Fermi National Accelerator Laboratory

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Shielding scaling calculations

Gerald Dugan
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

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G. Dugan
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Introduction

This report describes the methods used to determine the scaling factors for the dependence of the attenuation of radiation dose with depth of soil-equivalent shielding, and for the dependence of the radiation dose on the primary energy.

Dependence of the dose on soil-equivalent shielding

The basic assumption for the functional forms of the dose-shielding dependence is an exponential dependence of the radiation dose per incident proton on the depth of soil-equivalent shielding:

x = radiation dose (mrem) per incident proton(in units of 10^{13}),
y = soil-equivalent shielding (ft),

$$y = y_0 + s \log_{10} x,$$

where y_0 = shielding to give 1 mrem for 10^{13} protons, and s = shielding required to give factor of 10 attenuation in dose per proton.

The quantities y_0 and s are determined as follows. Referring to TM-1140, the graphs of stars/cm^3/proton vs depth(z) and radius are analyzed to determine the correlation between radius (which is related to the amount of soil-equivalent shielding) and maximum of the star density/proton along z. This was done for 6 cases: magnet in 3' enclosure for 400 and 1000 GeV (fig. 1 and 3 in TM 1140); thin pipe in 3' enclosure for 400 and 1000 GeV (fig. 9 and 11 in TM 1140); and buried steel pipe for 400 and 1000 GeV (fig 17 and 18 in TM 1140).

For each of these pairs of cases, the star density/proton was converted to dose/proton (mrem/proton) using the conversion factor of 10.8 μrem/(star/cm^3), which is cited in the Fermilab Radiation Guide as appropriate for soil. The resulting correlations of dose/proton (x) vs soil-equivalent shielding (y). are plotted in figs 1,2 and 3 of this report. Each correlation was fitted to the functional form cited above to determine y_0 and s for each of the 6 cases. This information is shown in the figures.

As a check on the results, the fits were used to calculate the requirements for soil-equivalent shielding for the various dose levels cited in the 12/11/90 memo of Don Cossairt to J. Peoples. The relation between doses specified in this memo (D) and the quantity x used in the fits is the following:

No interlocked detectors:

$x(\text{mrem/hr}/10^{13}\ \text{protons/hr}) = D(\text{mrem/hr})/120$,

(for $2\text{x}10^{13}$ protons/pulse,60 pulses/hr)

Interlocked detectors:

$x(\text{mrem}/10^{13}\ \text{protons}) = D(\text{mrem})/2$

(for $2\text{x}10^{13}$ protons)

Figures 4 and 5 of this report compare the fits (lines) with the numbers in Don's memo (symbols). As can be seen, the fit reproduce the numbers reasonably well. The only peculiar feature is that Don's numbers look systematically slightly low relative to the fit for the "buried pipe, interlocked detectors" case.

Dependence of the dose per proton on the primary proton energy

We are interested in how the dose per proton, x, depends on the energy of the primary proton, over the range from 1000 GeV to 8 GeV. We assume a power- law dependence of the radiation dose per proton on the primary energy.

From the above equation, solving for x gives:

$$x = 10^{(y-y_0)/s}.$$

In principle, both y_0 and s are functions of the primary energy, E. However(see below), the dependence of s on E is very weak, and will be neglected. Then, for a fixed amount of shielding, the dose per proton at primary energy E, x(E), relative to the dose at E=1000 GeV, is given by

$$R(E) = x(E)/x(1000) = 10^{(y_0(1000)-y_0(E))/s}$$

We parameterize the dependence of R on E by a power law:

$$R(E) = R_0E^b.$$

The exponent b characterizes the dependence on E. In order to determine this exponent, the document "High Energy Particle Interactions in Large Targets", by A. vanGinneken and M. Awschalom, has been used. In this volume, on pp 83-86, graphs (figs.

VIII.18-21) are presented for star density vs depth and radius, for protons of energies 1000, 300, 100, and 30 GeV interacting in a solid concrete cylinder.

For each of these graphs, the same analysis to determine y_0 and s as described above has been done. The results are displayed in fig 6 of this report, and in the following table:

Energy (GeV)	y_0 (E) (ft)	s(E) (ft)	R(E) = $10^{(y_0(1000)-y_0(E))/s(E)}$
1000	19.511	-2.949	1.0
300	18.503	-2.9145	.4509
100	17.743	-3.009	.25848
30	16.74	-2.962	.1160

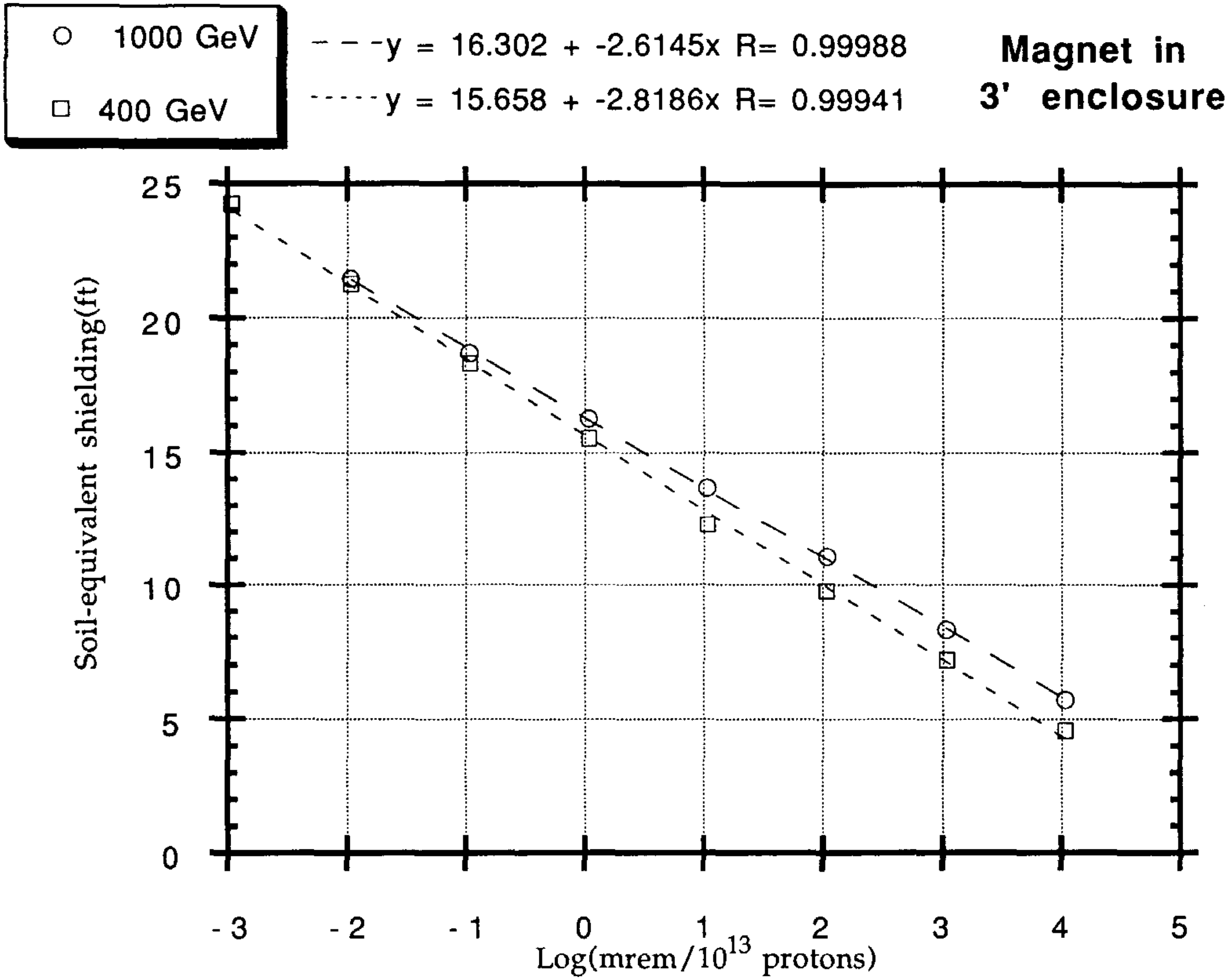
In fig 7, the function R(E) is plotted vs E and fitted to the power law, giving an exponent b = 0.605.

