KEK Internal 2004-1
June 2004
A/R

BULK-I：

Radiation Shielding Tool for Proton Accelerator Facilities

（English Part）

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BULK-I：Radiation Shielding Tool for Proton Accelerator Facilities

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Abstract

The BULK-I has been developed as a tool for radiation shielding design of proton accelerator facilities with medium energy ranging from 50 to 500 MeV. This tool has characteristics that new formula adopted for thin concrete shield is employed, and parameters of radiation shielding calculations for concrete or two layers with iron and concrete are implemented, which have been calculated with the MCNPX code. This tool, in addition, is capable of radiation shielding calculations considering various proton energies and proton beam directions like proton beam treatment facilities.

In this report, outline, installation, and input/output of the BULK-I are explained.

Contents

English Part

1. Introduction

Accelerators using protons in an energy range from 50 to 500MeV are taken notice of in such fields as medicines and biology like cancer therapy and improvement of breed, respectively. When the protons strike an accelerator component and a target in a proton accelerator facility, secondary neutrons are produced by (p, xn) reactions, and are main source term for radiation shielding designs. The angular and energy distributions of the neutrons are very important for calculating the wall thickness of the facility.

An exponential curve fit as a function of the shield thickness like Moyer model [1)] is generally used in the radiation shielding calculations in the proton accelerator facility. Parameters used in the curve fit i.e. source term and attenuation length, have been numerically and experimentally obtained by many researchers [2)-7)]. The curve fit is adopted only for deep penetration of the shield where the neutron spectrum is not changed (equilibrium region). However the curve fit cannot be used, when the shield is thin where the neutron energy spectrum is changed (build-up region). It is also difficult to calculate dose rates accurately by the curve fit, when two layers with iron and concrete is adopted as the radiation shield.

In this report, a simple formula adopted for not only equilibrium region but also build-up region is proposed, and the parameters for concrete or two layers with iron and concrete are numerically obtained with the Monte Carlo code MCNPX. These are summarized as a radiation shielding tool for the proton accelerator facility.

The outline of the tool is described in the second chapter. The installation and input/output of the tool are explained in the third and fourth chapters, respectively.

2. Outline of the tool

2.1 Characteristics

The BULK-I is a tool for calculating neutron and photon effective dose rates after penetrating through concrete or two layers with iron and concrete in a medium energy range proton accelerator facility.

A geometry used in the tool is shown in Figure 2-1. A target (radiation source) is set at the origin in the rectangular room surrounded by six concrete walls. The target is assumed to be thick iron as a typical component of the proton accelerator. Protons with various energies and directions are taken into account in the dose rate calculation based on the gantry employed in a proton beam treatment facility. The dose rates at estimator points are calculated considering the emission angle θ_e relative to each proton beam direction, and incident angle θ_i relative to X, Y or Z axis, which are automatically calculated by the tool. The distance from the target to the inner surface, and the thickness of each concrete wall are given by users. The fixed type and the beam direction dependent type of iron shields can be dealt with. For the former, the barrier thickness in iron as measured radiation path through the shield is given for each estimator, and for the latter the thickness and solid angle relative to the beam direction are given. Estimators are set at any positions in and outside the concrete walls. The attenuation in the air is ignored.

The application limits of the tool are as follows.

1) Proton energy: 50 - 500MeV
2) Emission angle relative to beam direction: 0 – 180 deg (12 bins)
3) Barrier thickness in concrete: 100 – 735 g/cm^2 (including build-up region)
4) Barrier thickness in iron: 0, 25, 50 and 70 cm (density 7.83 g/cm^3)

The tool is not applicable for radiation streaming problems like a maze and a duct, and skyshine problems, and the DUCT-III code [8] and SHINE-III code [9] are recommended, respectively.

2.2 Formula

The effective dose rate in an equilibrium region, where the radiation energy spectrum is stabilized in a shield is expressed as follows.

$$H(r,t) = \frac{H_0 e^{-\frac{t}{\cos\theta_i \lambda}}}{r^2} \qquad (2\text{-}1)$$

where $H(r,t)$: effective dose per unit proton (pSv)

H_0: source term per unit proton (pSv cm^2)

λ: attenuation length (g cm^{-2})

r: distance from target to estimator (cm)

t: thickness of shield (g cm^{-2})

θ_i: incident angle (deg)

and H_0 and λ are given as a function of proton energy, emission angle of radiations, target material, and shielding material. The bigger the emission angle of radiations is, the thicker the build-up region in the shield is. This tendency is remarkable with decreasing proton energy. The backward shield relative to the proton beam direction is, in addition, thinner than the forward one, because the radiation production rate is decreased with increasing the emission angle. If the needed thickness of the backward shield is within the build-up region, the dose rate calculated with equation (2-1) can be underestimated. Another formula by which the dose rate in the build-up region is calculated is necessary in this case. Next formula considering radiation production due to the slow down process, and absorption is proposed in this report.

$$H(r,t) = \frac{H_0}{r^2} e^{-\frac{t}{\cos\theta_i \lambda}} \left\{ \alpha - \left[1 - e^{-\frac{\beta}{\cos\theta_i} t} \right] \times (\alpha - 1) \right\} \tag{2-2}$$

where α:$H(r,0)\ r^2/H_0$

β: fitting parameters

and these are given as a function of proton energy, emission angle of radiations, and shielding material. This formula is capable of expanding the application range for the emission angle and proton energy compared with equation (2-1), and can be adopted in the build-up region.

2.3 Parameters

Parameters in equation (2-2) have been estimated with calculated neutron and photon dose rates by MCNPX2.1.5 [10] (see Appendix A). The parameters for neutrons have been estimated for three energy bins, i.e. 500 – 5MeV, 5MeV – 0.414eV, and 0.414 – 0.001eV, because each neutron attenuation curve in build-up region is deferent. When the proton energy is high and the emission angle of the radiation is small, the photon dose rate can be smaller than the neutron one by a factor of 10 - 100. When the proton energy is small and the emission angle of the radiation is big, the photon dose rate cannot be ignored. For this reason, the parameters for photon have been estimated, too. The parameters have been tabulated for twelve emission angle bins, i.e. six bins in a range from 0 to 60deg, and six bins in a rage from 60 to 180deg. In the estimation of the parameters, we have paid attention to avoiding the underestimation of the calculated dose rate with equation (2-2). Figures 2-2 to 2-5 show the relationship between the logarithm of the source term H_0 and proton energy for 0, 25, 50, or 70 cm thick iron shield, respectively. The relationship between the attenuation length λ of concrete and proton energy for each thick iron shield is shown in Figures 2-6 to 2-9. The relationship between logarithm of αH_0 or αH_0 and proton energy for each thick iron shield is shown in Figures 2-10 to 2-13. The relationship between the β and proton energy for each thick iron shield is shown in Figures 2-14 to 2-17. These parameters are well related with proton energy in the range from 50 to 500 MeV, and are approximated with the 6th order polynomial curve fit. The deviation of total dose rate due to this approximation is –18 to 30 %, which is correspond to a few percentages of concrete thickness. In some cases, the equation (2-2) is not adopted for concrete thickness below 100 g/cm^2, which is lower limit of the tool. Attention must be paid, as the dose rate calculated with the tool is overestimated for concrete thickness below 100 g/cm^2.

2.4 Barrier thickness in concrete

The barrier thickness t_e as measured radiation path through concrete is calculated with the concrete thickness t and the incident angle θ_i expressed in the equation (2-2). The dose rate calculated with the equation (2-2) can be underestimated when θ_i is large, because the radiation scattered near the estimator is bigger than the un-collided radiation. The upper limit of θ_i in the equation (2-2) is 45degfor iron and concrete, which has been estimated with MCNPX calculations. In the tool, the barrier thickness t_e is given by the following equations.

1) 0deg≤θi≤45deg

$$t_e = \frac{t}{\cos\theta_i} \tag{2-3}$$

2) 45deg<θi

$$t_e = \frac{t}{\cos 45^\circ} \tag{2-4}$$

2.5 Iron shield

The fixed type and the beam direction dependent type of iron shields can be mounted. For the former, the barrier thickness in iron is given for each estimator, and for the latter the thickness and solid angle relative to the beam direction are given. When the beam direction dependent type of iron shield is mounted between the radiation source and the estimator, the tool calculates the barrier thickness t_e in iron with the following equations.

1) 0deg≤θi≤45deg

$$t_e = \frac{t}{\cos\theta_i} \tag{2-5}$$

2) 45deg<θi

$$t_e = \frac{t}{\cos 45^\circ} \tag{2-6}$$

Total barrier thickness in two types of iron shields is used for the selection of the parameters described in section 2.3 according to the following equations.

1) t_e<25cm: parameters for 0 cm thick iron shield

2) 25cm≤t_e<50cm: parameters for 25 cm thick iron shield

3) 50cm≤t_e<70cm: parameters for 50 cm thick iron shield

4) 70cm≤t_e: parameters for 70 cm thick iron shield

3. Installing and running the BULK-I

3.1 Installing

(1) Extraction of the package

The BULK-I is made with Microsoft EXCEL* and Visual Basic Editor. The package containing sample input, output data and the file 'tool.xls' is a compressed file with self-extraction application. The package is uncompressed and extracted by double-click of the package. The directory structure of the package is shown in Figure 3-1.

