protons per pulse and a 2 second repetition rate. Dose rates approaching 1 rem per hour might occur near the north east corner. However, the dose per pulse in these cases is still quite small - only ~0.5 mrem per pulse. Thus, interlocked detectors (e.g. Chipmunks - 20 second time constant) will be very effective in limiting the dose from accidental losses. Trip points set at 50 mrem/hr, for example, could be used to limit the dose from accidental losses while having minimal impact on normal running. If the loss rates suddenly increased to 10% of full beam intensity then within about 20 seconds the Chipmunks would trip the beam off and the total dose outside the shielding would be about 0.5 mrem per "accident".

C. Radiation Guide Criteria

The Fermilab Radiation Guide specifies that radiation signs and ropes are required for areas where the dose rate due to normal running is greater than 2.5 mrem per hour but less than 10 mrem per hour. This applies to areas that are "minimally occupied". The parking area outside the west wall certainly meets the occupancy criterion. A rope at the 2.5 mrem boundary will be required. This boundary will be determined by surveys. A fence is preferable since this installation will be in place for more than a year and ropes tend to fall down.

Areas inside IB1 would require similar ropes at the 2.5 mrem/hour boundary. This may be an inconvenience to other work in IB1. An alternative would be to increase the shielding along the north and east walls to reduce the dose everywhere to less than 2.5 mrem per hour if surveys show the dose rate to be too high.

The control room area will be adjacent to the south wall and cannot be considered a minimal occupancy area. The Radiation Guide requires that dose rates not exceed 0.25 mrem per hour in such areas. This may require additional shielding along the south wall if surveys show dose rates along the south wall to be higher than expected due to losses in the south straight section.

APPENDIX

Figures 9 through 11 show the calculated dose attenuation for 150, 200, and 250 MeV taken from [1], together with simple exponential fits for several angular bins. The effective angle, θ_{eff}, for an angular bin (θ_i,θ_f) is given by $\cos\theta_{eff}=1/2(\cos\theta_i+\cos\theta_f)$ [2]. The two fit parameters (normalization and slope) for each angular bin at a given energy are themselves well described by smooth curves as a function of θ_{eff} (see figures 12 through 14). The normalization constants as a function of angle for fixed incident energy are reasonably well-described by an exponential function, while the slope constants are well-described by a second order polynomial. Thus, the SAIC dose attenuation curves are parameterized by

$$R^2\ \text{Dose} = A_i(\theta)\ 10^{B_i(\theta)\ R}\ \text{, with}$$

$$A_i(\theta) = a_i\ 10^{k_i\ \theta}\ \text{, and}$$

$$B_i(\theta) = b_i + c_i\ \theta + d_i\ \theta^2$$

The fit parameters are displayed on each figure and listed in Table A.1

Table A.1

Fit Parameters for SAIC Dose Attenuation Calculations

Energy (MeV)	a_i (cm^2 rem proton^{-1})	k_i (degrees^{-1})	b_i (cm^{-1})	c_i (cm^{-1} degrees^{-1})	d_i (cm^{-1} degrees^{-2})
150	1.711×10^{-8}	-0.0229	-0.0104	-5.148×10^{-5}	2.155×10^{-8}
200	2.921×10^{-8}	-0.0216	-0.0091	-5.575×10^{-5}	9.974×10^{-8}
250	4.283×10^{-8}	-0.0205	-0.0086	-4.554×10^{-5}	4.978×10^{-8}

References

1. W. K. Hagen, B. L. Colburn, T. W. Armstrong, "Radiation Shielding Calculations for the Loma Linda Proton Therapy Facility", SAIC Report No. 87/1072, June, 1987.

2. M. Awschalom, "Radiation Shielding for 250 MeV Protons", Fermilab TM-1354 Rev. 4/1/87, April, 1987

Table Captions

1. Side Wall Geometry - Mrem per hour vs. angle for three incident proton energies and three concrete shield thicknesses. Distance to wall is 2 ft.

2. Side Wall Geometry - Mrem per hour vs. angle for three incident proton energies and three concrete shield thicknesses. Distance to wall is 3 ft.

3. Side Wall Geometry - Mrem per hour vs. angle for three incident proton energies and three concrete shield thicknesses. Distance to wall is 23 ft.

4. End Wall Geometry - Mrem per hour vs. angle for three incident proton energies and three concrete shield thicknesses. Distance to wall is 15 ft.

Side Wall Geometry

Lost protons/second 2.50E+08 / distance to wall (ft) 2.00	250 MeV	200 MeV	150 MeV	250 MeV	200 MeV	150 MeV	250 MeV	200 MeV	150 MeV
A (norm const.)	1.32E-08	8.42E-09	4.58E-09	1.32E-08	8.42E-09	4.58E-09	1.32E-08	8.42E-09	4.58E-09
B (slope const.)	-0.00971	-0.01043	-0.01167	-0.00971	-0.01043	-0.01167	-0.00971	-0.01043	-0.01167
Shield Thickness (ft)	2.5	2.5	2.5	3	3	3	6	6	6
input cell ------>	25								

Table of mrem per hour vs. angle

Formulae Cells ---->	2.00E+00	9.47E-01	3.07E-01	7.23E-01	3.23E-01	9.44E-02	2.24E-03	6.97E-04	1.10E-04
10	4.12E-03	1.50E-03	2.37E-04	5.35E-04	1.73E-04	2.12E-05	3.59E-09	5.60E-10	1.48E-11
15	1.26E-01	5.35E-02	1.28E-02	2.90E-02	1.13E-02	2.28E-03	6.01E-06	1.39E-06	1.01E-07
20	7.16E-01	3.27E-01	9.52E-02	2.19E-01	9.32E-02	2.39E-02	2.48E-04	6.93E-05	8.25E-06
25	2.00E+00	9.47E-01	3.07E-01	7.23E-01	3.23E-01	9.44E-02	2.24E-03	6.97E-04	1.10E-04
30	3.82E+00	1.85E+00	6.41E-01	1.54E+00	7.08E-01	2.25E-01	9.24E-03	3.08E-03	5.79E-04
35	5.82E+00	2.85E+00	1.03E+00	2.54E+00	1.18E+00	3.95E-01	2.40E-02	8.36E-03	1.77E-03
40	7.62E+00	3.74E+00	1.38E+00	3.51E+00	1.65E+00	5.68E-01	4.63E-02	1.66E-02	3.79E-03
45	8.94E+00	4.40E+00	1.64E+00	4.29E+00	2.02E+00	7.10E-01	7.25E-02	2.64E-02	6.37E-03
50	9.67E+00	4.74E+00	1.78E+00	4.79E+00	2.25E+00	7.99E-01	9.73E-02	3.59E-02	8.96E-03
55	9.81E+00	4.79E+00	1.80E+00	4.97E+00	2.33E+00	8.30E-01	1.16E-01	4.32E-02	1.10E-02
60	9.45E+00	4.58E+00	1.71E+00	4.87E+00	2.27E+00	8.06E-01	1.26E-01	4.70E-02	1.21E-02
65	8.70E+00	4.18E+00	1.55E+00	4.54E+00	2.10E+00	7.41E-01	1.27E-01	4.72E-02	1.21E-02
70	7.70E+00	3.67E+00	1.35E+00	4.05E+00	1.86E+00	6.49E-01	1.19E-01	4.41E-02	1.13E-02
75	6.58E+00	3.10E+00	1.12E+00	3.48E+00	1.58E+00	5.44E-01	1.05E-01	3.86E-02	9.74E-03
80	5.44E+00	2.54E+00	9.02E-01	2.88E+00	1.30E+00	4.38E-01	8.79E-02	3.20E-02	7.90E-03
85	4.36E+00	2.01E+00	7.00E-01	2.30E+00	1.02E+00	3.39E-01	6.96E-02	2.50E-02	6.02E-03
90	3.39E+00	1.54E+00	5.25E-01	1.78E+00	7.81E-01	2.52E-01	5.23E-02	1.85E-02	4.31E-03
95	2.55E+00	1.14E+00	3.80E-01	1.33E+00	5.75E-01	1.81E-01	3.72E-02	1.30E-02	2.91E-03
100	1.86E+00	8.20E-01	2.65E-01	9.58E-01	4.08E-01	1.24E-01	2.50E-02	8.56E-03	1.83E-03
105	1.31E+00	5.68E-01	1.78E-01	6.65E-01	2.78E-01	8.19E-02	1.58E-02	5.30E-03	1.07E-03
110	8.87E-01	3.78E-01	1.14E-01	4.42E-01	1.82E-01	5.14E-02	9.36E-03	3.06E-03	5.82E-04
115	5.76E-01	2.41E-01	7.01E-02	2.80E-01	1.13E-01	3.05E-02	5.12E-03	1.63E-03	2.88E-04
120	3.57E-01	1.46E-01	4.06E-02	1.68E-01	6.63E-02	1.70E-02	2.56E-03	7.90E-04	1.27E-04

Table 1

Side Wall Geometry

Lost protons/second 2.50E+08 / distance to wall (ft) 3.00	250 MeV	200 MeV	150 MeV	250 MeV	200 MeV	150 MeV	250 MeV	200 MeV	150 MeV
A (norm const.)	1.32E-08	8.42E-09	4.58E-09	1.32E-08	8.42E-09	4.58E-09	1.32E-08	8.42E-09	4.58E-09
B (slope const.)	-0.00971	-0.01043	-0.01167	-0.00971	-0.01043	-0.01167	-0.00971	-0.01043	-0.01167
Shield Thickness (ft)	2.5	2.5	2.5	3	3	3	6	6	6
input cell ------>	25								