Application: criteria for Main Ring/Tevatron shielding

An EXCEL spreadsheet has been used to employ the results of the above scaling arguments to determine the shielding requirements associated with the Main Ring/Tevatron enclosures. This spreadsheet is attached as an appendix to this report.

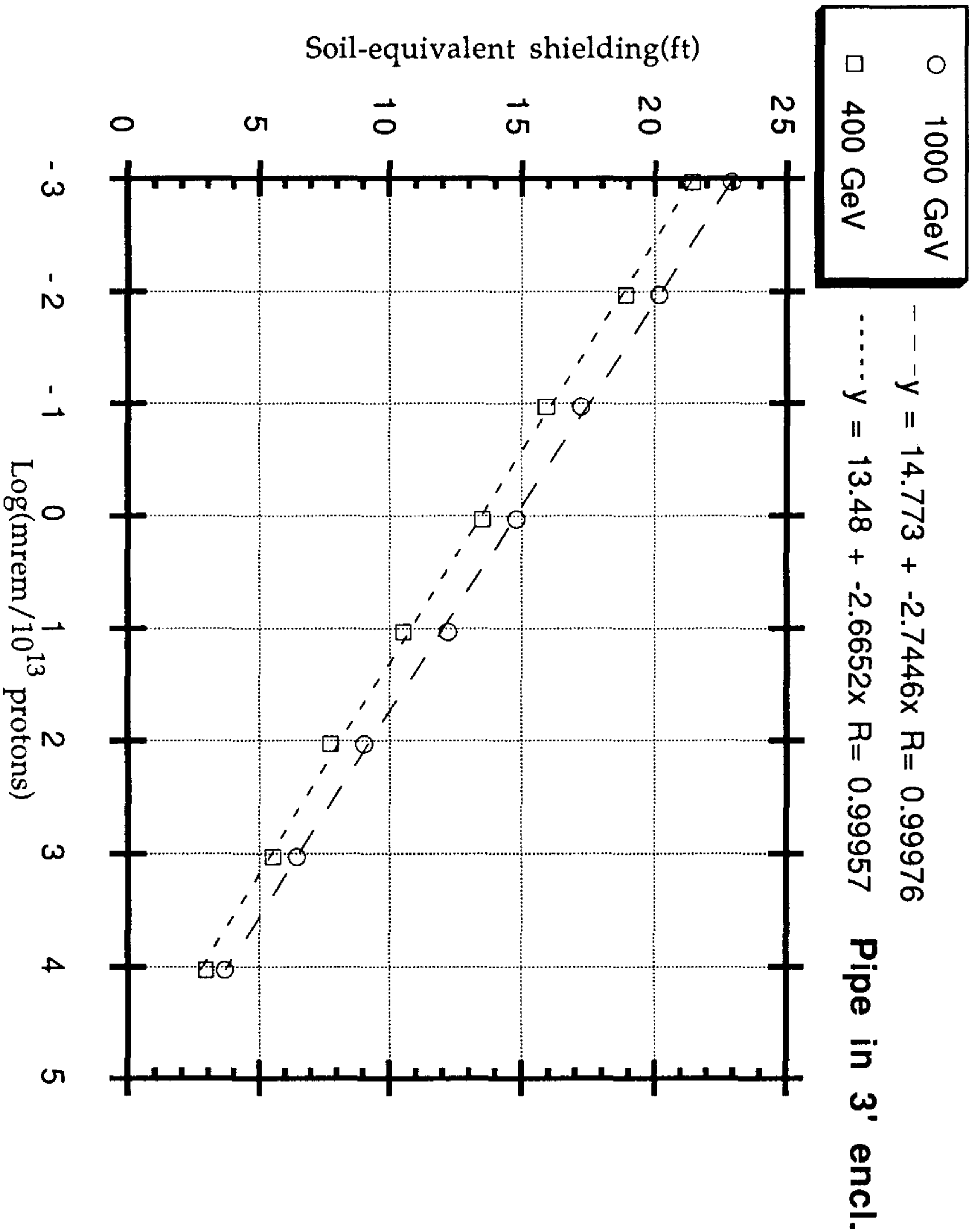
The "reference" soil-equivalent shielding, from which the scaling has been made, is the set of numbers in the 12/11/90 memo from Don Cossairt to J. Peoples. These numbers correspond to the shielding required for $2x10^{13}$ protons/pulse at 60 pulses/hr.