*: Copyright (C) Microsoft Corporation.

(2) Sheets in the tool.xls

Table 3-1 shows the explanation of the sheets in the file 'tool.xls', stored in the directory "TOOL".

3.2 Running

The file 'tool.xls' is opened and the sheet 'input' shown in Figure 3-2 is selected. When you press Ctrl+Shift+R key after filling input data, the BULK-I start running. The sheet 'output' shown in Table 3-2 is displayed after your calculation is ended. You must check whether there are any error massages in the sheet 'comment', even if your calculation is normally ended. Sample input data and corresponding output data are stored in the package as shown in Figure 3-1. You must confirm that the calculated results with the sample input data are consistent with the corresponding sample output data.

4. Input/output of the BULK-I

(1) Input data

It explains about the input data of the BULK-I based on the following samples.

1) Sample problem 1

The geometry and the input data of sample problem 1 are shown in the Figure 4-1. This problem is an example that effective dose rates in the concrete on +Y axis are calculated when 200MeV protons are bombarded with an iron target. The proton intensity is $6.25 \times 10^{10} s^{-1}$ (10nA). Operation time of an accelerator is 10 h/week. A distance from the target to inner surface of the 2.5m thick concrete wall is 2m, and the concrete density is $2.1 g/cm^3$. Estimators are set at seven positions in the concrete, which thickness is from 1m to 2.5m. The effective dose distribution (μSv/w) in the concrete is finally obtained.

2) Sample problem 2

Sample problem 2 is the example that 50cm thick iron shield (beam direction dependent type) is mounted in a solid angle range from 0 to 30deg relative to the proton beam direction in addition to the sample problem 1. It is noted that “ thickness” is iron thickness (barrier thickness is calculated in the program with each position of the target and the estimator). If the dose rate in μSv/h is calculated, the operation time of the accelerator is 1h/week.

3) Sample problem 3

The geometry of sample problem 3 is shown in Figure 4-3. This problem is an example that effective dose rates at outer surface of each concrete wall on X, Y and Z axes, when protons are incident to +Y axis. Four proton energies in a range from 100 to 250MeV and their frequency are used as shown in Figure 4-3, where the sum of their frequency must be unity. If not, the program normalizes it to unity, and a warning is printed out in the "comment" sheet.

4) Sample problem 4

Sample problem 4 shown in Figure 4-4 is an example that effective dose rates at outer surface of each concrete wall on X, Y and Z axes, when 250MeV protons are incident to three directions. The beam directions are inputted with unit vector, where the target is at the origin (0,0,0). The sum of their frequency must be unity. If not, the program normalizes it to unity, and a warning is printed out in the "comment" sheet.

5) Sample problem 5

Sample problem 5 is the example that 25cm, 25cm and 50cm thick iron shields (fixed type) are mounted against Point 2, 3, and 5 of Sample problem 4, respectively. As shown in Figure 4-5, the fixed type iron shield is inputted against each estimator. It is noted that “thickness” means the barrier thickness, which is different from the beam direction dependent iron shield.

(2) Output

Calculated results are printed out on the following sheets.

1) "output" sheet

A sample of "output" sheet is shown in Table 3-2. On this sheet, followings are printed out for each estimator.

a) distance : distance from target to estimator (cm)

b) concrete thickness : barrier thickness in the concrete wall (cm)

c) iron thickness : barrier thickness in the fixed type iron shield (cm)

d) photon dose : photon effective dose (μSv/w)

e) neutron dose : neutron effective dose (μSv/w)

f) total dose : photon and neutron effective dose (μSv/w)

Where the barrier thickness in the beam direction dependent iron shield is not included in c). If the beam direction dependent iron shield is taken into account in the radiation shielding calculation, “beam direction dependent iron shield” is mentioned in the remark column, and the corresponding barrier thickness in the iron shield is printed out on the "comment" sheet. This is because the existence of the iron shield is different for various beam directions.

2) "comment" sheet

A sample of " comment " sheet is shown in Table 4-1. On this sheet, followings are printed out.

a) Warning when the sum of the frequency for proton energy is not unity.

b) Warning when the sum of the frequency for beam direction is not unity.

c) Warning when a beam direction vector is not unit vector.

d) Error when proton energy is smaller than 50MeV(lower limit).

e) Error when proton energy is bigger than 500MeV(upper limit).

f) Estimators considering the beam direction dependent iron shield, their beam direction number, emission angle and barrier thickness in the iron shield

g) Estimators that incident angle exceeds 45deg.

h) Estimators that barrier thickness in the concrete is out of the application range.

This tool normalizes the frequency to unity and input data on the "input" sheet are rewritten for a) – c). Wrong results are printed out for d), e) and h). The incident angle is changed to 45deg for g). You must confirm the "comment" sheet after your calculation is ended, because it is carried out even if input data are out of the application range.

Please refer sample output data for each sample problem described above, which are stored in the package.

Appendix A Calculations of radiation shielding parameters

1. General

We have calculated secondary neutron and photon yields, emitted from a thick iron target for 50 to 500MeV protons, and effective dose distributions in concrete or two layers of iron and concrete with the Monte Carlo code MCNPX in order to obtain radiation shielding parameters dependent on emission angles.

It is written about the calculations of the parameters below.

2. Calculations

(1) Geometry

A geometry used in radiation shielding calculations is shown in Figure A-1. A cylindrical iron target with enough thickness to stop primary protons is mounted at the center of spherical shielding shell. The protons are assumed to be pencil beams, and are incident into the center axis of the target. The concrete shell is set outside of 0, 25, 50, or 70cm thick iron shell. Each shell is divided by 24 in thickness, and 12 in solid angle relative to the beam direction. The concrete thickness is 4m, and the angular dependent effective dose distributions in concrete up to 3.5m are calculated (The rest is a reflection area). Surface crossing estimators are used.

(2) Code and cross sections

A three-dimensional Monte Carlo code MCNPX2.1.5 [10] is used. Cross sections used in the calculations are LA150 library [11] based on pre- equilibrium model for particles up to 150 MeV, and the Intranuclear Cascade (INC) model Bertini [12] for particles above 150 MeV implemented in the MCNPX2.1.5. The MCPLIB02 library is used for photons.

(3) Materials

Atomic number densities of the target and radiation shields are shown in Table A-1. The composition of concrete is based on ANL-5800 Type02-a[14]. The densities of the iron target and the iron shield are assumed to be 7.86 g/cm^3 (pure) and 7.83 g/cm^3 (SS400 base), respectively. The cross sections of impurities such as carbon and silicon contained in SS400 can cover the bump of the cross section of iron in resonance region. Two layers of iron and concrete are proposed, because concrete is much superior than iron including the impurities as radiation shielding material for neutrons below 1 MeV. It can be effective in radiation shielding design, i.e. lightweight and low cost to evaluate the thickness of iron shield on the assumption that concrete with enough thickness to attenuate neutrons below 1 MeV is mounted. In the calculations of radiation shielding parameters, the impurities in SS400 are therefore not taken into account.

(4) Effective dose conversion factors

Flux to effective dose conversion factors for neutrons and photons are shown in Table A-2. The factors are based on ICRP Publ. 74 for photons and neutrons up to 200 MeV, and data evaluated by Iwai et al. [15] for neutrons above 200 MeV.

(5) Histories and variance reduction

Proton histories of 10^6 – 10^7 are followed until the fractional standard deviation of each dose rate reaches within a few percents. Weight window with one and three energy bins for photons and neutrons respectively are used as variance reduction technique.

Appendix B Explanation of input data

Explanation of the input data shown in Figure 3-2 is as follows.

1. Proton energies and their frequency

(1) Number of proton energy: Number of proton energies given below is inputted.

(2) Proton energies and their frequency:

1) Energy (MeV): proton energy from 50 to 500MeV is inputted, otherwise an error message as shown in Table 4-1 is printed out.

2) Frequency: Frequency of each proton energy is inputted where the sum must be 1. If not, a warning shown in Table 4-1 is printed out, and this tool normalizes it to unity and input data on the "input" sheet are rewritten.

2. Proton beam

(1) Number of protons: Number of protons per second (s^{-1}) is inputted.

(2) Operation time: Operation time per week (h/w) is inputted.

(3) Number of beam direction: Number of proton beam directions given below is inputted.

(4) Beam direction dependent iron shield:

1) Thickness: Thickness (cm) of beam direction dependent iron shield is inputted, where the density is 7.83g/cm^3.

2) Solid angle range: Solid angle range in degree is inputted relative to proton beam direction.

(5) Vectors of proton beam and their frequency:

1) Unit vector(u, v, w): Unit vector of each proton beam direction is inputted(the geometry used in this tool is shown in Figure 2-1).

2) Frequency: Frequency of each direction vector is inputted, where the sum must be 1. If not, a warning shown in Table 4-1 is printed out, and this tool normalizes it to unity and input data on the "input" sheet are rewritten.

3. Geometry

(1) Distance from target to concrete wall and wall thickness:

1) Distance: Distance (cm) from target to inner surface of each concrete wall is inputted.