Table of mrem per hour vs. angle

Formulae Cells ---->	1.34E+00	6.34E-01	2.06E-01	5.02E-01	2.24E-01	6.56E-02	1.77E-03	5.51E-04	8.69E-05
10	2.75E-03	1.00E-03	1.59E-04	3.72E-04	1.20E-04	1.47E-05	2.83E-09	4.43E-10	1.17E-11
15	8.43E-02	3.58E-02	8.58E-03	2.02E-02	7.85E-03	1.59E-03	4.75E-06	1.10E-06	7.99E-08
20	4.80E-01	2.19E-01	6.37E-02	1.52E-01	6.47E-02	1.66E-02	1.96E-04	5.48E-05	6.52E-06
25	1.34E+00	6.34E-01	2.06E-01	5.02E-01	2.24E-01	6.56E-02	1.77E-03	5.51E-04	8.69E-05
30	2.56E+00	1.24E+00	4.29E-01	1.07E+00	4.92E-01	1.56E-01	7.30E-03	2.43E-03	4.57E-04
35	3.90E+00	1.91E+00	6.87E-01	1.76E+00	8.21E-01	2.74E-01	1.90E-02	6.60E-03	1.40E-03
40	5.10E+00	2.51E+00	9.25E-01	2.44E+00	1.14E+00	3.94E-01	3.66E-02	1.31E-02	2.99E-03
45	5.98E+00	2.94E+00	1.10E+00	2.98E+00	1.40E+00	4.93E-01	5.72E-02	2.09E-02	5.03E-03
50	6.47E+00	3.18E+00	1.19E+00	3.32E+00	1.57E+00	5.55E-01	7.69E-02	2.84E-02	7.08E-03
55	6.57E+00	3.21E+00	1.21E+00	3.45E+00	1.62E+00	5.76E-01	9.19E-02	3.41E-02	8.69E-03
60	6.32E+00	3.07E+00	1.15E+00	3.38E+00	1.58E+00	5.60E-01	9.98E-02	3.72E-02	9.55E-03
65	5.82E+00	2.80E+00	1.04E+00	3.15E+00	1.46E+00	5.15E-01	1.00E-01	3.73E-02	9.59E-03
70	5.15E+00	2.46E+00	9.01E-01	2.81E+00	1.29E+00	4.51E-01	9.41E-02	3.48E-02	8.90E-03
75	4.40E+00	2.08E+00	7.51E-01	2.42E+00	1.10E+00	3.78E-01	8.32E-02	3.05E-02	7.70E-03
80	3.64E+00	1.70E+00	6.04E-01	2.00E+00	9.00E-01	3.04E-01	6.95E-02	2.53E-02	6.24E-03
85	2.92E+00	1.34E+00	4.68E-01	1.60E+00	7.11E-01	2.35E-01	5.50E-02	1.98E-02	4.76E-03
90	2.27E+00	1.03E+00	3.51E-01	1.24E+00	5.43E-01	1.75E-01	4.13E-02	1.46E-02	3.41E-03
95	1.71E+00	7.64E-01	2.54E-01	9.24E-01	3.99E-01	1.26E-01	2.94E-02	1.02E-02	2.30E-03
100	1.24E+00	5.49E-01	1.77E-01	6.66E-01	2.83E-01	8.63E-02	1.98E-02	6.76E-03	1.45E-03
105	8.76E-01	3.80E-01	1.19E-01	4.62E-01	1.93E-01	5.69E-02	1.25E-02	4.19E-03	8.49E-04
110	5.94E-01	2.53E-01	7.66E-02	3.07E-01	1.26E-01	3.57E-02	7.40E-03	2.42E-03	4.60E-04
115	3.86E-01	1.62E-01	4.69E-02	1.95E-01	7.84E-02	2.12E-02	4.05E-03	1.29E-03	2.27E-04
120	2.39E-01	9.80E-02	2.72E-02	1.17E-01	4.60E-02	1.18E-02	2.02E-03	6.24E-04	1.01E-04

Table 2

Side Wall Geometry

Lost protons/second 2.50E+08 / distance to wall (ft) 23.00	250 MeV	200 MeV	150 MeV	250 MeV	200 MeV	150 MeV	250 MeV	200 MeV	150 MeV
A (norm const.)	1.32E-08	8.42E-09	4.58E-09	1.32E-08	8.42E-09	4.58E-09	1.32E-08	8.42E-09	4.58E-09
B (slope const.)	-0.00971	-0.01043	-0.01167	-0.00971	-0.01043	-0.01167	-0.00971	-0.01043	-0.01167
Shield Thickness (ft)	2.5	2.5	2.5	3	3	3	6	6	6
input cell ------->	25								

Table of mrem per hour vs. angle

Formulae Cells ---->	6.22E-02	2.95E-02	9.57E-03	2.67E-02	1.19E-02	3.49E-03	1.71E-04	5.31E-05	8.37E-06
10	1.28E-04	4.66E-05	7.38E-06	1.98E-05	6.38E-06	7.82E-07	2.73E-10	4.26E-11	1.13E-12
15	3.92E-03	1.67E-03	3.99E-04	1.07E-03	4.18E-04	8.45E-05	4.57E-07	1.06E-07	7.70E-09
20	2.23E-02	1.02E-02	2.96E-03	8.10E-03	3.45E-03	8.83E-04	1.89E-05	5.28E-06	6.28E-07
25	6.22E-02	2.95E-02	9.57E-03	2.67E-02	1.19E-02	3.49E-03	1.71E-04	5.31E-05	8.37E-06
30	1.19E-01	5.76E-02	2.00E-02	5.71E-02	2.62E-02	8.31E-03	7.03E-04	2.34E-04	4.40E-05
35	1.81E-01	8.87E-02	3.20E-02	9.38E-02	4.37E-02	1.46E-02	1.83E-03	6.36E-04	1.34E-04
40	2.37E-01	1.17E-01	4.30E-02	1.30E-01	6.09E-02	2.10E-02	3.52E-03	1.26E-03	2.88E-04
45	2.78E-01	1.37E-01	5.12E-02	1.59E-01	7.48E-02	2.63E-02	5.51E-03	2.01E-03	4.85E-04
50	3.01E-01	1.48E-01	5.56E-02	1.77E-01	8.34E-02	2.96E-02	7.41E-03	2.74E-03	6.82E-04
55	3.06E-01	1.49E-01	5.61E-02	1.84E-01	8.63E-02	3.07E-02	8.85E-03	3.29E-03	8.37E-04
60	2.94E-01	1.43E-01	5.34E-02	1.80E-01	8.41E-02	2.98E-02	9.62E-03	3.58E-03	9.20E-04
65	2.71E-01	1.30E-01	4.83E-02	1.68E-01	7.78E-02	2.74E-02	9.66E-03	3.59E-03	9.23E-04
70	2.40E-01	1.14E-01	4.19E-02	1.50E-01	6.89E-02	2.40E-02	9.07E-03	3.35E-03	8.57E-04
75	2.05E-01	9.66E-02	3.49E-02	1.29E-01	5.85E-02	2.01E-02	8.01E-03	2.94E-03	7.41E-04
80	1.69E-01	7.90E-02	2.81E-02	1.07E-01	4.79E-02	1.62E-02	6.69E-03	2.43E-03	6.01E-04
85	1.36E-01	6.25E-02	2.18E-02	8.52E-02	3.79E-02	1.25E-02	5.30E-03	1.90E-03	4.58E-04
90	1.05E-01	4.79E-02	1.63E-02	6.59E-02	2.89E-02	9.33E-03	3.98E-03	1.41E-03	3.28E-04
95	7.94E-02	3.56E-02	1.18E-02	4.92E-02	2.13E-02	6.68E-03	2.83E-03	9.86E-04	2.21E-04
100	5.78E-02	2.55E-02	8.26E-03	3.54E-02	1.51E-02	4.60E-03	1.90E-03	6.51E-04	1.39E-04
105	4.07E-02	1.77E-02	5.54E-03	2.46E-02	1.03E-02	3.03E-03	1.20E-03	4.03E-04	8.18E-05
110	2.76E-02	1.18E-02	3.56E-03	1.63E-02	6.71E-03	1.90E-03	7.12E-04	2.33E-04	4.43E-05
115	1.79E-02	7.52E-03	2.18E-03	1.04E-02	4.17E-03	1.13E-03	3.90E-04	1.24E-04	2.19E-05
120	1.11E-02	4.56E-03	1.27E-03	6.22E-03	2.45E-03	6.29E-04	1.95E-04	6.01E-05	9.69E-06

Table 3

LLUMC IB1 Shielding

			End Wall Geometry						
Lost protons/second 2.50E+08 **distance to wall (ft)** 15.00	**250 MeV**	**200 MeV**	**150 MeV**	**250 MeV**	**200 MeV**	**150 MeV**	**250 MeV**	**200 MeV**	**150 MeV**
A (norm const.)	1.04E-08	6.57E-09	3.52E-09	1.04E-08	6.57E-09	3.52E-09	1.04E-08	6.57E-09	3.52E-09
B (slope const.)	-0.00992	-0.01068	-0.01193	-0.00992	-0.01068	-0.01193	-0.00992	-0.01068	-0.01193
Shield Thickness (ft)	2.5	2.5	2.5	3	3	3	6	6	6
input cell ------>	30								

Table of mrem per hour vs. angle

Formulae Cells ---->	3.30E+00	1.79E+00	7.45E-01	2.09E+00	1.10E+00	4.34E-01	1.38E-01	6.00E-02	1.76E-02
5	2.24E+01	1.37E+01	6.32E+00	1.55E+01	9.32E+00	4.10E+00	1.77E+00	9.43E-01	3.17E-01
10	1.63E+01	9.77E+00	4.43E+00	1.12E+01	6.55E+00	2.84E+00	1.19E+00	6.12E-01	2.02E-01
15	1.16E+01	6.75E+00	3.01E+00	7.80E+00	4.45E+00	1.90E+00	7.59E-01	3.77E-01	1.22E-01
20	7.91E+00	4.51E+00	1.97E+00	5.25E+00	2.92E+00	1.22E+00	4.60E-01	2.19E-01	6.92E-02
25	5.22E+00	2.91E+00	1.24E+00	3.39E+00	1.83E+00	7.47E-01	2.61E-01	1.19E-01	3.64E-02
30	3.30E+00	1.79E+00	7.45E-01	2.09E+00	1.10E+00	4.34E-01	1.38E-01	6.00E-02	1.76E-02
35	1.99E+00	1.05E+00	4.23E-01	1.22E+00	6.19E-01	2.37E-01	6.61E-02	2.74E-02	7.62E-03
40	1.13E+00	5.74E-01	2.24E-01	6.63E-01	3.25E-01	1.20E-01	2.84E-02	1.11E-02	2.89E-03
45	5.91E-01	2.91E-01	1.09E-01	3.31E-01	1.56E-01	5.48E-02	1.05E-02	3.84E-03	9.24E-04
50	2.81E-01	1.32E-01	4.71E-02	1.48E-01	6.63E-02	2.20E-02	3.20E-03	1.08E-03	2.35E-04
55	1.16E-01	5.23E-02	1.75E-02	5.63E-02	2.39E-02	7.37E-03	7.42E-04	2.26E-04	4.31E-05
60	3.98E-02	1.68E-02	5.17E-03	1.72E-02	6.81E-03	1.91E-03	1.15E-04	3.08E-05	4.94E-06
65	1.01E-02	3.94E-03	1.08E-03	3.72E-03	1.34E-03	3.29E-04	9.58E-06	2.15E-06	2.69E-07
70	1.56E-03	5.42E-04	1.27E-04	4.51E-04	1.42E-04	2.87E-05	2.72E-07	4.70E-08	4.06E-09
75	9.23E-05	2.67E-05	4.77E-06	1.78E-05	4.50E-06	6.64E-07	9.33E-10	1.06E-10	4.93E-12

Table 4

Figure Captions

1. SAIC calculated neutron dose attenuation - protons on an iron target- 0-15°.

2. SAIC calculated neutron dose attenuation - protons on an iron target- 15-30°.

3. SAIC calculated neutron dose attenuation - protons on an iron target- 30-45°.

4. SAIC calculated neutron dose attenuation - protons on an iron target- 45-60°.

5. SAIC calculated neutron dose attenuation - protons on an iron target- 60-90°.

6. SAIC calculated neutron dose attenuation - protons on an iron target- 90-180°.

7. Two beam loss geometries considered in the text.

8. Schematic (not to scale) shielding arrangements for the Loma Linda Accelerator in IB1. Arrows indicate loss points and the resulting maximum doses outside the shielding, based on 2.5×10^8 interacting protons per second, as discussed in the text.

9. SAIC dose attenuation results and exponential fits, for six angular bins. Parameters of fitted curves are in the same order as the bins listed in the figure legend - 150 MeV.