The spreadsheet computes the soil-equivalent shielding needed for the various cases of different intensities and energies indicated on the spreadsheet, using the shielding attenuation factor of 10x = 2.67 ft (average for the three cases studied, for 1000 GeV), and an energy dependence of the dose per proton of $E^{0.605}$. The case of Main Ring injection, 8 GeV, is also included, although this is outside the range of the information used to compute the energy dependence. Hence, it is suspect and should be verified by appropriate CASIM runs.



1000 GeV
400 GeV
y = 16.302 + -2.6145x R= 0.99988
y = 15.658 + -2.8186x R= 0.99941
Magnet in
3' enclosure
Soil-equivalent shielding(ft)
25
20
15
10
5
0
- 3
- 2
- 1
0
1
2
3
4
5
Log(mrem/10^13 protons)

Figure 1



Pipe in 3' encl.
1000 GeV
400 GeV
y = 14.773 + -2.7446x R= 0.99976
y = 13.48 + -2.6652x R= 0.99957
Soil-equivalent shielding(ft)
0
5
10
15
20
25
-3
-2
-1
0
1
2
3
4
5
Log(mrem/10^13 protons)

Figure 2

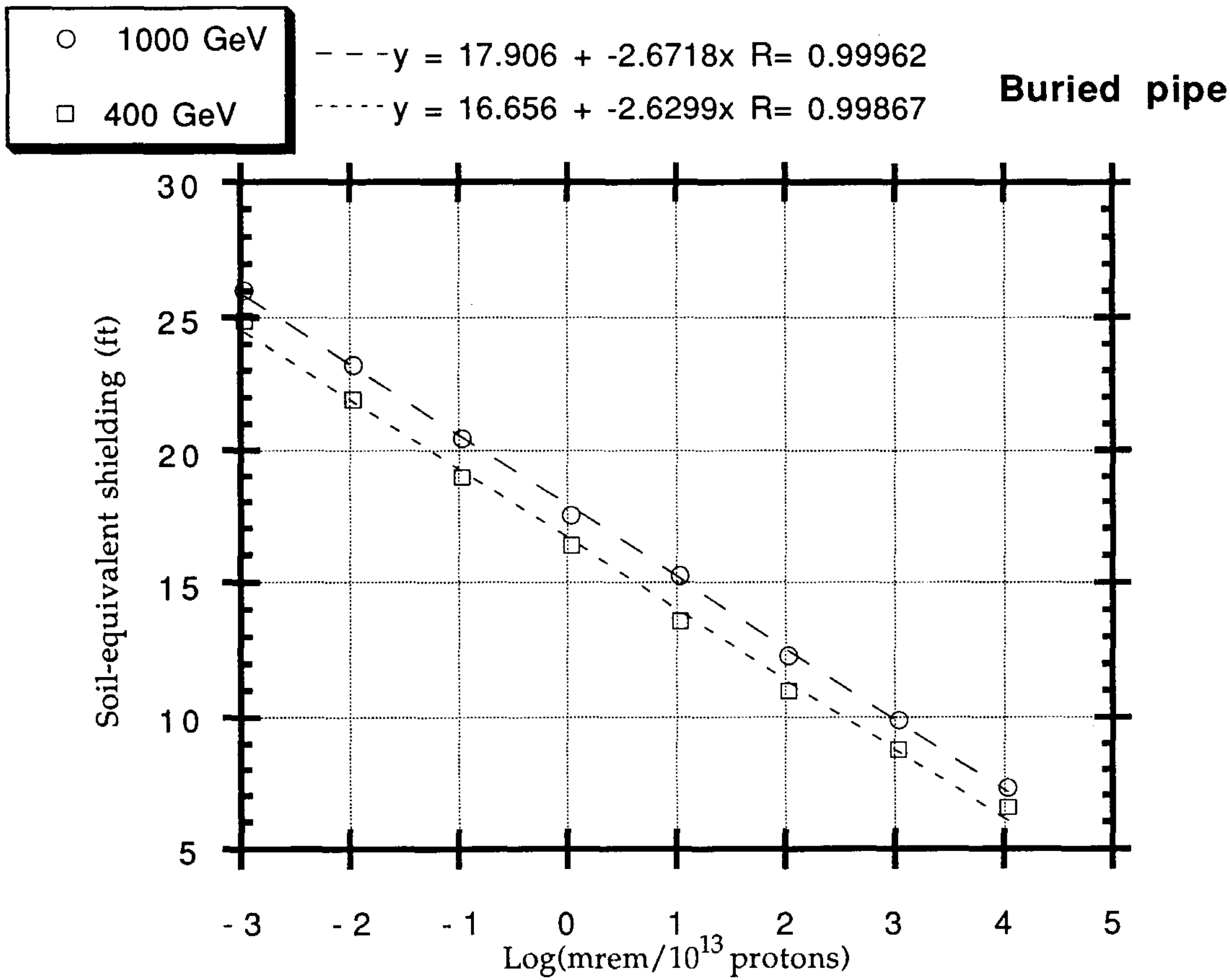

1000 GeV
400 GeV
y = 17.906 + -2.6718x R= 0.99962
y = 16.656 + -2.6299x R= 0.99867
Buried pipe
Soil-equivalent shielding (ft)
30
25
20
15
10
5
-3
-2
-1
0
1
2
3
4
5
Log(mrem/10^13 protons)