2) Thickness: Concrete wall thickness (cm) is inputted.

(2) Concrete density: The density (g/cm^3) of the concrete wall is inputted.

4. Coordinates of calculation points

(1) Number of points: Number of calculation points given below is inputted.

(2) Coordinates:

1) Name: Name of each point is inputted.

2) X, Y, Z: Coordinate (X, Y, Z) of each point is inputted in cm. The calculation points must be in the concrete walls, or outside of the concrete walls. In addition, the barrier thickness in concrete must be within 100 - 735g/cm^2, otherwise an error message as shown in Table 4-1 is printed out.

3) Iron thickness: Barrier thickness (cm) in iron for each point is inputted.

4) Crossing wall: Axis corresponding to concrete wall that particles penetrate to each calculation point is inputted.

You must confirm a "comment" sheet after your calculation is ended, because it is carried out even if input data are out of the application range.

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Tables

Table 3-1 Sheets in the TOOL.xls

input: input data sheet

output: output sheet

comment: comment sheet in the calculation, e.g. warnings

attenuation: attenuation cure of dose in the concrete at some energy and emission angle

photon: parameters for photon dose calculation

first: parameters for high energy neutron dose calculation

middle: parameters for middle energy neutron dose calculation

thermal: parameters for thermal neutron dose calculation

Table 3-2 Sample output sheet

calculation point	distance (cm)	concrete thickness (cm)	iron thickness (cm)	photon dose (micro-Sv/w)	neutron dose (micro-Sv/w)	toal dose (micro-Sv/w)	remarks
Point 1	300	100	0	4.2E+03	2.0E+05	2.0E+05	
Point 2	325	125	0	2.2E+03	1.0E+05	1.0E+05	
Point 3	350	150	0	1.1E+03	5.5E+04	5.6E+04	
Point 4	375	175	0	6.0E+02	2.9E+04	3.0E+04	
Point 5	400	200	0	3.2E+02	1.6E+04	1.6E+04	
Point 6	425	225	0	1.8E+02	8.7E+03	8.8E+03	
Point 7	450	250	0	9.6E+01	4.8E+03	4.9E+03	

Table 4-1 Sample comment sheet

warning: proton energy frequency is normalized
warning: beam direction frequency is normalized
warning: beam vector is normalized
error: proton energy is lower than lower limit(50MeV)!
error: proton energy exceed upper limit(500MeV)!

calculation points considering direction dependent iron shield

calculation point	direction No.	emission angle	iron thickness
Point 5	1	11.99466981	25.55800864

calculation points where their incident angle exceeds 45 deg

calculation point
Point 6

calculation points where their concrete thickness exceeds application range 100-735 g/cm^2

calculation point	thickness(g/cm^2)
Point 3	21
Point 4	1680
Point 6	742.461628

Table A-1 Atomic Number densities of materials used in MCNPX calculations

Materials	Air		Concrete		Iron (target)		Iron (shield)	
Density (g/cm^3)	1.239E-03		2.100E+00		7.860E+00		7.830E+00	
Element	Atomic number (×10^{24} cm^{-3})	Volume fraction (%)	Atomic number (×10^{24} cm^{-3})	Volume fraction (%)	Atomic number (×10^{24} cm^{-3})	Volume fraction (%)	Atomic number (×10^{24} cm^{-3})	Volume fraction (%)
H	7.402E-09	1.450E-02	1.299E-02	1.727E+01				
C	7.799E-09	1.528E-02	1.082E-04	1.439E-01				
N	4.020E-05	7.874E+01						
O	1.084E-05	2.123E+01	4.305E-02	5.724E+01				
Mg			1.161E-04	1.544E-01				
Al			1.632E-03	2.170E+00				
Si			1.558E-02	2.072E+01				
Ca			1.409E-03	1.873E+00				
Fe			3.235E-04	4.301E-01	8.472E-02	1.000E+02	8.440E-02	1.000E+02

Table A-2 Fluence to effective dose conversion factors for neutron and photon

Energy (MeV)	Conversion factor (pSv cm^2)	Energy (MeV)	Conversion factor (pSv cm^2)
1.00E-09	5.24	9.00E-01	267
1.00E-08	6.55	1.00E+00	282
2.50E-08	7.6	1.20E+00	310
1.00E-07	9.95	2	383
2.00E-07	11.2	3	432
5.00E-07	12.8	4	458
1.00E-06	13.8	5	474
2.00E-06	14.5	6	483
5.00E-06	15	7	490
1.00E-05	15.1	8	494
2.00E-05	15.1	9	497
5.00E-05	14.8	10	499
1.00E-04	14.6	12	499
2.00E-04	14.4	14	496
5.00E-04	14.2	15	494
1.00E-03	14.2	16	491
2.00E-03	14.4	18	486
5.00E-03	15.7	20	480
1.00E-02	18.3	30	458
2.00E-02	23.8	50	437
3.00E-02	29	75	429
5.00E-02	38.5	100	429
7.00E-02	47.2	130	432
1.00E-01	59.8	150	438
1.50E-01	80.2	180	445
2.00E-01	99	200	470.51
3.00E-01	133	400	520.54
5.00E-01	188	700	881.03
7.00E-01	231	1000	1004.7

ICRP Pub74+Yoshizawa et al.

Energy (MeV)	Conversion factor (pSv cm^2)
1.00E+01	2.38E+01
8.00E+00	1.99E+01
6.00E+00	1.60E+01
4.00E+00	1.20E+01
2.00E+00	7.49E+00
1.00E+00	4.48E+00
8.00E-01	3.73E+00
6.00E-01	2.91E+00
5.00E-01	2.47E+00
4.00E-01	2.00E+00
3.00E-01	1.51E+00
2.00E-01	1.00E+00
1.50E-01	7.52E-01
1.00E-01	5.17E-01
8.00E-02	4.40E-01
6.00E-02	3.78E-01
5.00E-02	3.57E-01
4.00E-02	3.38E-01
3.00E-02	3.00E-01
2.00E-02	2.05E-01
1.50E-02	1.25E-01
1.00E-02	4.85E-02