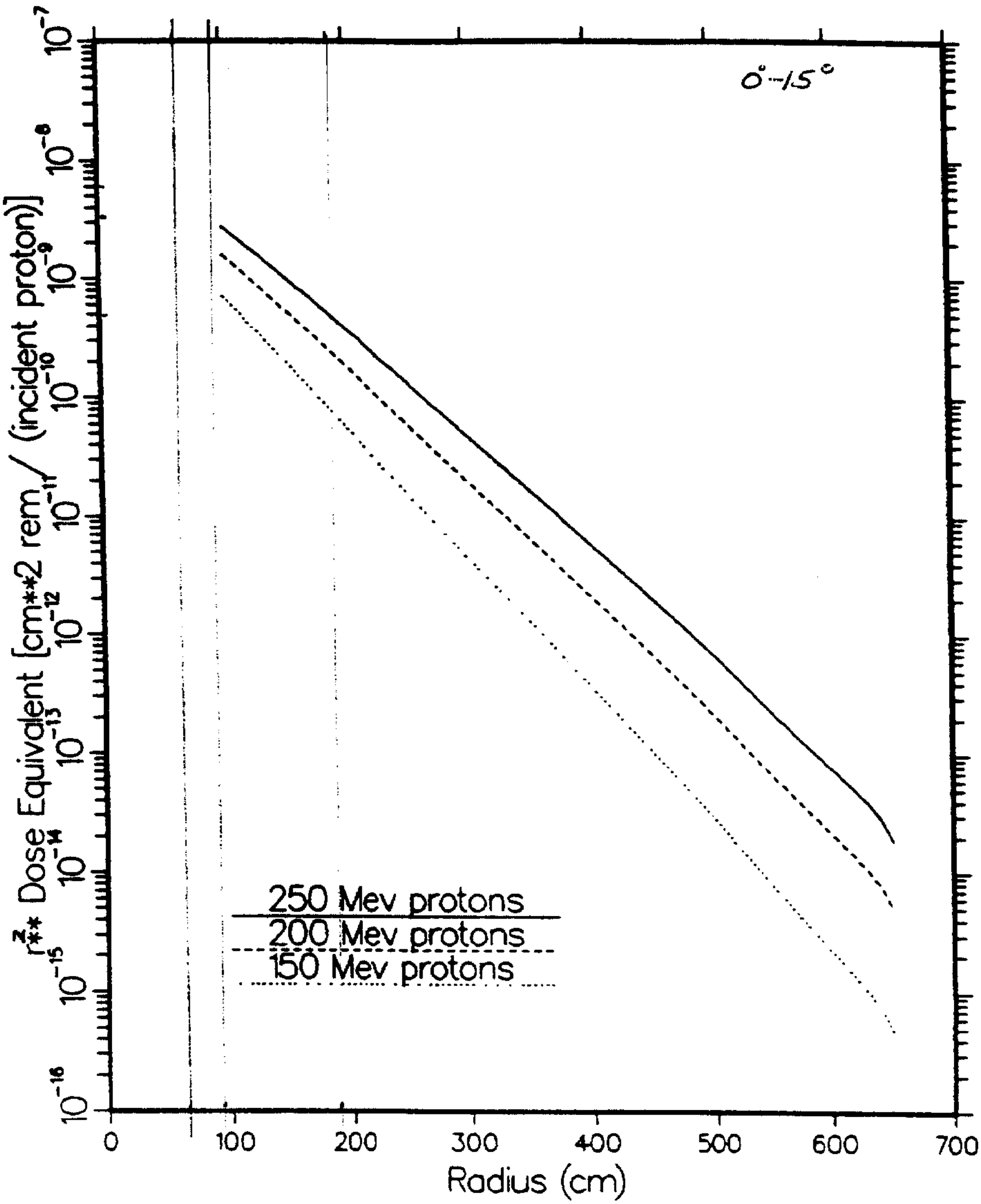
10. SAIC dose attenuation results and exponential fits, for six angular bins. Parameters of fitted curves are in the same order as the bins listed in the figure legend - 200 MeV.

11. SAIC dose attenuation results and exponential fits, for six angular bins. Parameters of fitted curves are in the same order as the bins listed in the figure legend - 250 MeV.

12. Parameterization of fit results for the slope and normalization constants of figure 9, as a function of the angle relative to the incident protons.

13. Parameterization of fit results for the slope and normalization constants of figure 10, as a function of the angle relative to the incident protons.

14. Parameterization of fit results for the slope and normalization constants of figure 11, as a function of the angle relative to the incident protons.



0°-15°
r^2** Dose Equivalent [cm**2 rem/ (incident proton)]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
250 Mev protons
200 Mev protons
150 Mev protons
0
100
200
300
400
500
600
700
Radius (cm)

Figure 1

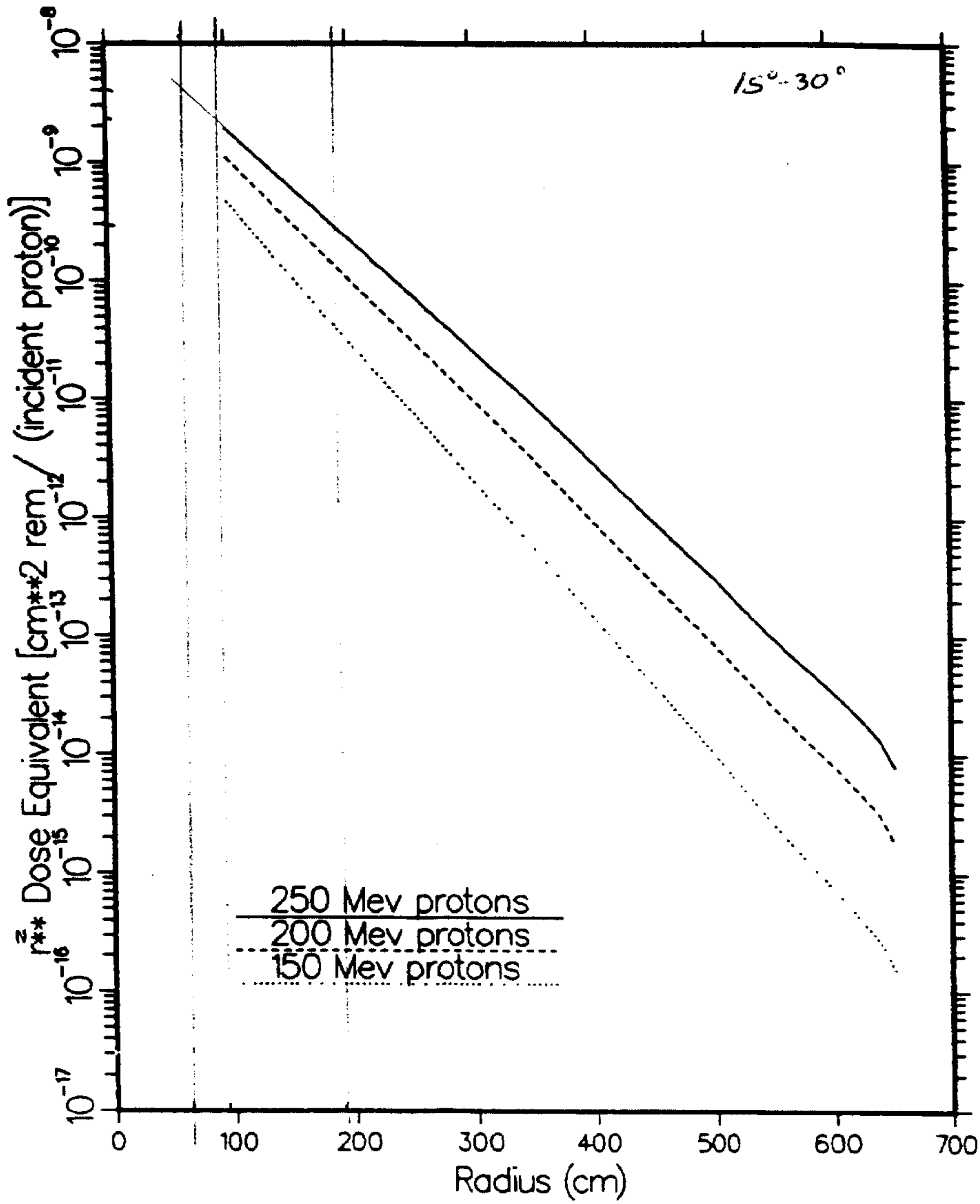

15°-30°
r^{2}** Dose Equivalent [cm**2 rem/(incident proton)]
Radius (cm)
250 Mev protons
200 Mev protons
150 Mev protons
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
0
100
200
300
400
500
600
700

Figure 2

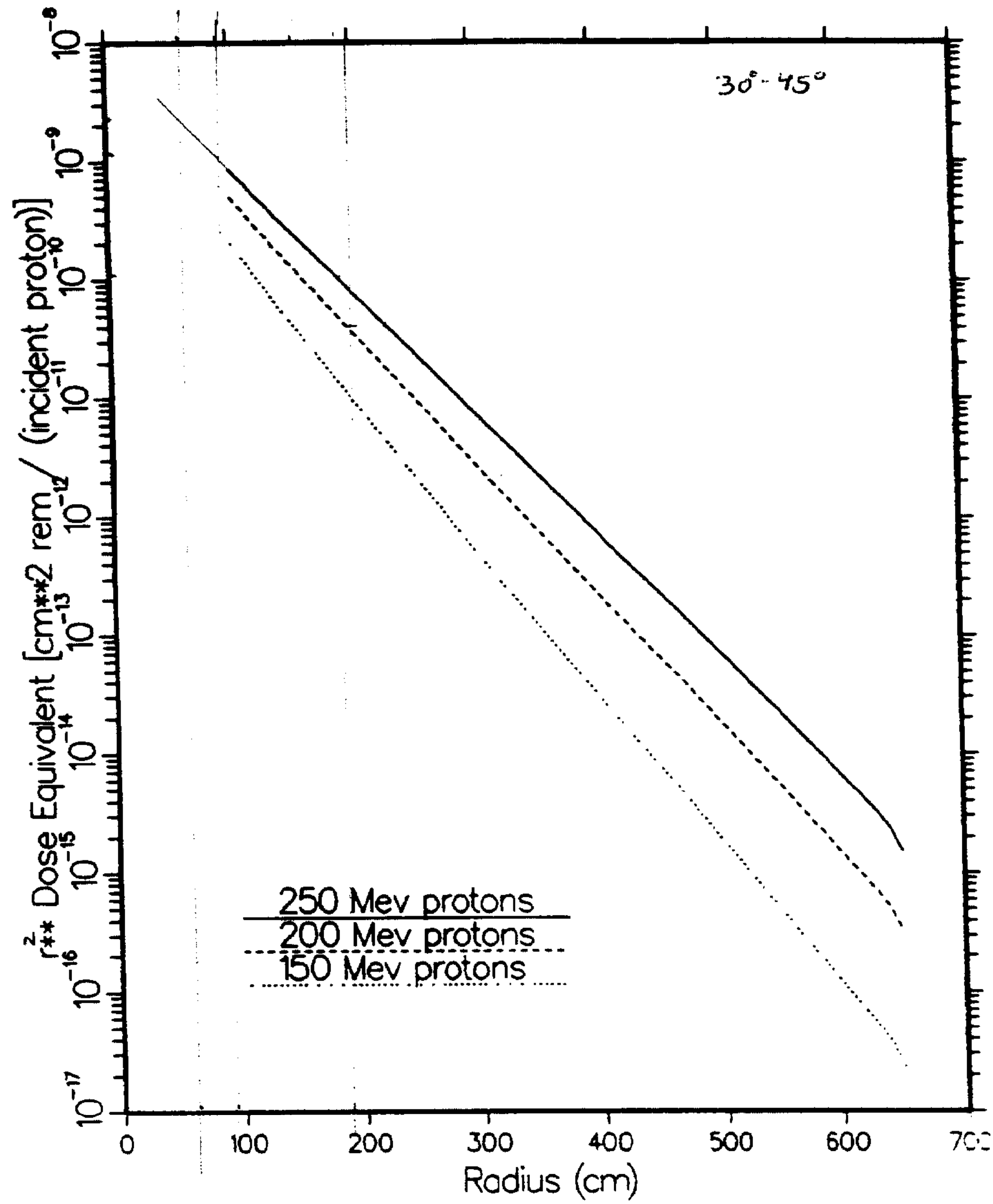

30°-45°
250 Mev protons
200 Mev protons
150 Mev protons
r** 2 Dose Equivalent [cm**2 rem/ (incident proton)]
Radius (cm)
0
100
200
300
400
500
600
700
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17