Figure 3

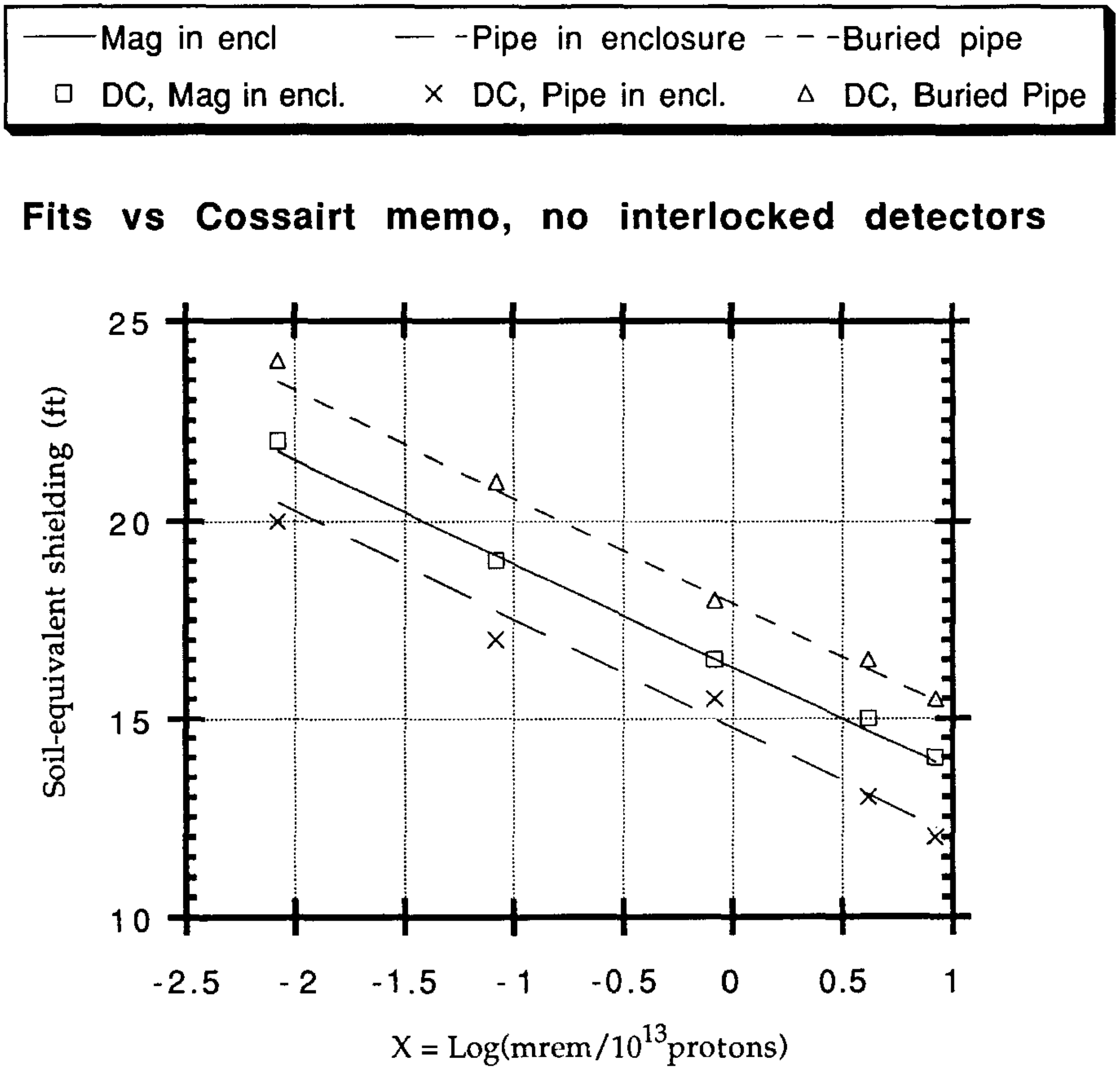

Mag in encl
Pipe in enclosure
Buried pipe
DC, Mag in encl.
DC, Pipe in encl.
DC, Buried Pipe
Fits vs Cossairt memo, no interlocked detectors
25
20
15
10
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Soil-equivalent shielding (ft)
X = Log(mrem/10^13 protons)