Figures

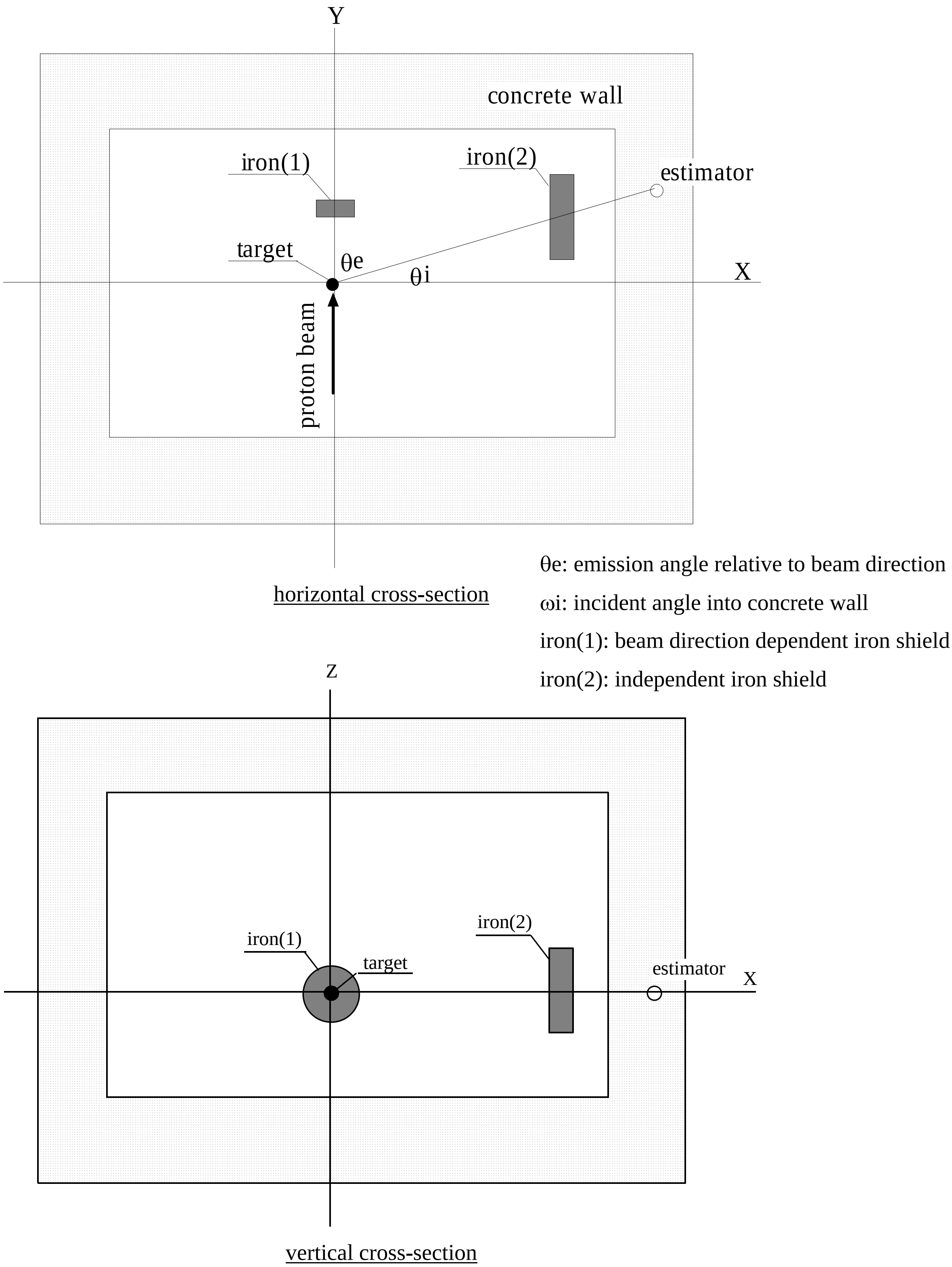


Figure 2-1 Geometry used in effective dose calculations

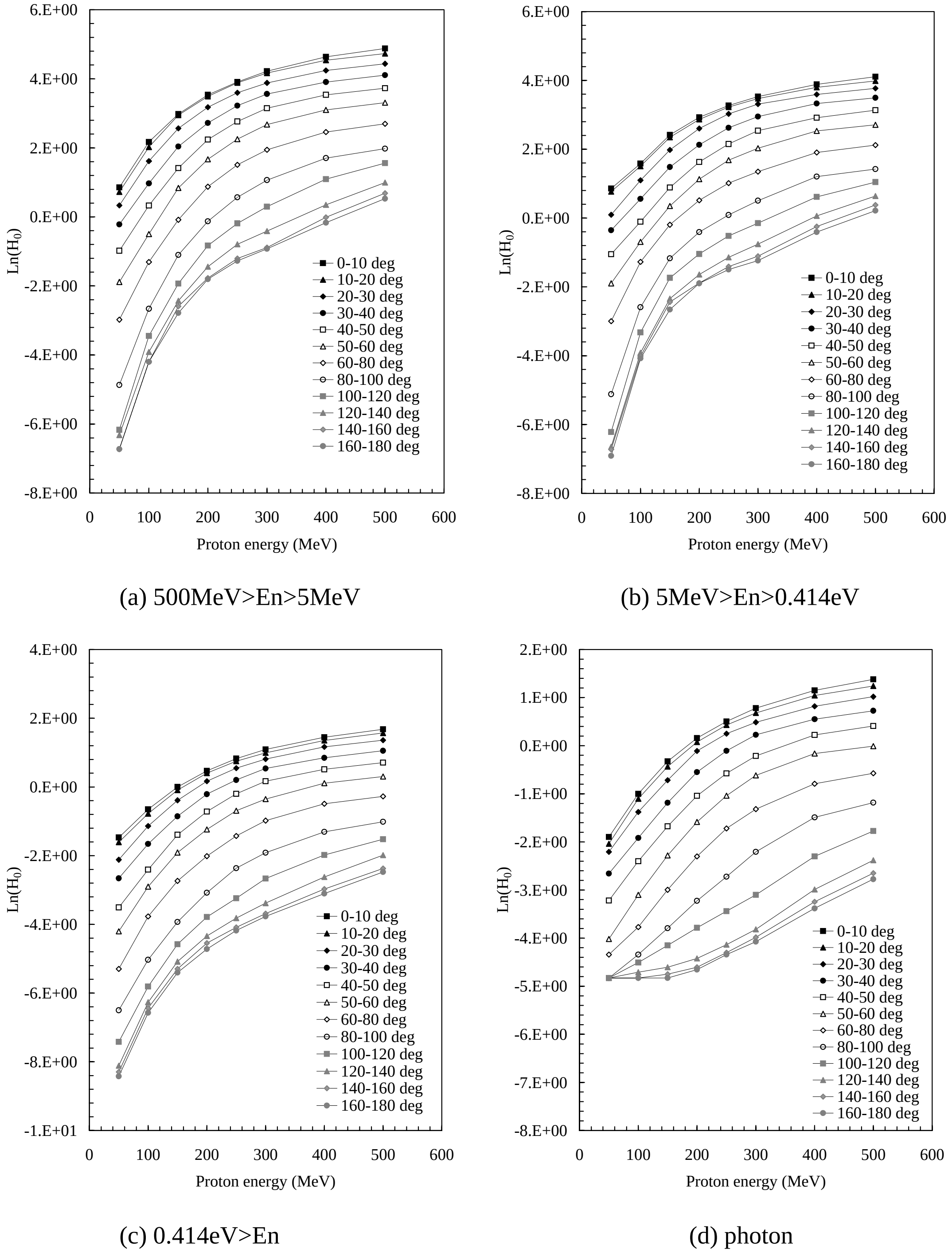
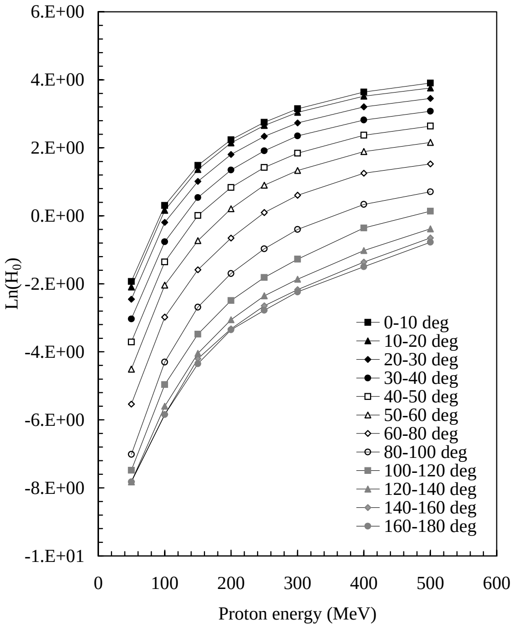
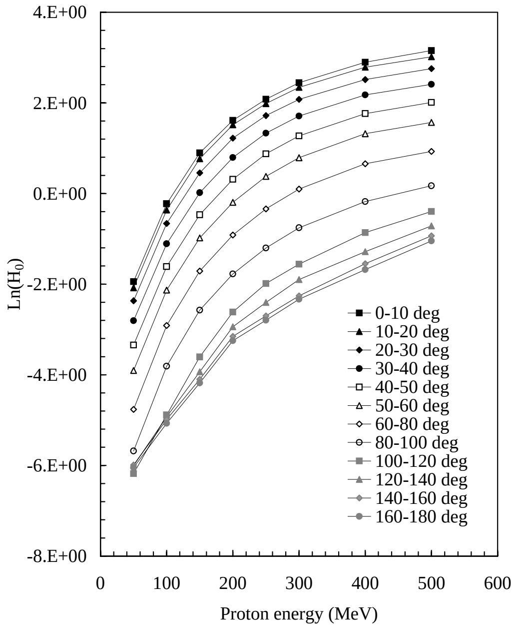


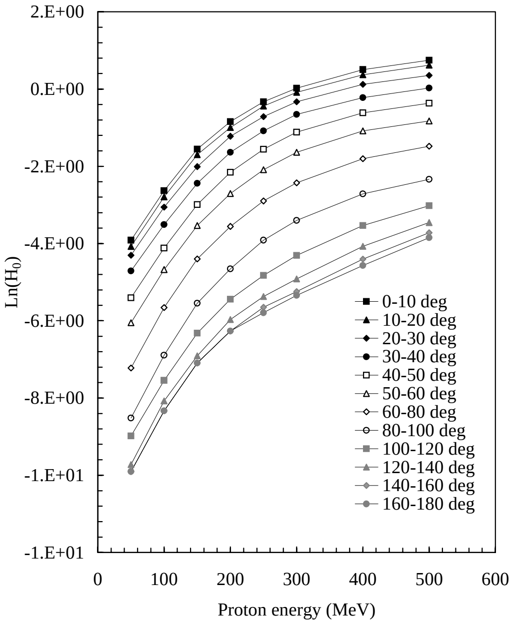
Figure 2-2 Proton energy vs. source term of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 0 cm.