Figure 3

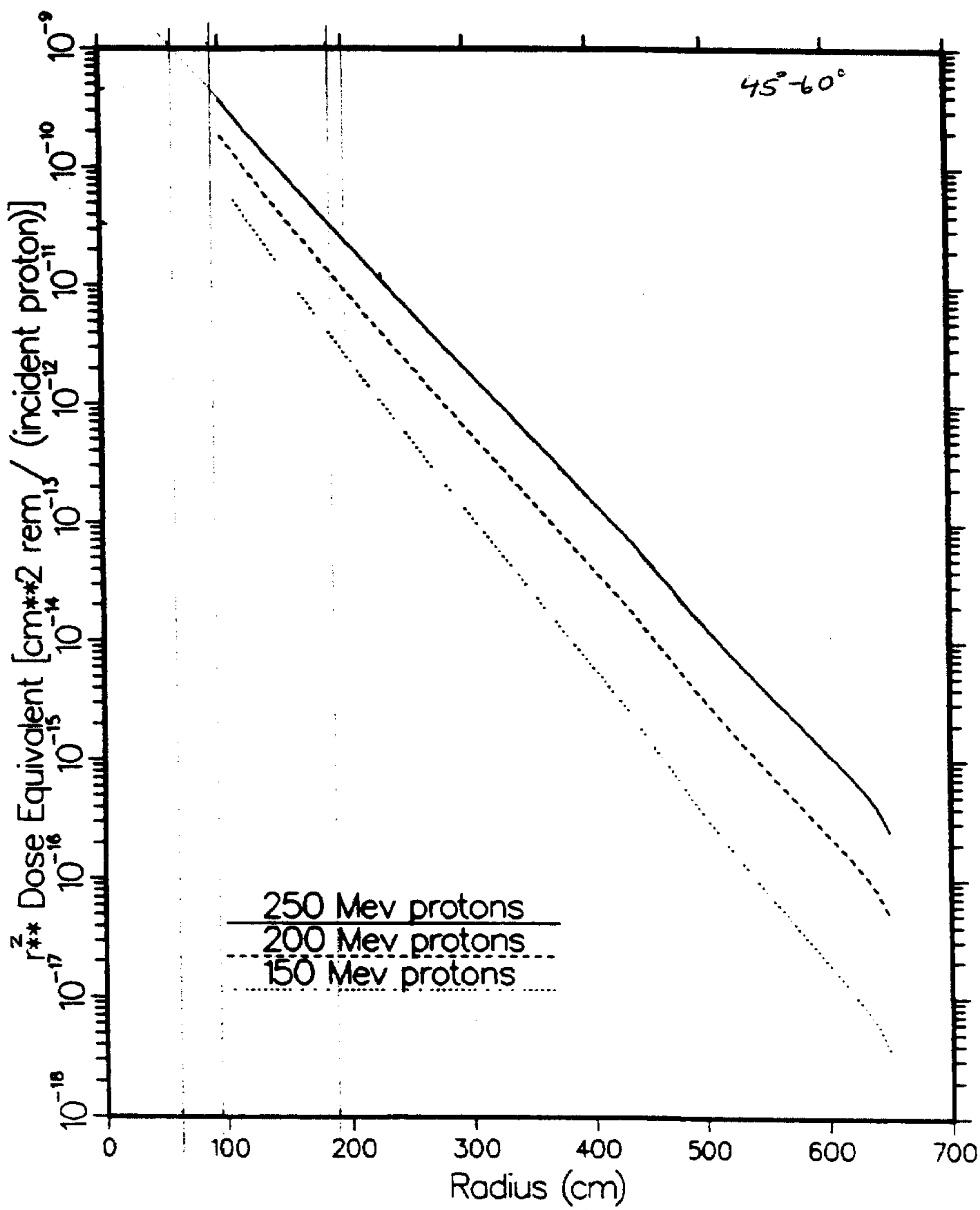

45°-60°
250 Mev protons
200 Mev protons
150 Mev protons
r**2 Dose Equivalent [cm**2 rem / (incident proton)]
Radius (cm)
0
100
200
300
400
500
600
700

Figure 4

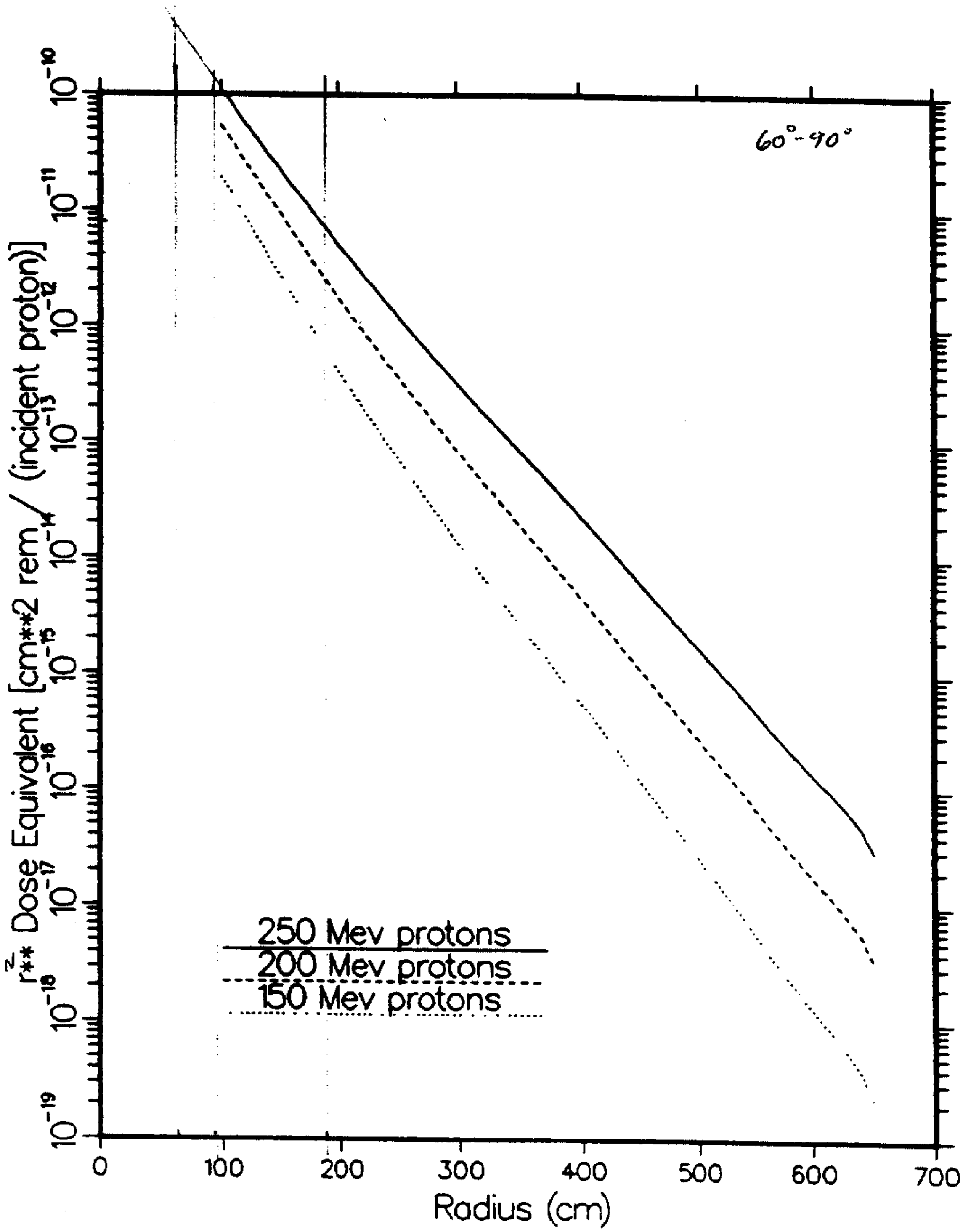
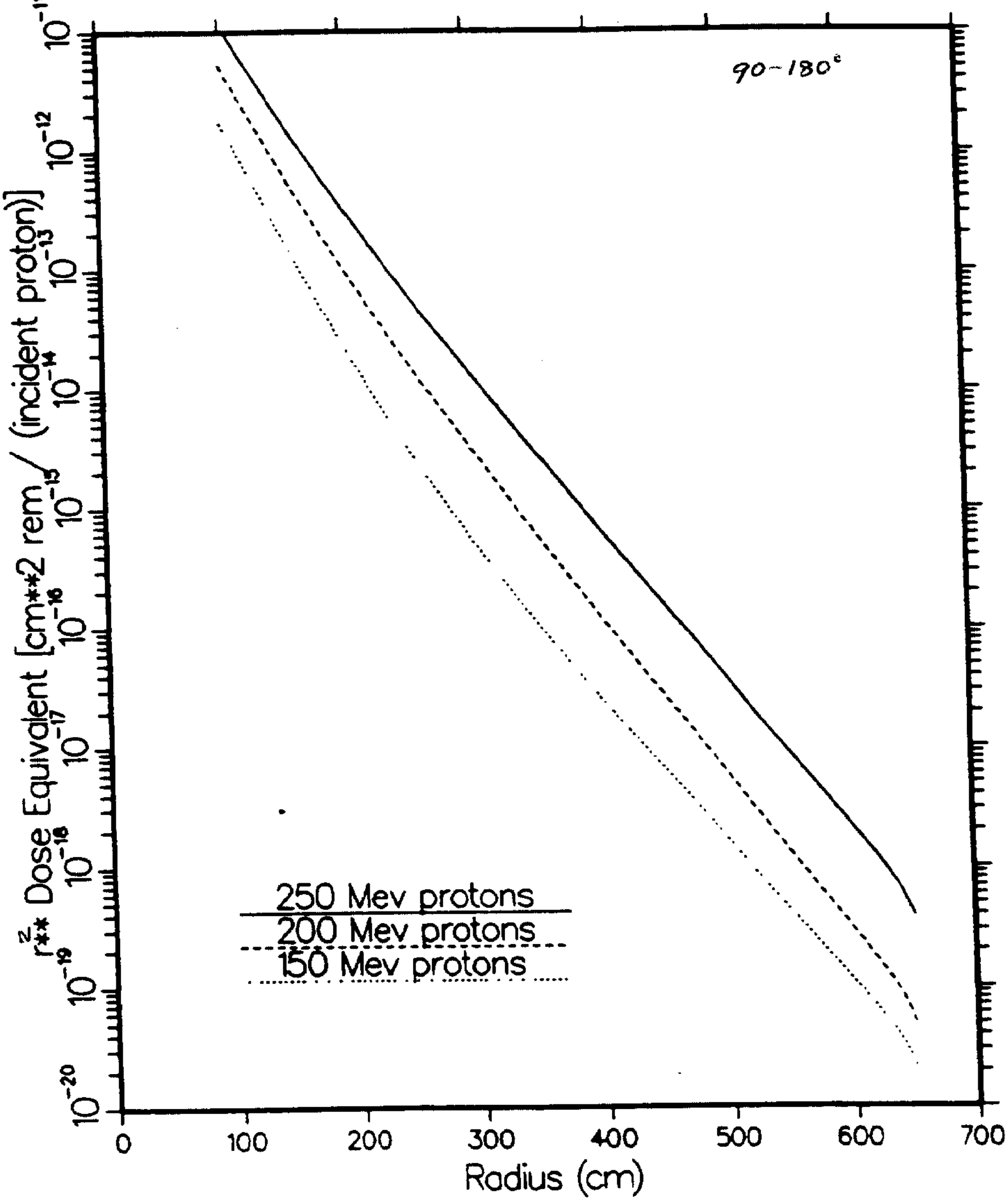