Figure 4

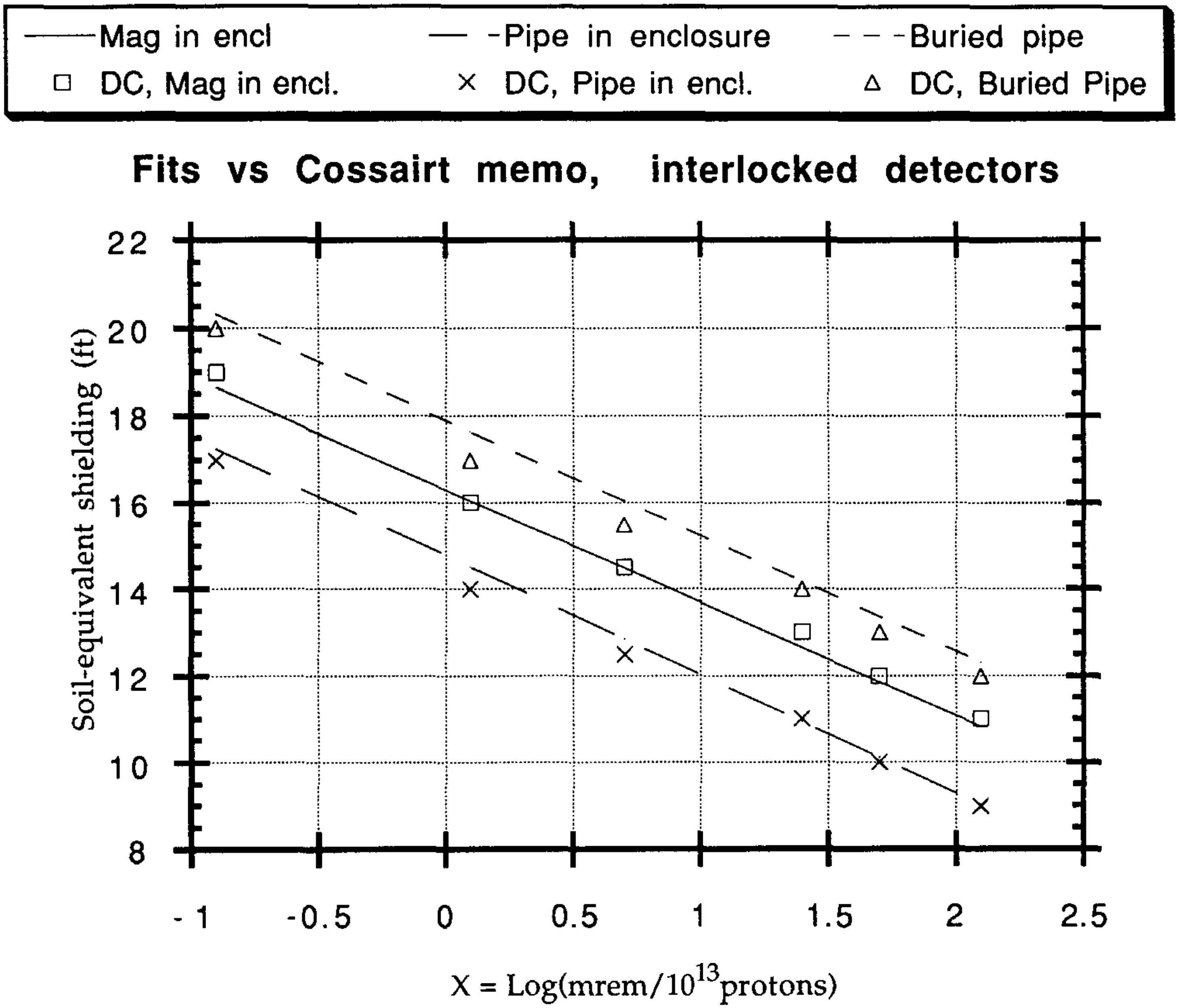
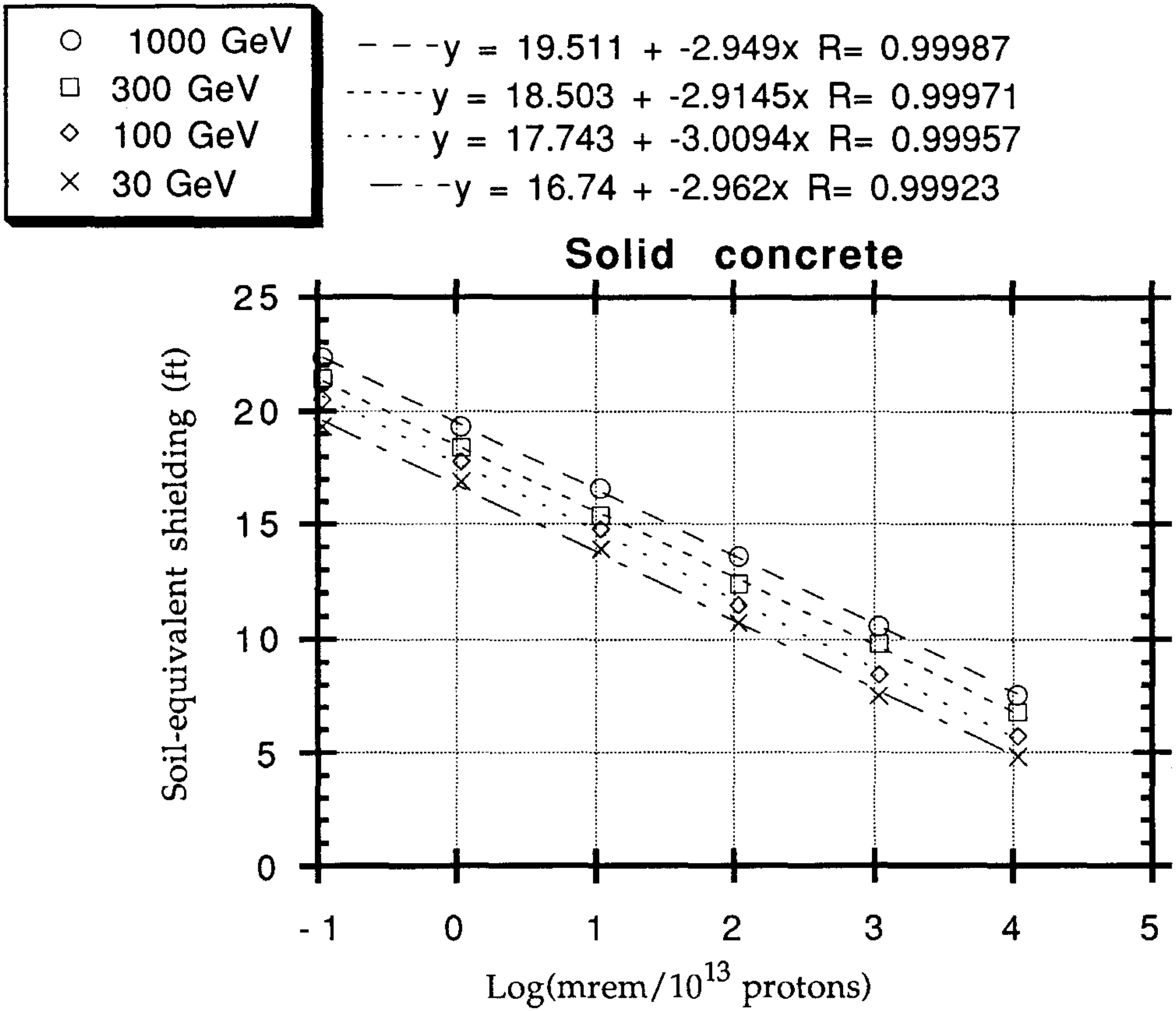
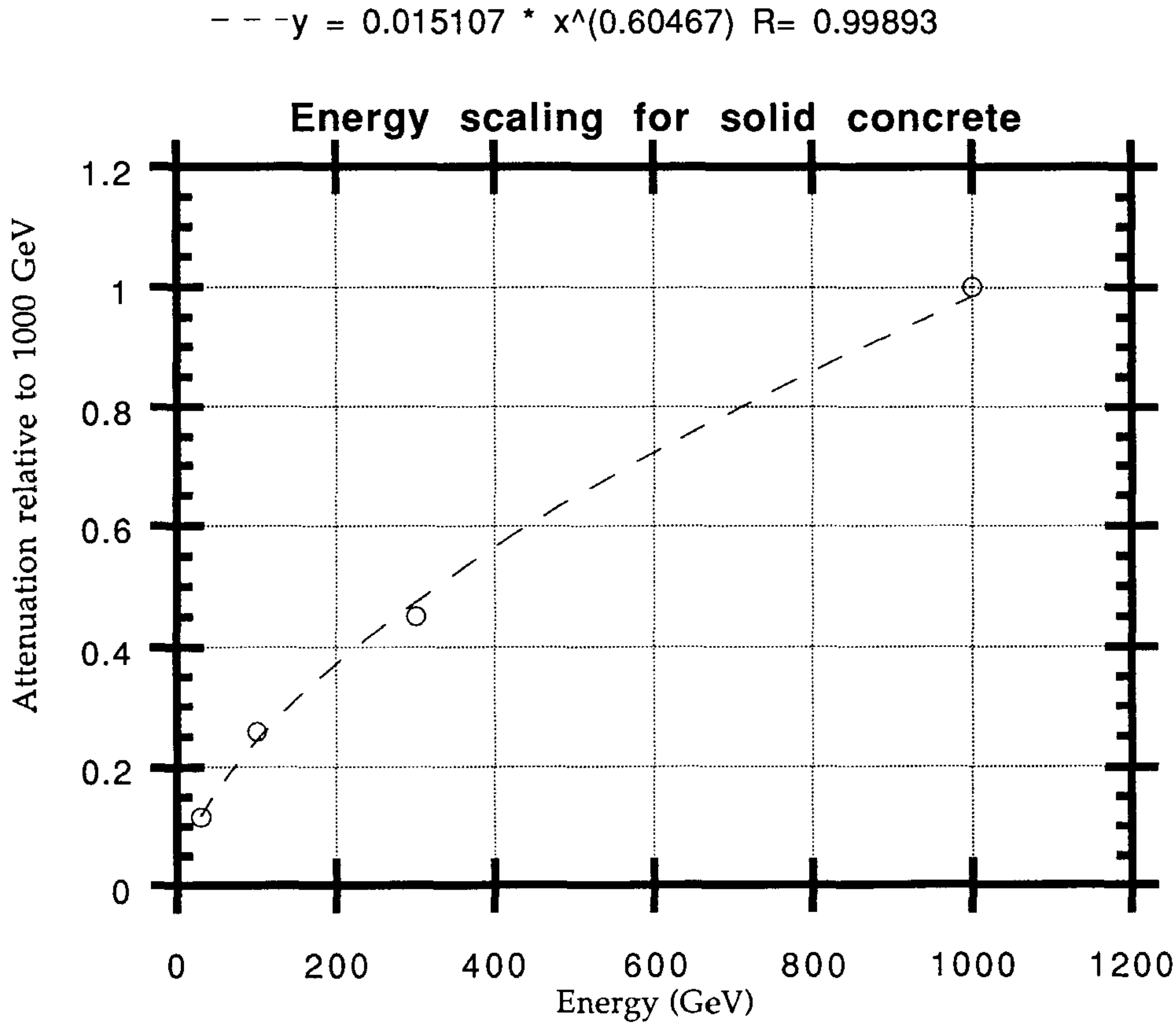