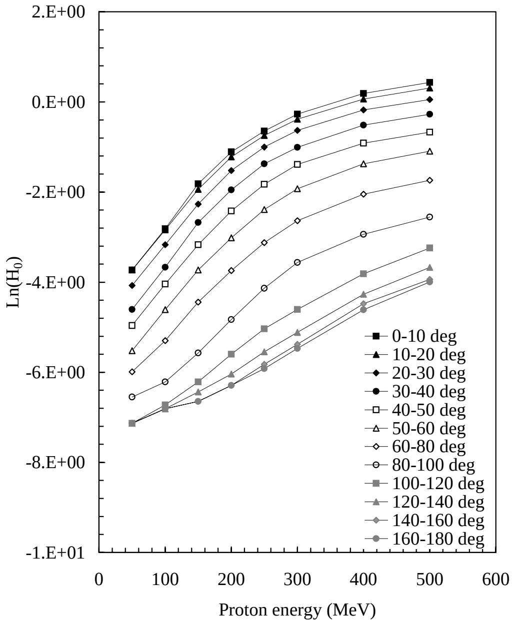
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

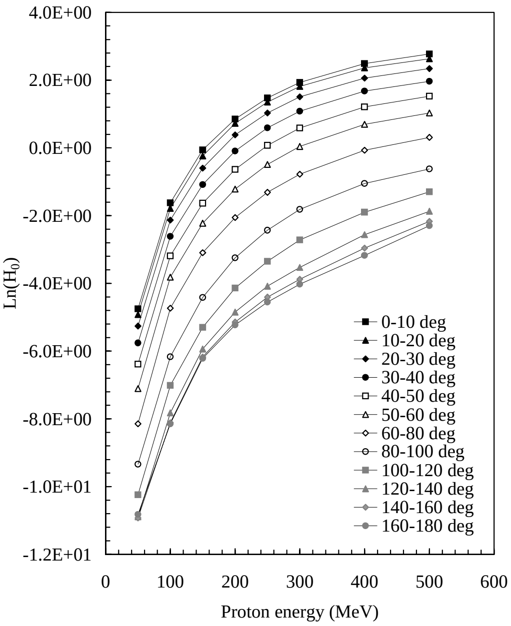


(c) 0.414eV>En

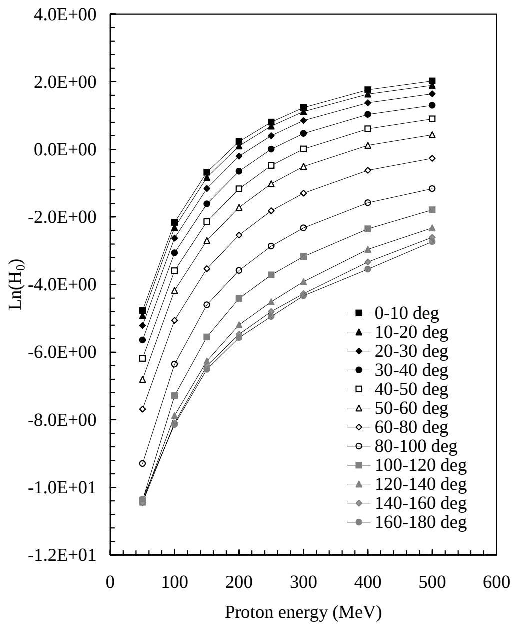


(d) photon

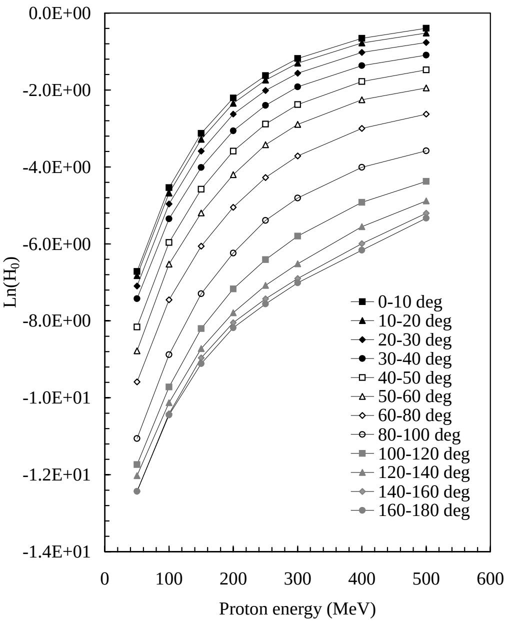
Figure 2-3 Proton energy vs. source term of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 25 cm.



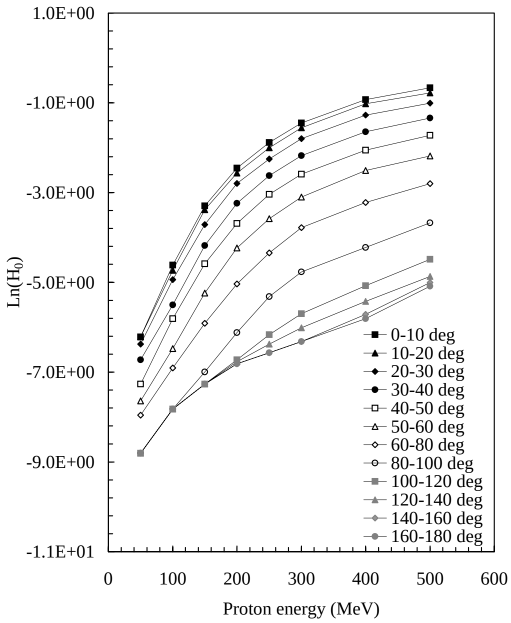
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

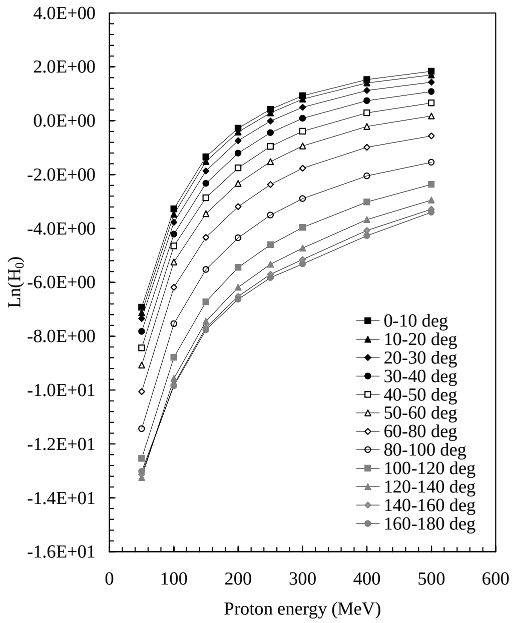


(c) 0.414eV>En

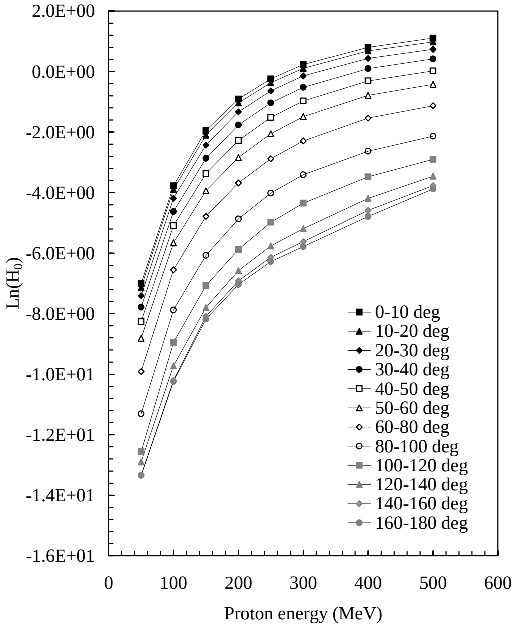


(d) photon

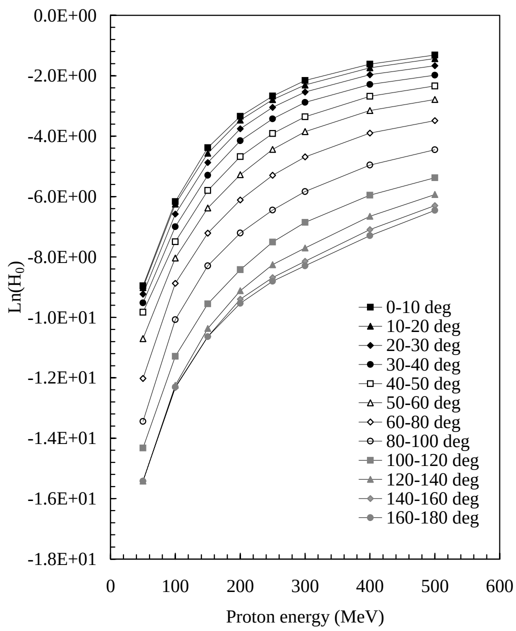
Figure 2-4 Proton energy vs. source term of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 50 cm.