60°-90°
r** Dose Equivalent [cm**2 rem / (incident proton)]
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
250 Mev protons
200 Mev protons
150 Mev protons
0
100
200
300
400
500
600
700
Radius (cm)

Figure 5



90-180°
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
r**2 Dose Equivalent [cm**2 rem/(incident proton)]
250 Mev protons
200 Mev protons
150 Mev protons
0
100
200
300
400
500
600
700
Radius (cm)

Figure 6

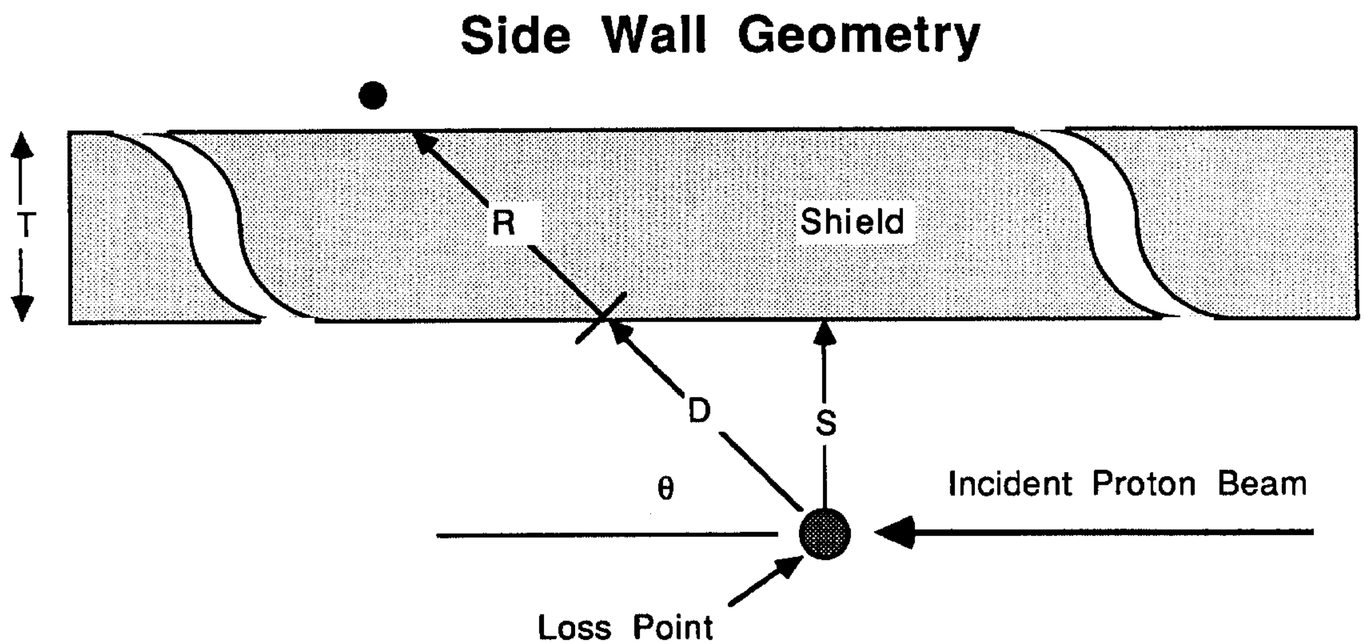


Figure 7b

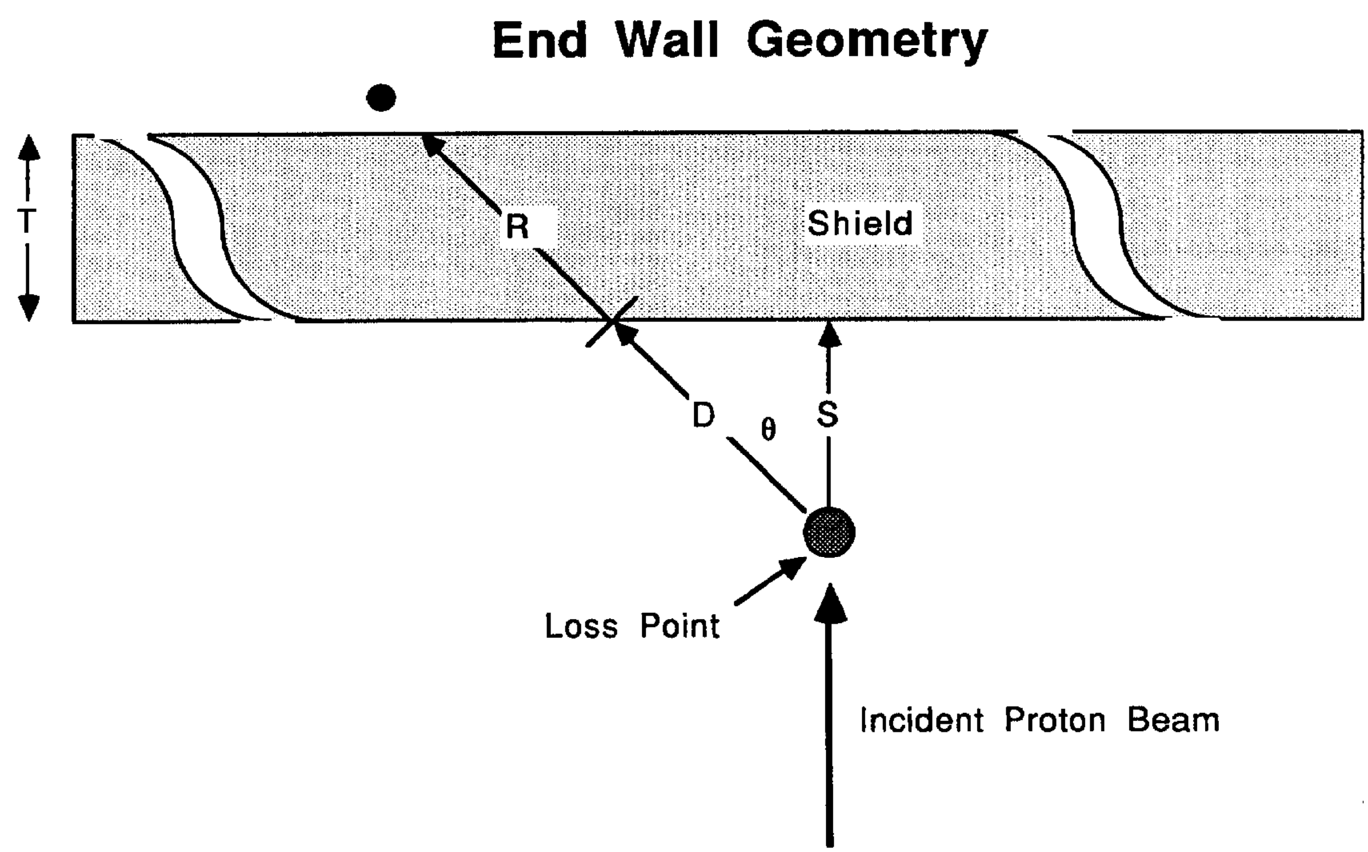


Figure 7a

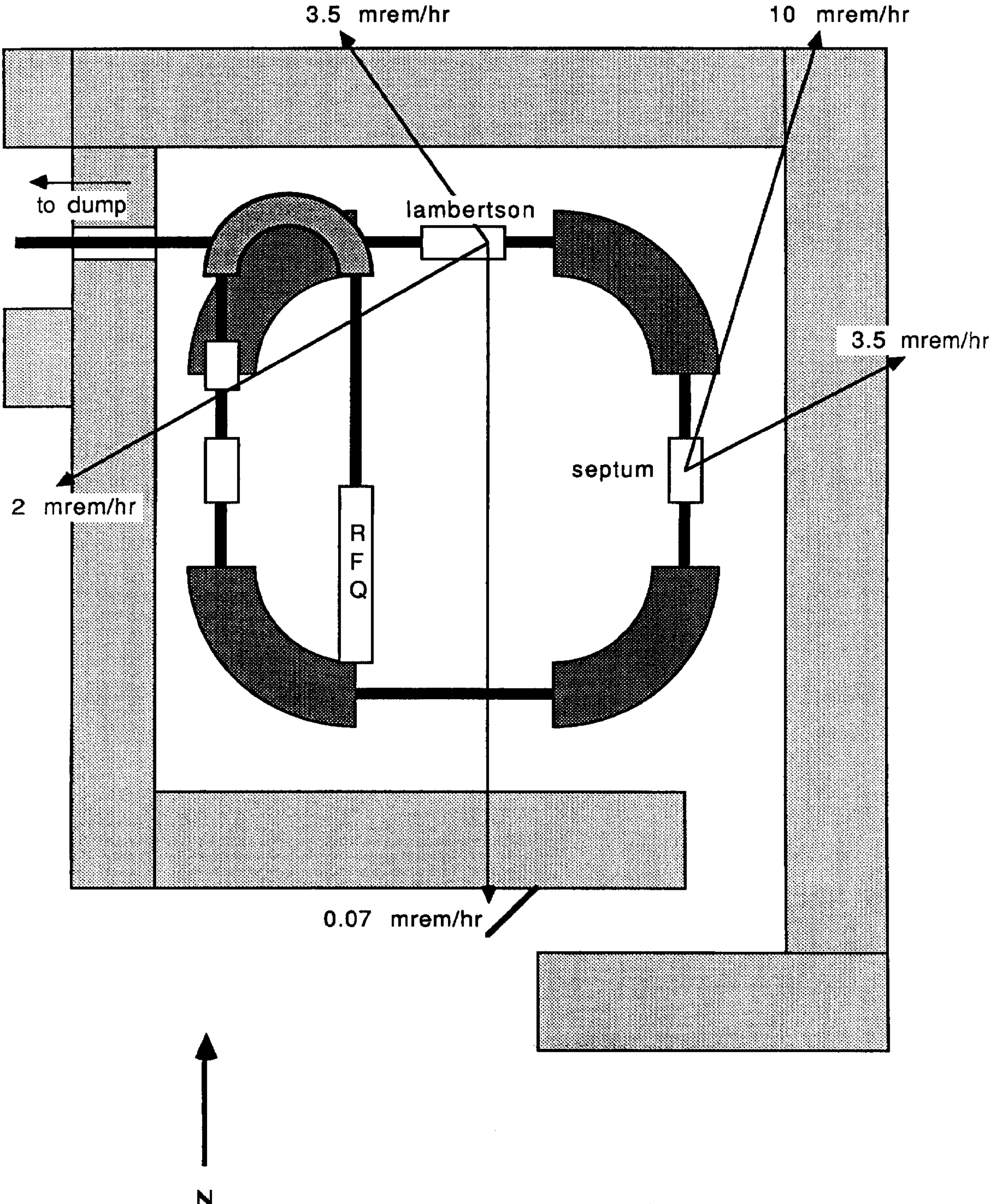

3.5 mrem/hr
10 mrem/hr
to dump
lambertson
3.5 mrem/hr
septum
2 mrem/hr
R
F
Q
0.07 mrem/hr
N

Figure 8

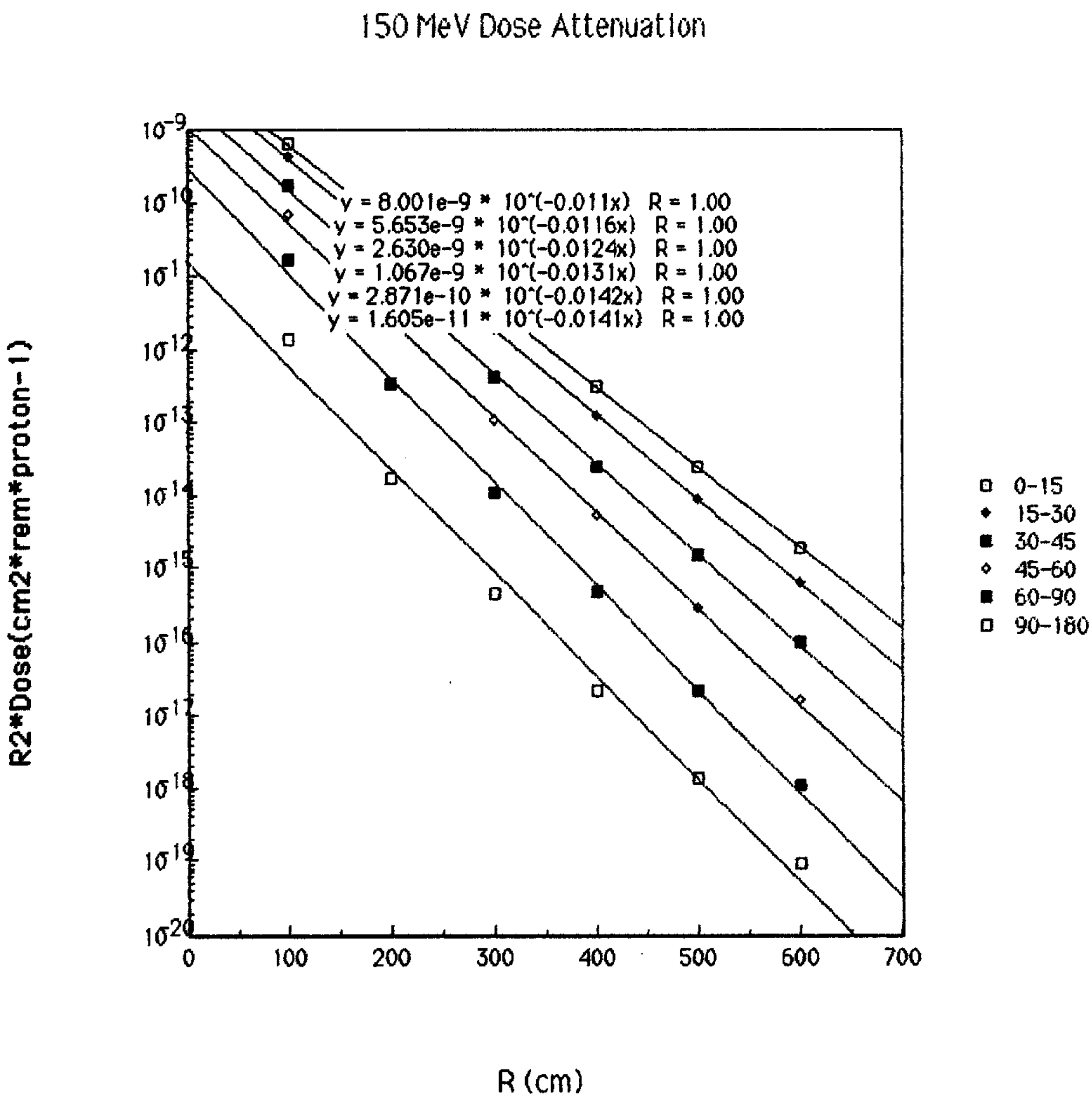

150 MeV Dose Attenuation
y = 8.001e-9 * 10^(-0.011x) R = 1.00
y = 5.653e-9 * 10^(-0.0116x) R = 1.00
y = 2.630e-9 * 10^(-0.0124x) R = 1.00
y = 1.067e-9 * 10^(-0.0131x) R = 1.00
y = 2.871e-10 * 10^(-0.0142x) R = 1.00
y = 1.605e-11 * 10^(-0.0141x) R = 1.00
R2*Dose(cm2*rem*proton-1)
R (cm)
0-15
15-30
30-45
45-60
60-90
90-180