Mag in encl
-Pipe in enclosure
- - -Buried pipe
DC, Mag in encl.
DC, Pipe in encl.
DC, Buried Pipe
Fits vs Cossairt memo, interlocked detectors
Soil-equivalent shielding (ft)
22
20
18
16
14
12
10
8
-1
-0.5
0
0.5
1
1.5
2
2.5
X = Log(mrem/10^13 protons)

Figure 5



1000 GeV
300 GeV
100 GeV
30 GeV
y = 19.511 + -2.949x R= 0.99987
y = 18.503 + -2.9145x R= 0.99971
y = 17.743 + -3.0094x R= 0.99957
y = 16.74 + -2.962x R= 0.99923
Solid concrete
Soil-equivalent shielding (ft)
25
20
15
10
5
0
- 1
0
1
2
3
4
5
Log(mrem/10^13 protons)

Figure 6



- - -y = 0.015107 * x^(0.60467) R= 0.99893
Energy scaling for solid concrete
Attenuation relative to 1000 GeV
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
Energy (GeV)

Figure 7

Fermilab

December 11, 1990

TO: John Peoples

FROM: Don Cossairt

SUBJECT: Generic Shielding Criteria for Compliance with Chapter 6 of the Fermilab Radiation Guide

In view of this morning's discussion at the Laboratory Scheduling Meeting, I am proposing the attached "generic" shielding criteria to be used in determinations of shielding adequacy as a screening tool to identify areas where further calculations, analysis of beam loss conditions, and/or measurements may be indicated. The calculations upon which these criteria are based have been taken from TM-1140, " A Collection of CASIM Calculations" which I wrote in 1982. The calculations were done for worst case scenarios involving point losses of beam. The calculations described in detail in that document used here were all done for 1 TeV protons. For the present situation, the difference between the results and those which would be obtained for 800 GeV gives us a bit of a cushion which is insignificant. The calculations all assume the soil shielding to have a density of 2.24 g/cm^3. In the attachment, I list the dose per hour (where interlocked detectors are not intended to be used) and dose per pulse (where interlocked detectors are provided) regions stated in Tables 2A and 2B of the above referenced chapter in the Radiation Guide along with the quantities of earth-equivalent <u>overburden</u> required to attenuate the radiation sufficiently to qualify for the precautions specified in the Radiation Guide for that particular range of dose/hour or dose/interlock trip.

This is done for three situations deemed to be typical; the point loss of beam on the upstream face of a typically sized conventional magnet placed 3 ft. below the ceiling of a beam enclosure, the loss of beam on the end of a 4 inch diameter aluminum beam pipe with 1/8 inch thick walls placed 3 ft. below the ceiling of an enclosure, and the point loss of beam on the end of a 1 ft. diameter steel beam pipe with 1/2 inch thick walls buried in soil. The results for the enclosure overburden <u>include</u> the modeled 1 ft. thick concrete ceiling. I assumed a beam intensity of 2 X 10^{13} protons per spill and 60 spills per hour of operation. This is appropriate for the imminent fixed target run but does not address future operations at potentially higher intensities.

This criteria considers accidental losses of beam only. Radiation fields due to normal operations should be well documented by routine surveys, etc. The results of calculations involving thick shields are typically good to about a factor of 2-3 where we have compared them with well-understood measurements. This corresponds to about 1-1.5 ft. of earth-equivalent. I suspect that the error in the shielding calculations thus is roughly equivalent to our understanding of shielding thicknesses in most locations.

cc: D. Theriot, K. Stanfield, R. Orr, T. Yamanouchi, P. Garbincius, G. Dugan, H. Casebolt, W. Freeman, A. Elwyn

Earth Overburden Needed for Various Ranges of Dose/Hour or Dose/Interlock Trip

Earth Overburden:		**magnet in enclosure (feet)**	**pipe in enclosure (feet)**	**buried pipe (feet)**
No interlocked Detectors Used Dose/Hour Allowed (mrem)				
D<1	no occupancy limit	22	20	24
1<D<10	minimal occupancy	19	17	21
10<D<100	signs and ropes	16.5	15.5	18
100<D<500	signs, fences, locked gates	15	13	16.5
500<D<1000	signs, fences, interlocked gat	14	12	15.5
Interlocked Detectors Used Dose/Trip (mrem)				
D<0.25	no occupancy limit	19	17	20
0.25<D<2.5	minimal occupancy	16	14	17
0.25<D<10	signs and ropes, minimal occ.	14.5	12.5	15.5
10<D<50	signs, fences, locked gates	13	11	14
50<D<100	signs, fences, interlocked gat	12	10	13
100<D<250	8' high fences, etc. etc.	11	9	12