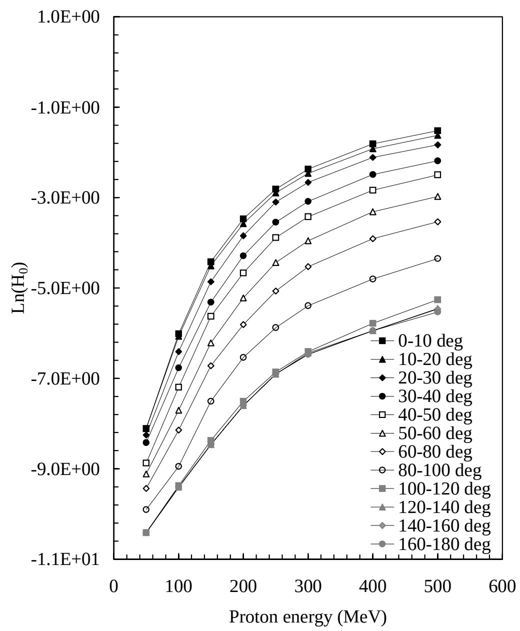
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

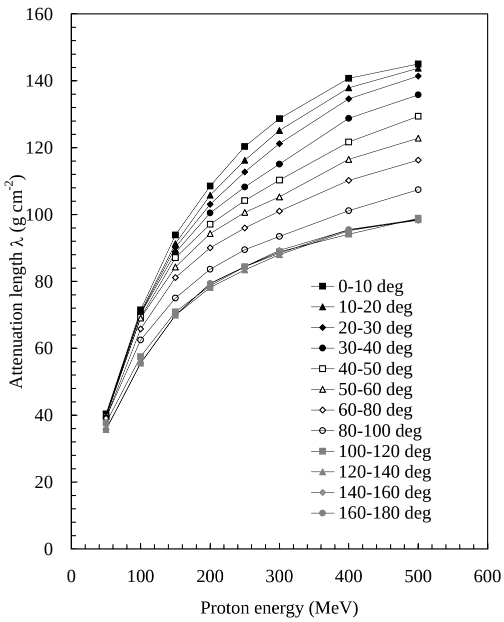


(c) 0.414eV>En

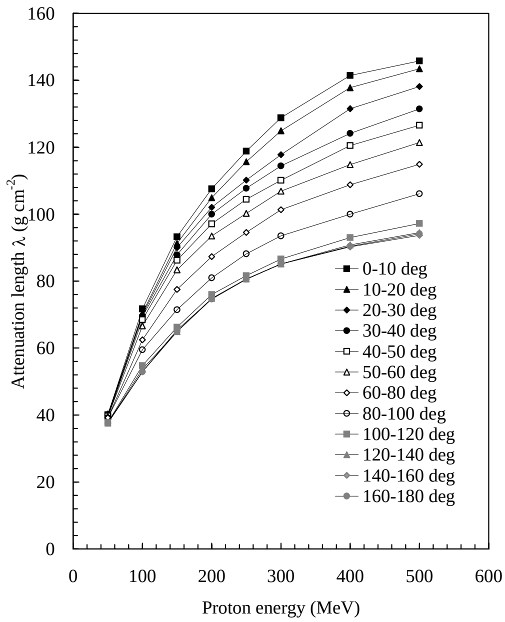


(d) photon

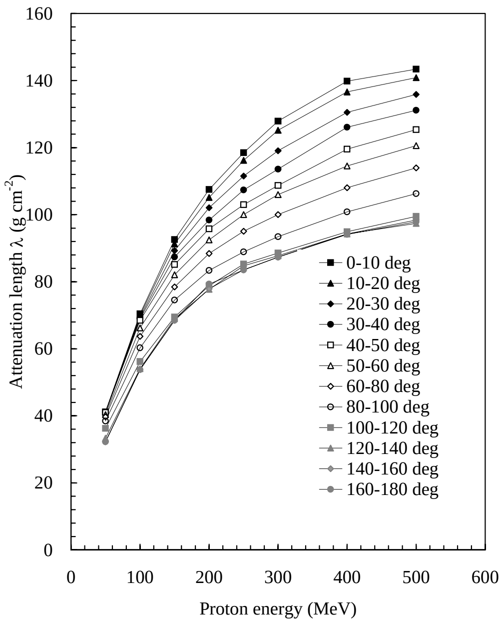
Figure 2-5 Proton energy vs. source term of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 70 cm.



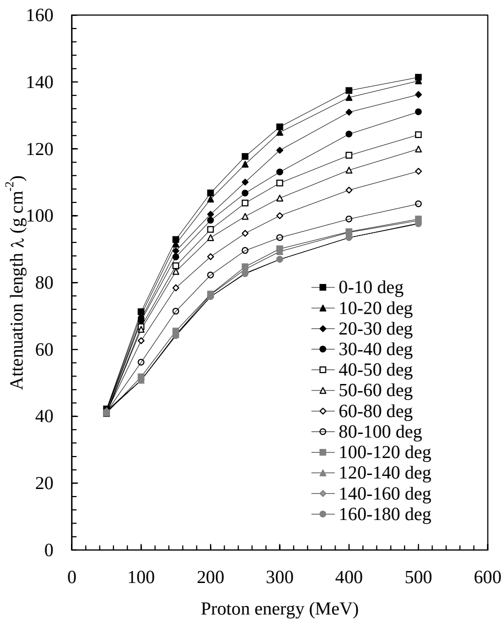
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

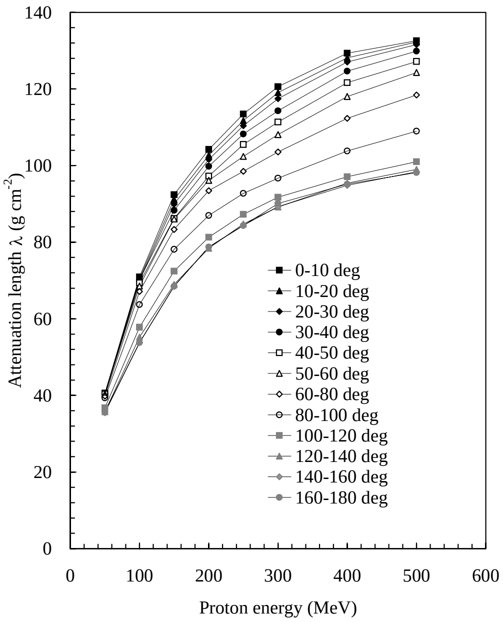


(c) 0.414eV>En

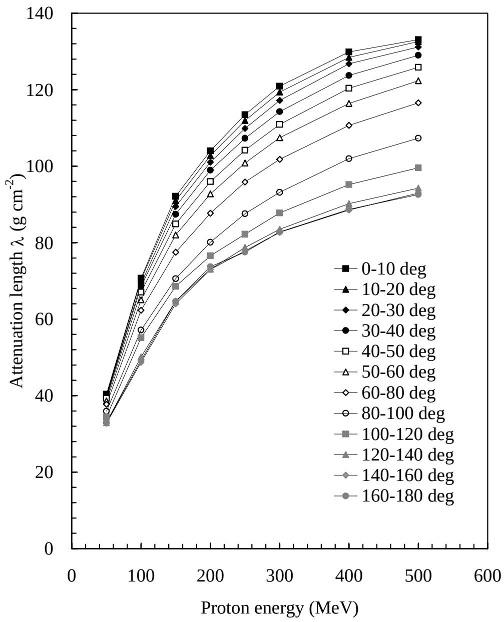


(d) photon

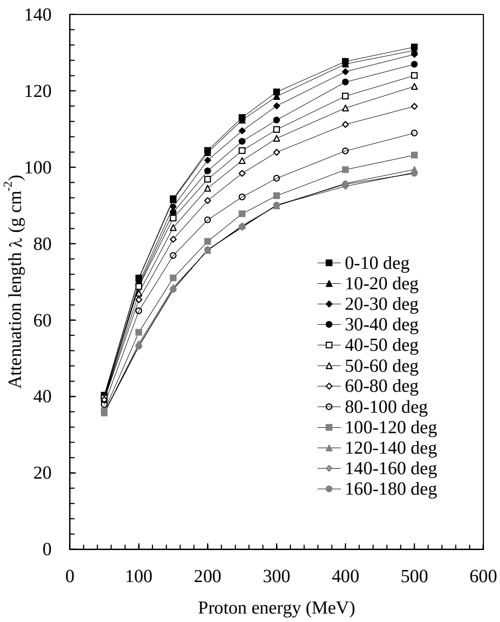
Figure 2-6 Proton energy vs. attenuation length of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 0 cm.



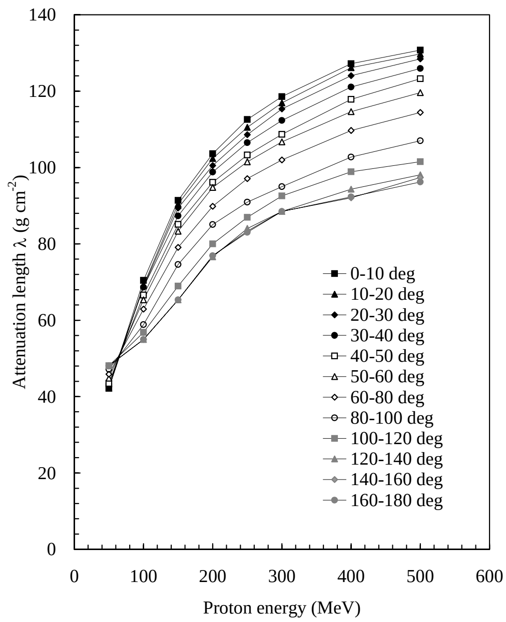
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