Figure 9

200 MeV Dose Attenuation

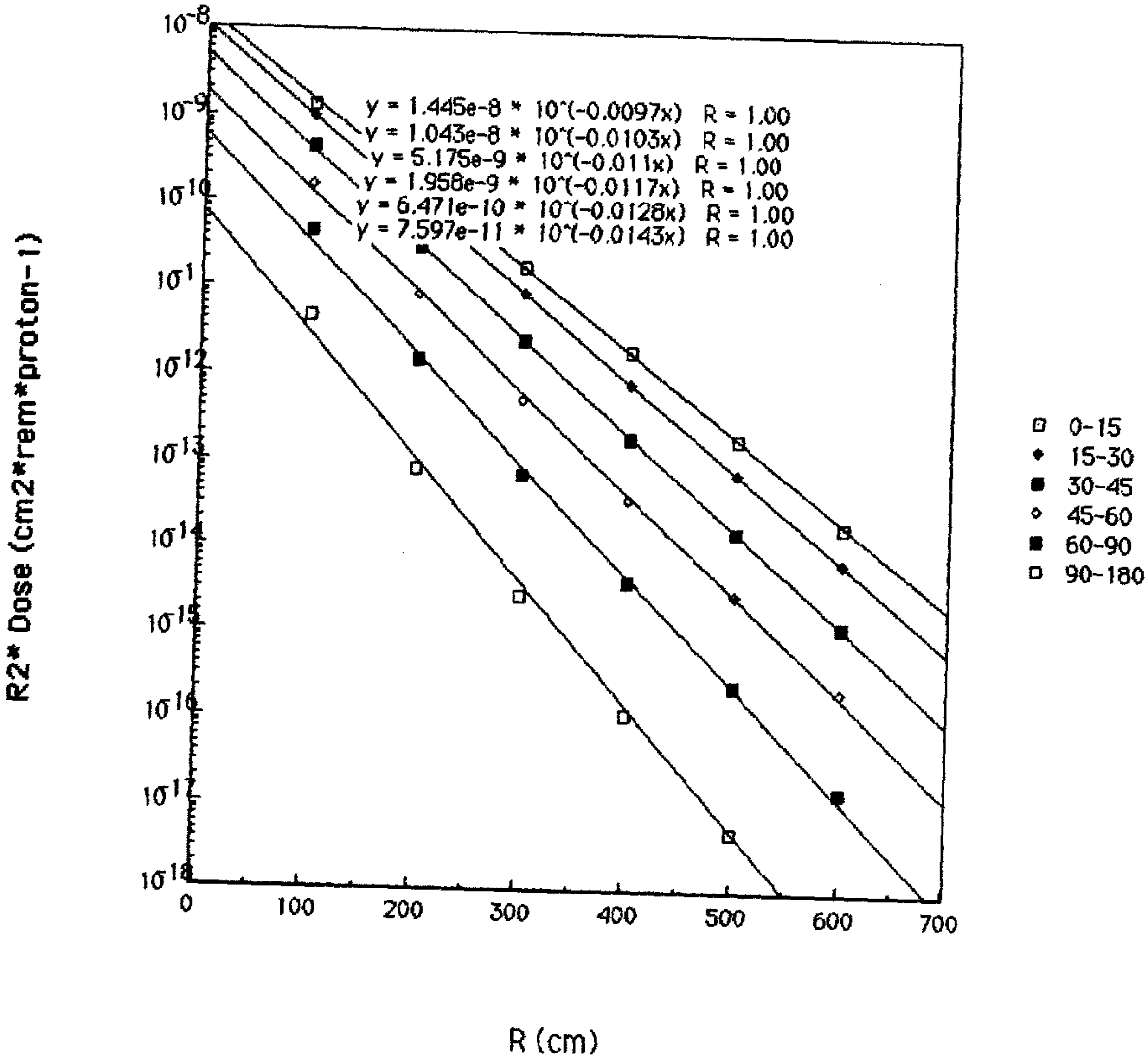
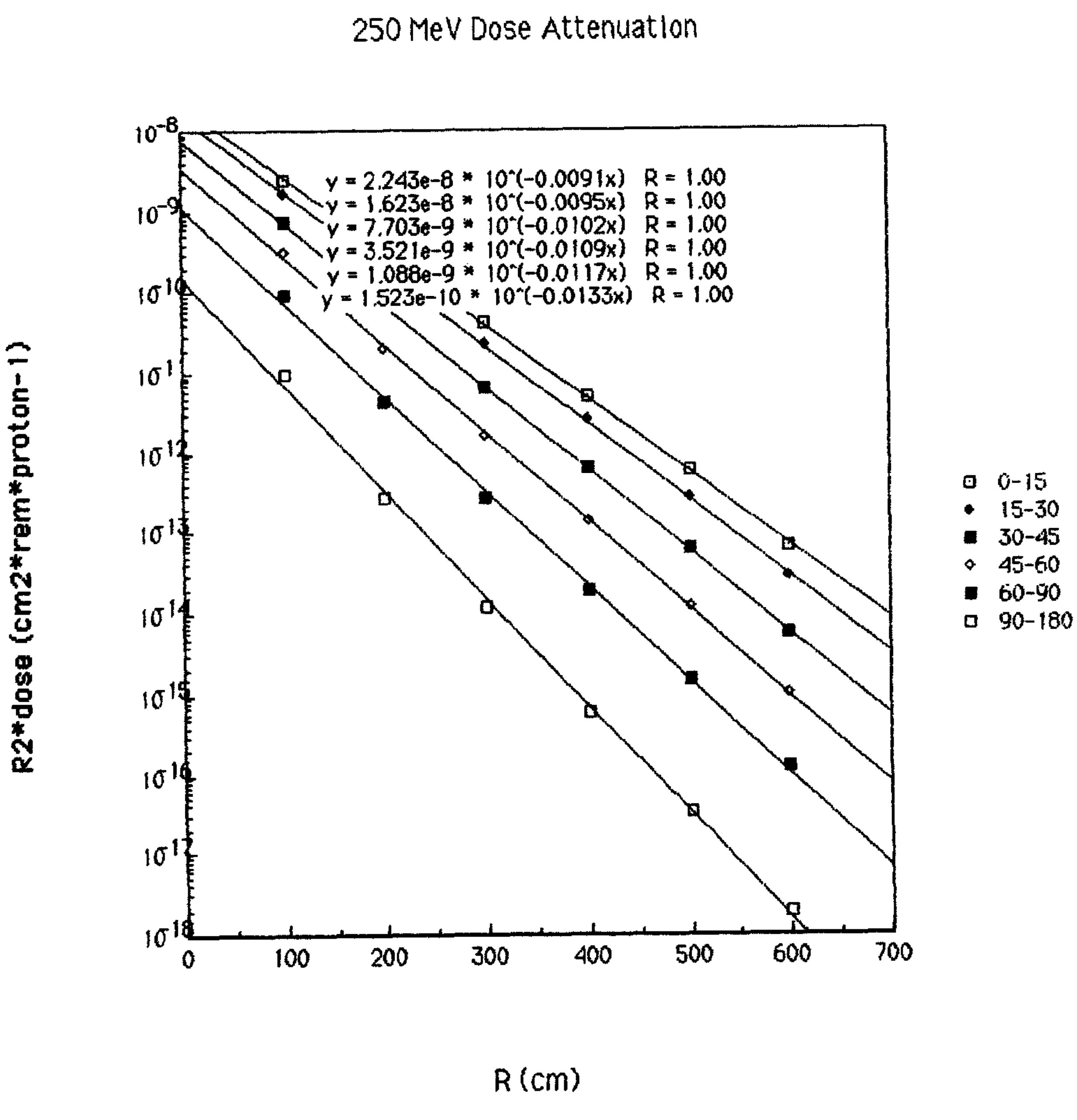
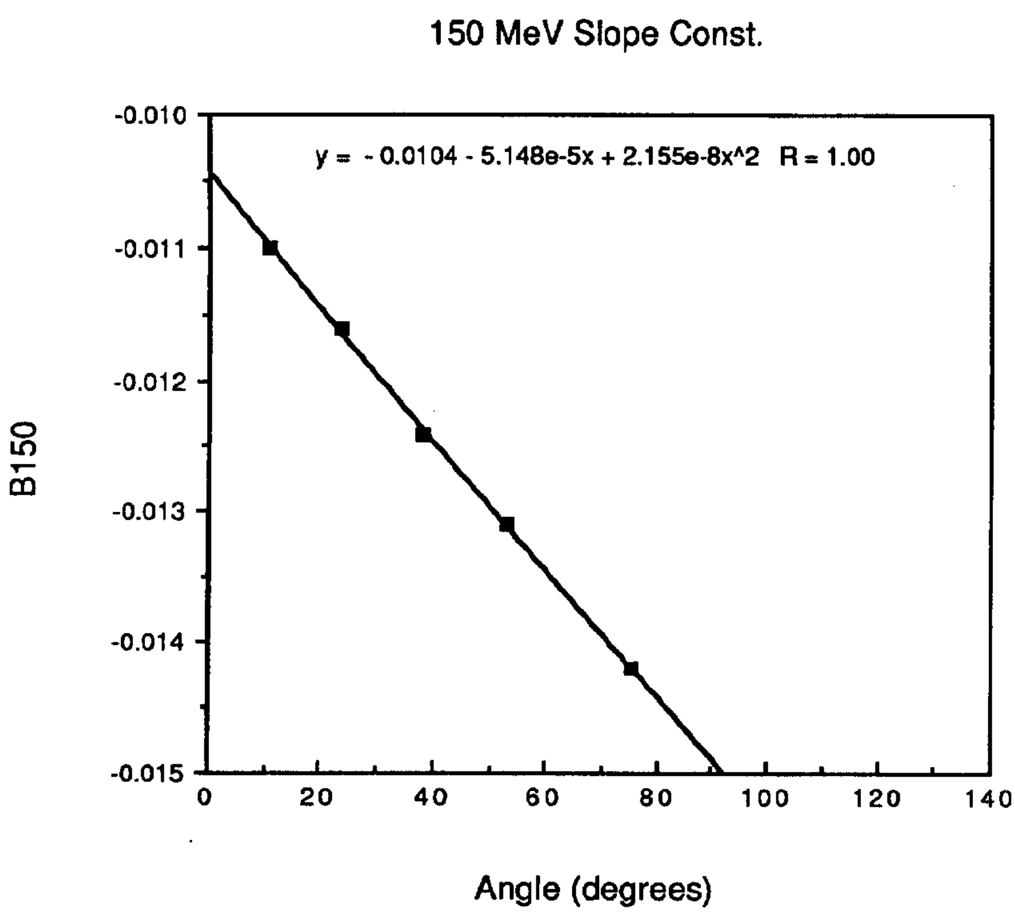


Figure 10



250 MeV Dose Attenuation
y = 2.243e-8 * 10^(-0.0091x) R = 1.00
y = 1.623e-8 * 10^(-0.0095x) R = 1.00
y = 7.703e-9 * 10^(-0.0102x) R = 1.00
y = 3.521e-9 * 10^(-0.0109x) R = 1.00
y = 1.088e-9 * 10^(-0.0117x) R = 1.00