Spreadsheet for calculation of soil-equivalent shielding by scaling								
Scaling rules:								
Exponent for energy scaling:				**0.605**				
Ft of shielding for x10 attenuation:				**2.67**				
					Soil-equivalents, in feet			
Reference 1:	**Energy**	**Intensity**	**Rate**	**Current**	**Magnet**	**Pipe**	**Buried**	
No occupancy limit	**(GeV)**	**(prot/cy)**	**(cy/hr)**	**(prot/hr)**	**in Encl.**	**in Encl.**	**pipe**	
D<1								
	1000	2E+13	60	1.2E+15	22	20	24	
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13	60	1.2E+15	22.0	20.0	24.0	
MR C0 extraction	120	3E+12	1800	5.4E+15	22.3	20.3	24.3	
	150	2E+13	60	1.2E+15	20.7	18.7	22.7	
MR F17 extraction	120	3E+12	1800	5.4E+15	22.3	20.3	24.3	
TeV circulating	1000	2E+13	1	2E+13	17.3	15.3	19.3	
MR circulating	150	2E+13	10	2E+14	18.6	16.6	20.6	
MR 8 GeV injection	8	4E+12	1800	7.2E+15	20.7	18.7	22.7	
Summary (worst case):								
C0 line					22.3	20.3	24.3	
F17 line					22.3	20.3	24.3	
8 GeV line					20.7	18.7	22.7	
Circulating					18.6	16.6	20.6	

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet			
Reference 2:	**Energy**	**Intensity**	**Rate**	**Current**	**Magnet**	**Pipe**	**Buried**	
Minimal Occupancy	**(GeV)**	**(prot/cy)**	**(cy/hr)**	**(prot/hr)**	**in Encl.**	**in Encl.**	**pipe**	
1<D<10								
	1000	2E+13	60	1.2E+15	19	17	21	
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13	60	1.2E+15	19.0	17.0	21.0	
MR C0 extraction	120	3E+12	1800	5.4E+15	19.3	17.3	21.3	
	150	2E+13	60	1.2E+15	17.7	15.7	19.7	
MR F17 extraction	120	3E+12	1800	5.4E+15	19.3	17.3	21.3	
TeV circulating	1000	2E+13	1	2E+13	14.3	12.3	16.3	
MR circulating	150	2E+13	10	2E+14	15.6	13.6	17.6	
MR 8 GeV injection	8	4E+12	1800	7.2E+15	17.7	15.7	19.7	
Summary (worst case):								
C0 line					19.3	17.3	21.3	
F17 line					19.3	17.3	21.3	
8 GeV line					17.7	15.7	19.7	
Circulating					15.6	13.6	17.6	

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet			
Reference 3:	**Energy**	**Intensity**	**Rate**	**Current**	**Magnet**	**Pipe**	**Buried**	
Signs and ropes	**(GeV)**	**(prot/cy)**	**(cy/hr)**	**(prot/hr)**	**in Encl.**	**in Encl.**	**pipe**	
10<D<100								
	1000	2E+13	60	1.2E+15	16.5	15.5	18	
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13	60	1.2E+15	16.5	15.5	18.0	
MR C0 extraction	120	3E+12	1800	5.4E+15	16.8	15.8	18.3	
	150	2E+13	60	1.2E+15	15.2	14.2	16.7	
MR F17 extraction	120	3E+12	1800	5.4E+15	16.8	15.8	18.3	
TeV circulating	1000	2E+13	1	2E+13	11.8	10.8	13.3	
MR circulating	150	2E+13	10	2E+14	13.1	12.1	14.6	
MR 8 GeV injection	8	4E+12	1800	7.2E+15	15.2	14.2	16.7	
Summary (worst case):								
C0 line					16.8	15.8	18.3	
F17 line					16.8	15.8	18.3	
8 GeV line					15.2	14.2	16.7	
Circulating					13.1	12.1	14.6	

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet		
Reference 4:	**Energy**	**Intensity**	**Rate**	**Current**	**Magnet**	**Pipe**	**Buried**
Signs, fences,	**(GeV)**	**(prot/cy)**	**(cy/hr)**	**(prot/hr)**	**in Encl.**	**in Encl.**	**pipe**
locked gates							
100<D<500	1000	2E+13	60	1.2E+15	15	13	16.5
Scaled cases:							
Tev C0, A0 extractio	1000	2E+13	60	1.2E+15	15.0	13.0	16.5
MR C0 extraction	120	3E+12	1800	5.4E+15	15.3	13.3	16.8
	150	2E+13	60	1.2E+15	13.7	11.7	15.2
MR F17 extraction	120	3E+12	1800	5.4E+15	15.3	13.3	16.8
TeV circulating	1000	2E+13	1	2E+13	10.3	8.3	11.8
MR circulating	150	2E+13	10	2E+14	11.6	9.6	13.1
MR 8 GeV injection	8	4E+12	1800	7.2E+15	13.7	11.7	15.2
Summary (worst case):							
C0 line					15.3	13.3	16.8
F17 line					15.3	13.3	16.8
8 GeV line					13.7	11.7	15.2
Circulating					11.6	9.6	13.1

					Soil-equivalents, in feet		
Reference 5:	**Energy**	**Intensity**	**Rate**	**Current**	**Magnet**	**Pipe**	**Buried**
Signs, fences,	**(GeV)**	**(prot/cy)**	**(cy/hr)**	**(prot/hr)**	**in Encl.**	**in Encl.**	**pipe**
interlocked gates							
500<D<1000	1000	2E+13	60	1.2E+15	14	12	15.5
Scaled cases:							
Tev C0, A0 extractio	1000	2E+13	60	1.2E+15	14.0	12.0	15.5
MR C0 extraction	120	3E+12	1800	5.4E+15	14.3	12.3	15.8
	150	2E+13	60	1.2E+15	12.7	10.7	14.2
MR F17 extraction	120	3E+12	1800	5.4E+15	14.3	12.3	15.8
TeV circulating	1000	2E+13	1	2E+13	9.3	7.3	10.8
MR circulating	150	2E+13	10	2E+14	10.6	8.6	12.1
MR 8 GeV injection	8	4E+12	1800	7.2E+15	15.2	14.2	16.7
Summary (worst case):							
C0 line					14.3	12.3	15.8
F17 line					14.3	12.3	15.8
8 GeV line					15.2	14.2	16.7
Circulating					10.6	8.6	12.1