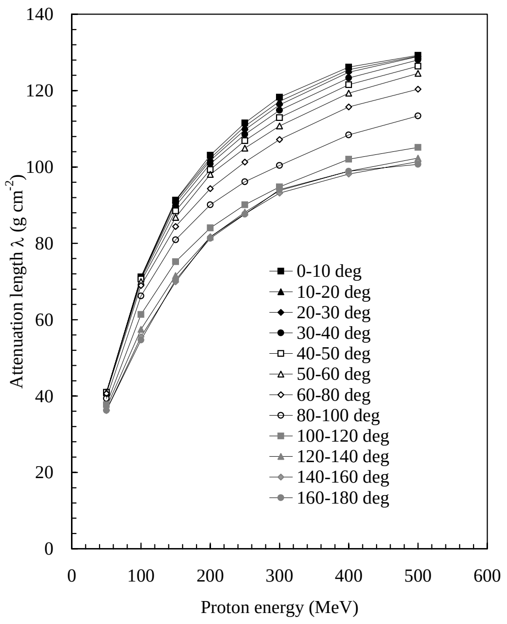


(c) 0.414eV>En

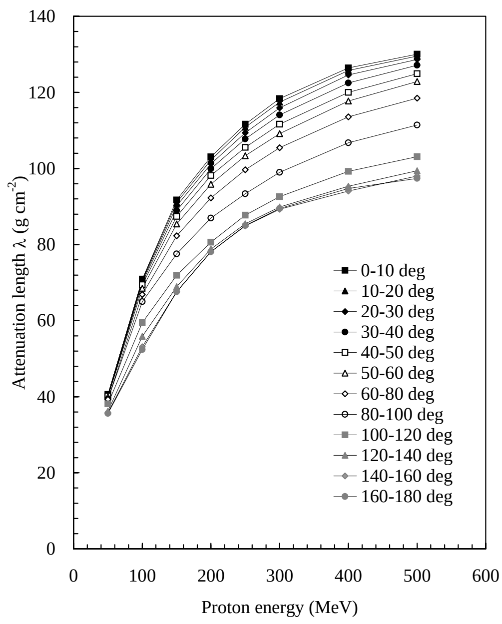


(d) photon

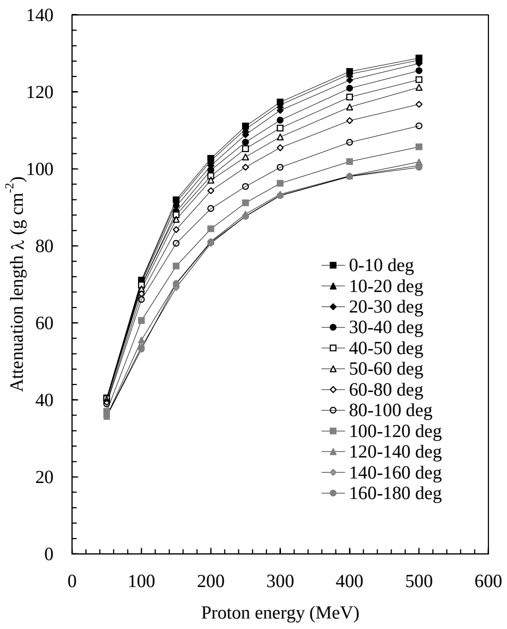
Figure 2-7 Proton energy vs. attenuation length of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 25 cm.



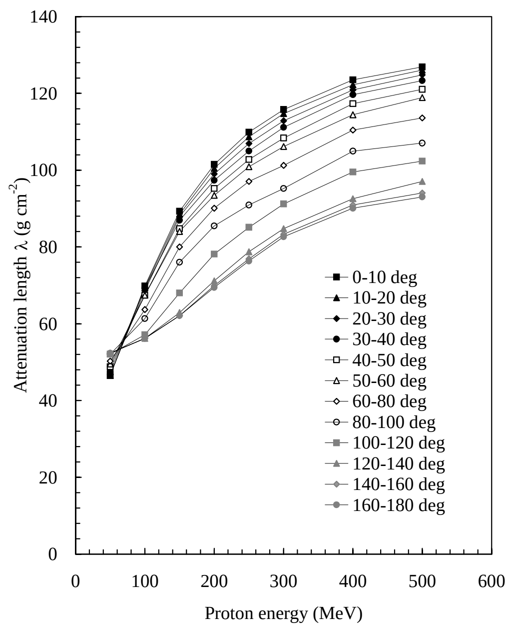
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

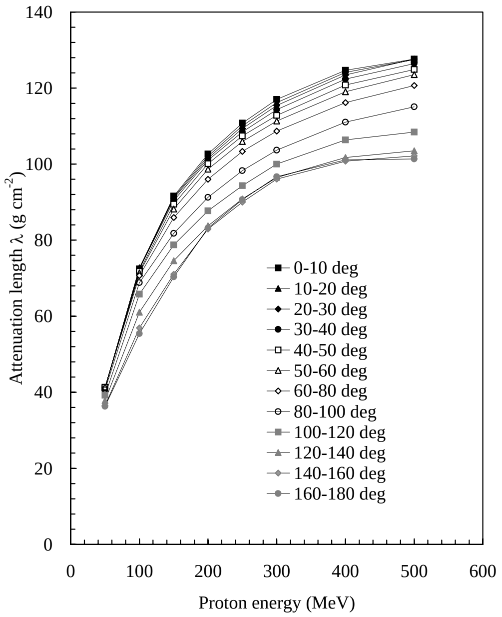


(c) 0.414eV>En

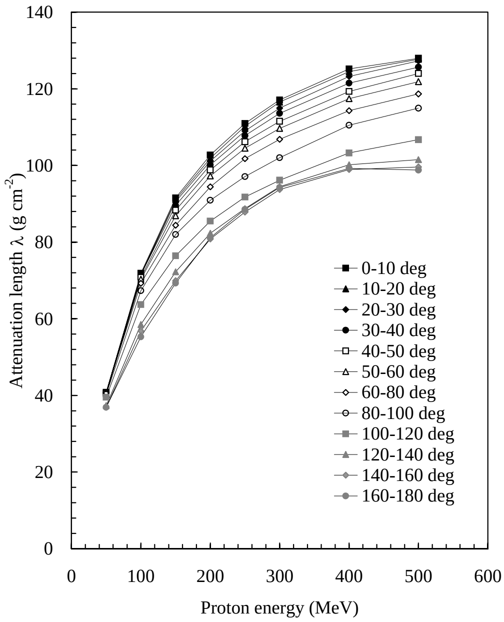


(d) photon

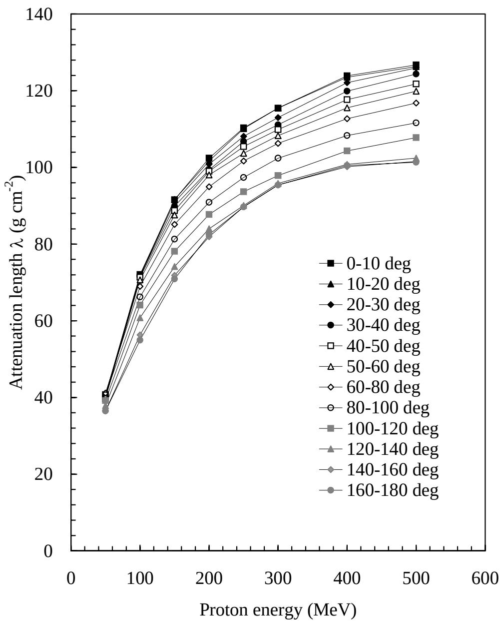
Figure 2-8 Proton energy vs. attenuation length of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 50 cm.



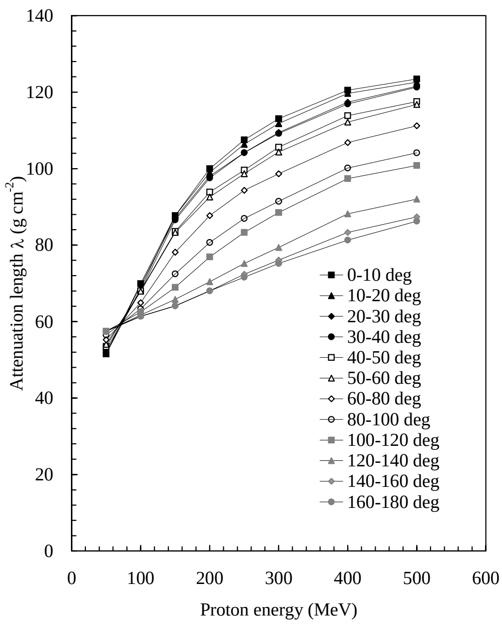
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