y = 1.523e-10 * 10^(-0.0133x) R = 1.00
R2*dose (cm2*rem*proton-1)
R (cm)
0-15
15-30
30-45
45-60
60-90
90-180

Figure 11


150 MeV Slope Const.
y = - 0.0104 - 5.148e-5x + 2.155e-8x^2 R = 1.00
-0.010
-0.011
-0.012
-0.013
-0.014
-0.015
B150
0
20
40
60
80
100
120
140
Angle (degrees)

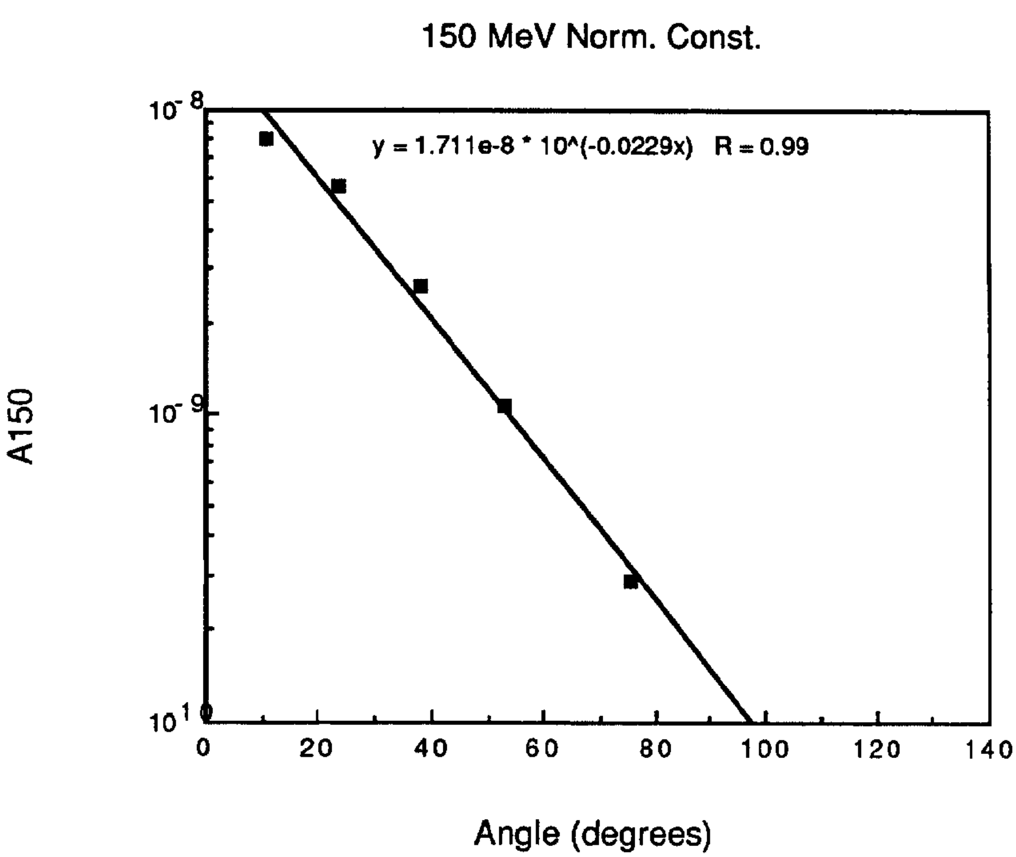
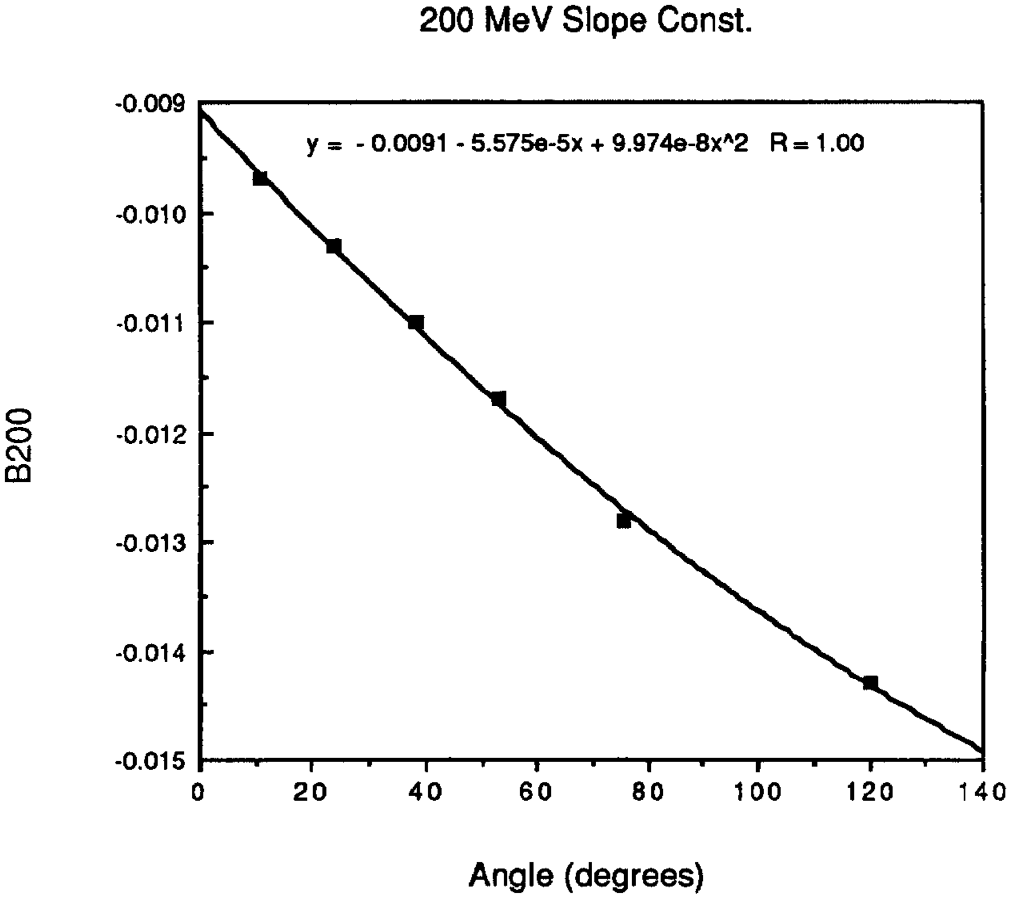