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet			
Reference 6:	**Energy**	**Intensity**			**Magnet**	**Pipe**	**Buried**	
No occup. limit,	**(GeV)**	**(prot/cy)**			**in Encl.**	**in Encl.**	**pipe**	
Interlocked								
detectors	1000	2E+13			19	17	20	
D<0.25								
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13			19.0	17.0	20.0	
MR C0 extraction	120	3E+12			15.3	13.3	16.3	
	150	2E+13			17.7	15.7	18.7	
MR F17 extraction	120	3E+12			15.3	13.3	16.3	
TeV circulating	1000	2E+13			19.0	17.0	20.0	
MR circulating	150	2E+13			17.7	15.7	18.7	
MR 8 GeV injection	8	4E+13			16.4	14.4	17.4	
Summary (worst case):								
C0 line					19.0	17.0	20.0	
F17 line					15.3	13.3	16.3	
8 GeV line					16.4	14.4	17.4	
Circulating					19.0	17.0	20.0	

					Soil-equivalents, in feet			
Reference 7:	**Energy**	**Intensity**			**Magnet**	**Pipe**	**Buried**	
Minimal occup.,	**(GeV)**	**(prot/cy)**			**in Encl.**	**in Encl.**	**pipe**	
interlocked								
detectors	1000	2E+13			16	14	17	
0.25<D<2.5								
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13			16.0	14.0	17.0	
MR C0 extraction	120	3E+12			12.3	10.3	13.3	
	150	2E+13			14.7	12.7	15.7	
MR F17 extraction	120	3E+12			12.3	10.3	13.3	
TeV circulating	1000	2E+13			16.0	14.0	17.0	
MR circulating	150	2E+13			14.7	12.7	15.7	
MR 8 GeV injection	8	4E+13			13.4	11.4	14.4	
Summary (worst case):								
C0 line					16.0	14.0	17.0	
F17 line					12.3	10.3	13.3	
8 GeV line					13.4	11.4	14.4	
Circulating					16.0	14.0	17.0	

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet			
Reference 8:	**Energy**	**Intensity**			**Magnet**	**Pipe**	**Buried**	
Minimal occup.,	**(GeV)**	**(prot/cy)**			**in Encl.**	**in Encl.**	**pipe**	
signs and ropes,								
interlocked	1000	2E+13			14.5	12.5	15.5	
detectors								
2.5<D<10								
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13			14.5	12.5	15.5	
MR C0 extraction	120	3E+12			10.8	8.8	11.8	
	150	2E+13			13.2	11.2	14.2	
MR F17 extraction	120	3E+12			10.8	8.8	11.8	
TeV circulating	1000	2E+13			14.5	12.5	15.5	
MR circulating	150	2E+13			13.2	11.2	14.2	
MR 8 GeV injection	8	4E+13			11.9	9.9	12.9	
Summary (worst case):								
C0 line					14.5	12.5	15.5	
F17 line					10.8	8.8	11.8	
8 GeV line					11.9	9.9	12.9	
Circulating					14.5	12.5	15.5	

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet			
Reference 9:	**Energy**	**Intensity**			**Magnet**	**Pipe**	**Buried**	
Signs, fences	**(GeV)**	**(prot/cy)**			**in Encl.**	**in Encl.**	**pipe**	
Locked gates								
interlocked	1000	2E+13			13	11	14	
detectors								
10<D<50								
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13			13.0	11.0	14.0	
MR C0 extraction	120	3E+12			9.3	7.3	10.3	
	150	2E+13			11.7	9.7	12.7	
MR F17 extraction	120	3E+12			9.3	7.3	10.3	
TeV circulating	1000	2E+13			13.0	11.0	14.0	
MR circulating	150	2E+13			11.7	9.7	12.7	
MR 8 GeV injection	8	4E+13			10.4	8.4	11.4	
Summary (worst case):								
C0 line					13.0	11.0	14.0	
F17 line					9.3	7.3	10.3	
8 GeV line					10.4	8.4	11.4	
Circulating					13.0	11.0	14.0	

					Soil-equivalents, in feet			
Reference 10:	**Energy**	**Intensity**			**Magnet**	**Pipe**	**Buried**	
Signs, fences	**(GeV)**	**(prot/cy)**			**in Encl.**	**in Encl.**	**pipe**	
interocked gates								
interlocked	1000	2E+13			12	10	13	
detectors								
50<D<100								
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13			12.0	10.0	13.0	
MR C0 extraction	120	3E+12			8.3	6.3	9.3	
	150	2E+13			10.7	8.7	11.7	
MR F17 extraction	120	3E+12			8.3	6.3	9.3	
TeV circulating	1000	2E+13			12.0	10.0	13.0	
MR circulating	150	2E+13			10.7	8.7	11.7	
MR 8 GeV injection	8	4E+13			9.4	7.4	10.4	
Summary (worst case):								
C0 line					12.0	10.0	13.0	
F17 line					8.3	6.3	9.3	
8 GeV line					9.4	7.4	10.4	
Circulating					12.0	10.0	13.0	

MR/Tev shielding scaling calcs

					Soil-equivalents, in feet			
Reference 11:	**Energy**	**Intensity**			**Magnet**	**Pipe**	**Buried**	
8 ft high fences	**(GeV)**	**(prot/cy)**			**in Encl.**	**in Encl.**	**pipe**	
etc.,etc								
interlocked	1000	2E+13			11	9	12	
detectors								
100<D<250								
Scaled cases:								
Tev C0, A0 extractio	1000	2E+13			11.0	9.0	12.0	
MR C0 extraction	120	3E+12			7.3	5.3	8.3	
	150	2E+13			9.7	7.7	10.7	
MR F17 extraction	120	3E+12			7.3	5.3	8.3	
TeV circulating	1000	2E+13			11.0	9.0	12.0	
MR circulating	150	2E+13			9.7	7.7	10.7	
MR 8 GeV injection	8	4E+13			8.4	6.4	9.4	
Summary (worst case):								
C0 line					11.0	9.0	12.0	
F17 line					7.3	5.3	8.3	
8 GeV line					8.4	6.4	9.4	
Circulating					11.0	9.0	12.0	