150 MeV Norm. Const.
y = 1.711e-8 * 10^(-0.0229x) R = 0.99
10⁻⁸
10⁻⁹
10¹⁰
A150
0
20
40
60
80
100
120
140
Angle (degrees)

Figure 12


200 MeV Slope Const.
y = - 0.0091 - 5.575e-5x + 9.974e-8x^2 R = 1.00
B200
-0.009
-0.010
-0.011
-0.012
-0.013
-0.014
-0.015
0
20
40
60
80
100
120
140
Angle (degrees)

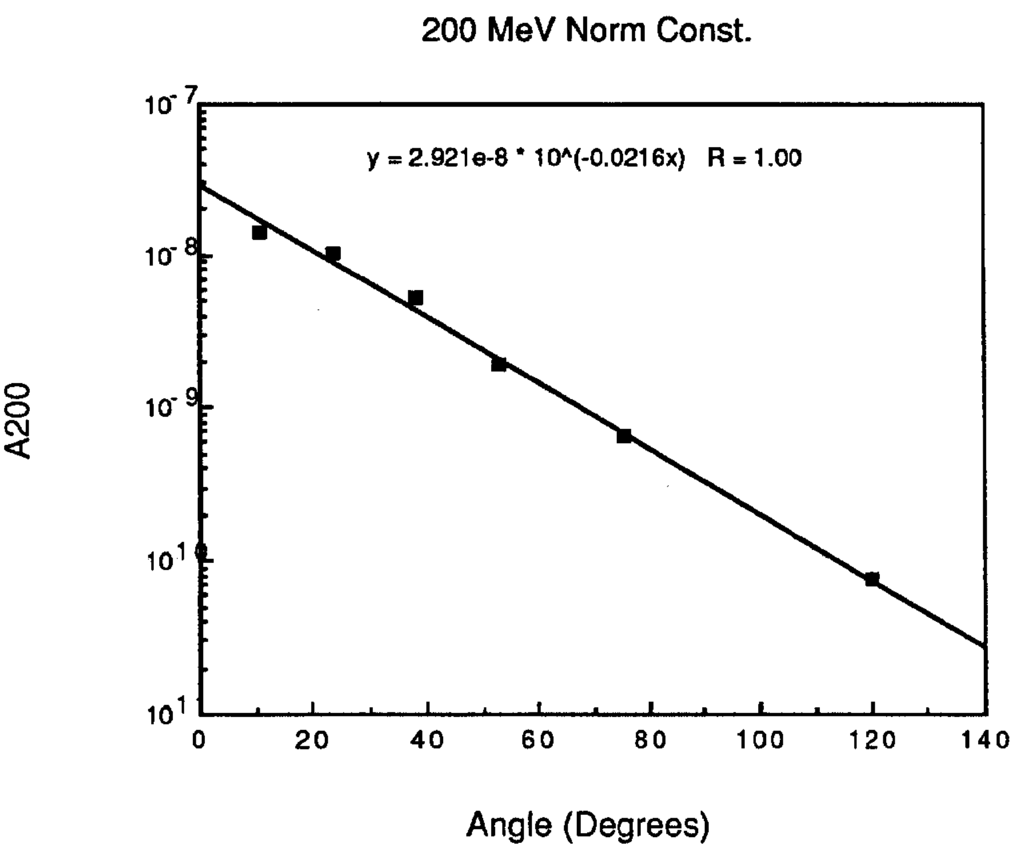
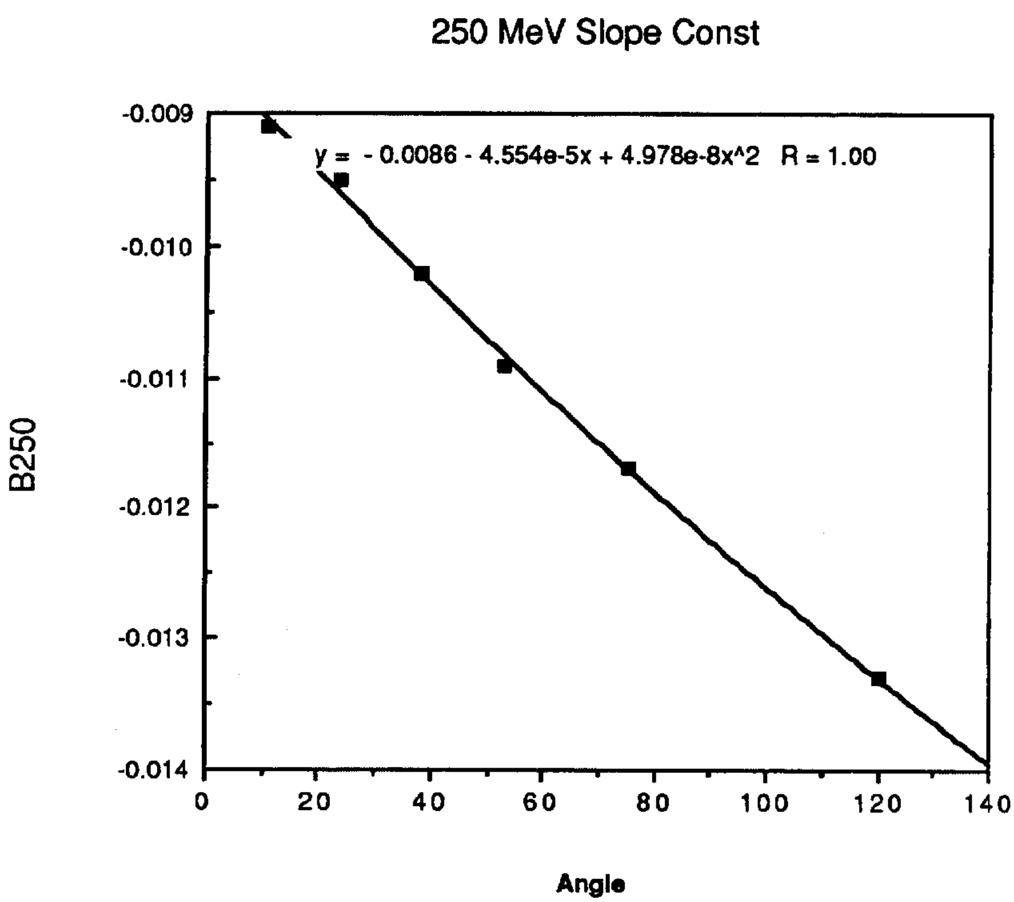
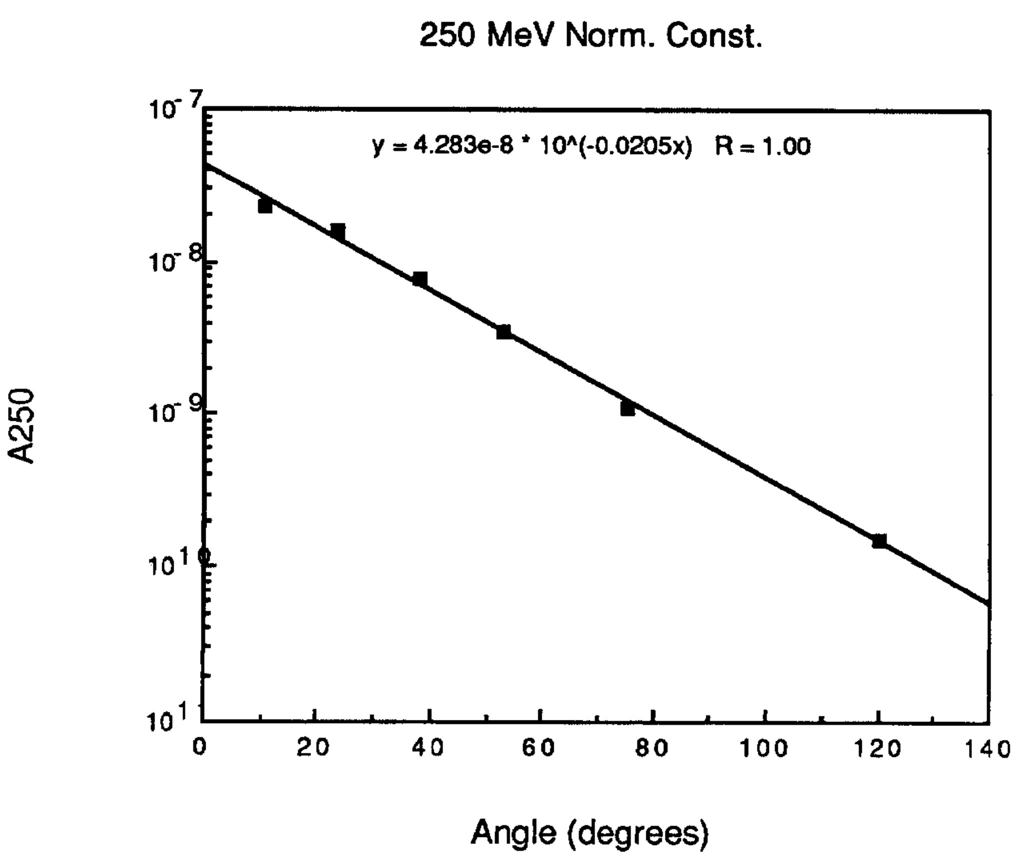

200 MeV Norm Const.
y = 2.921e-8 * 10^(-0.0216x) R = 1.00
A200
10-7
10-8
10-9
1010
101
0
20
40
60
80
100
120
140
Angle (Degrees)

Figure 13



250 MeV Slope Const
y = - 0.0086 - 4.554e-5x + 4.978e-8x^2 R = 1.00
-0.009
-0.010
-0.011
-0.012
-0.013
-0.014
B250
0
20
40
60
80
100
120
140
Angle



250 MeV Norm. Const.
y = 4.283e-8 * 10^(-0.0205x) R = 1.00
A250
0
20
40
60
80
100
120
140
Angle (degrees)

Figure 14