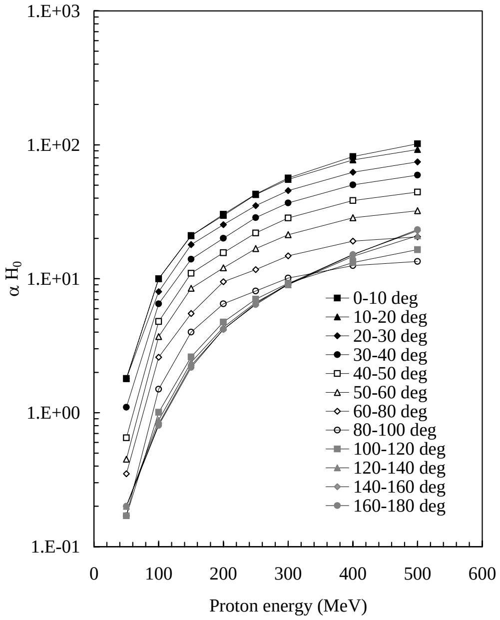


(c) 0.414eV>En

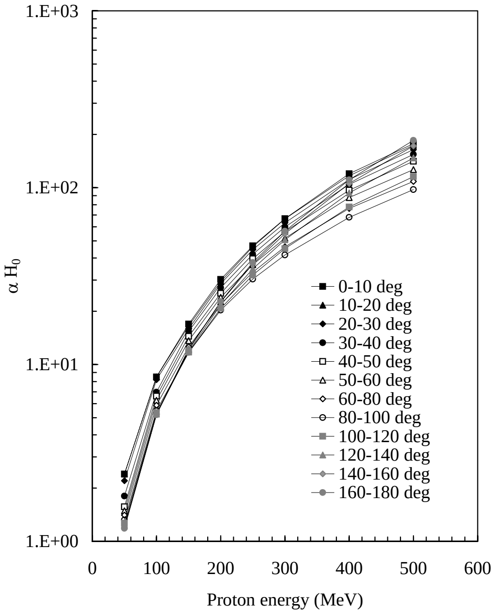


(d) photon

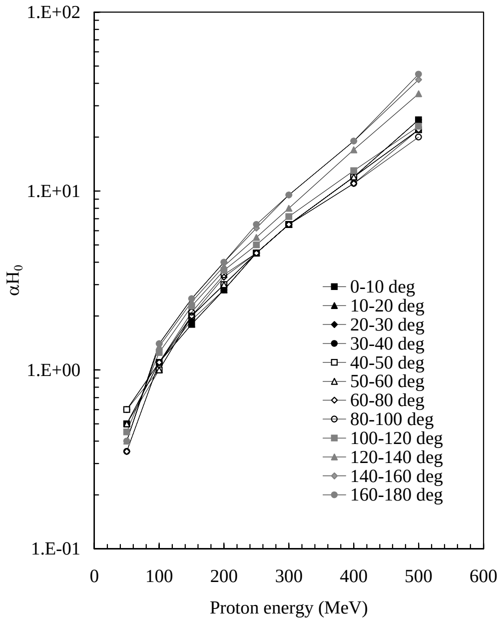
Figure 2-9 Proton energy vs. attenuation length of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 70 cm.



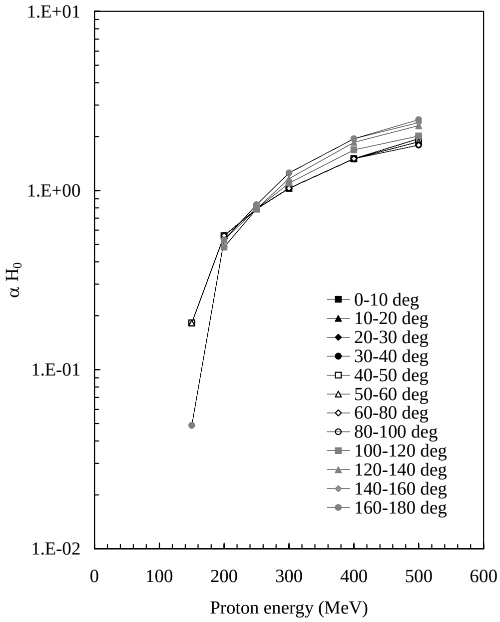
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV

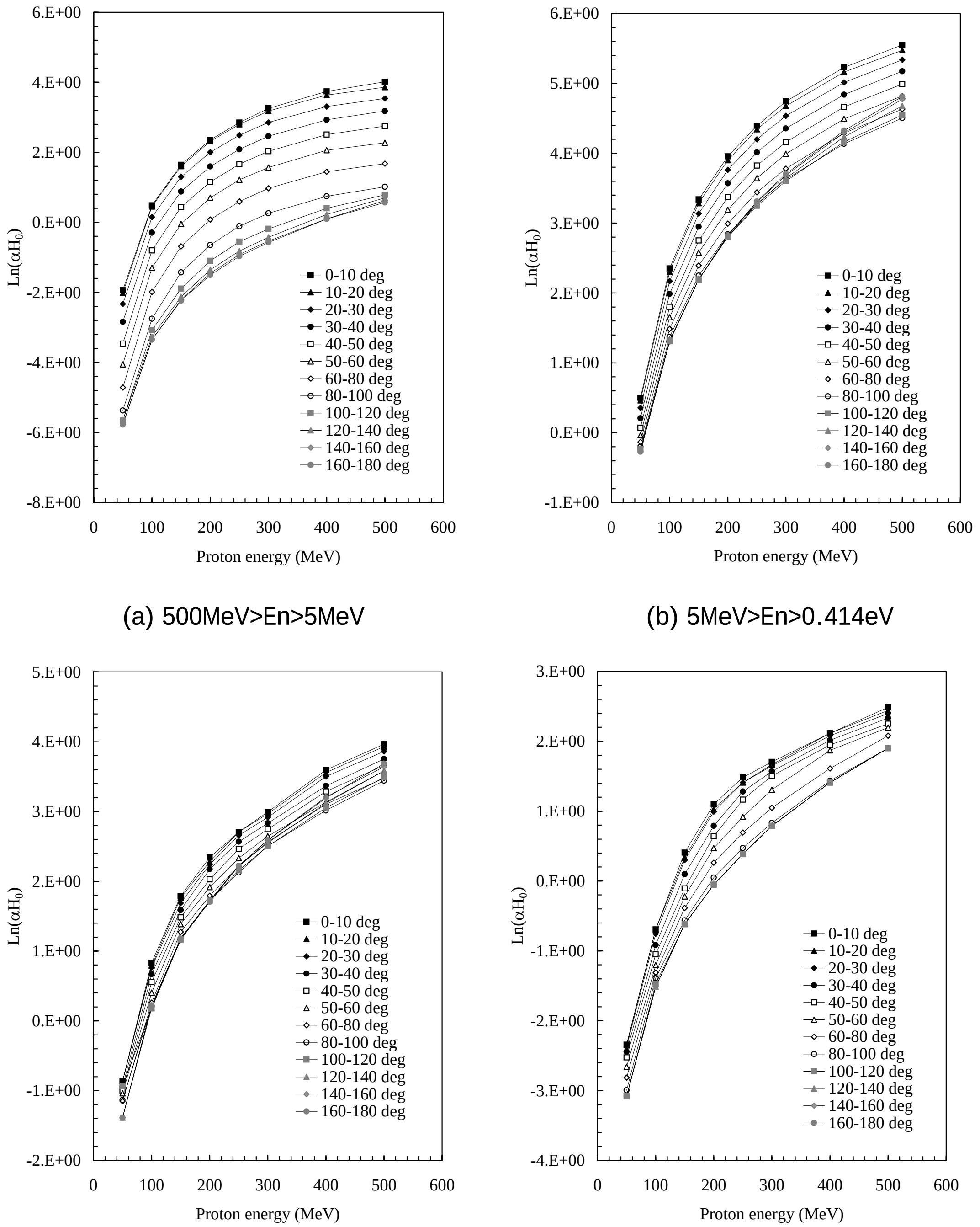


(c) 0.414eV>En



(d) photon

Figure 2-10 Proton energy vs. fitting parameter αH_0 of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 0 cm.



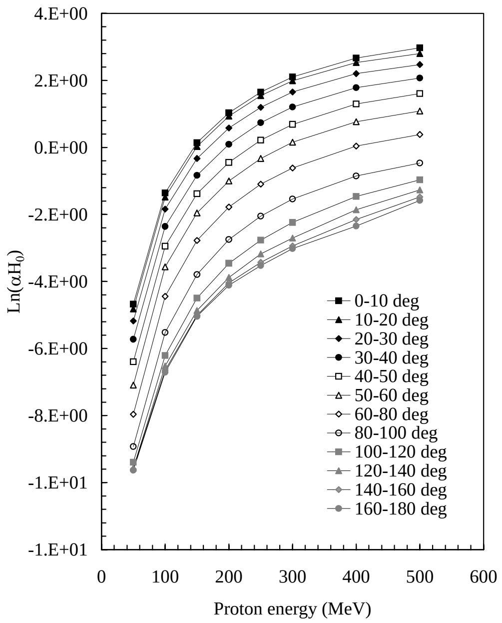
(a) 500MeV>En>5MeV

(b) 5MeV>En>0.414eV

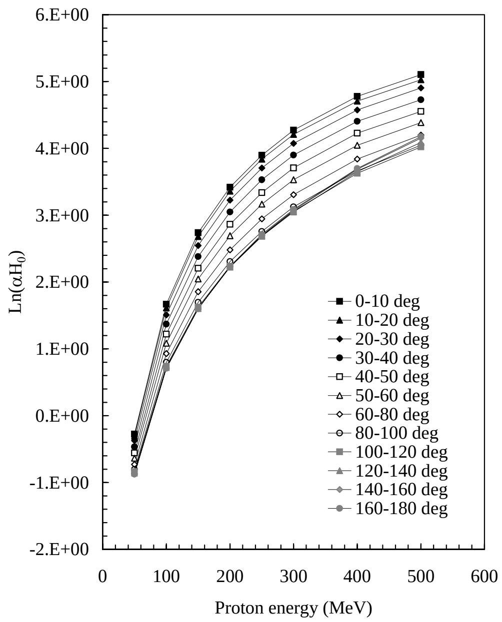
(c) 0.414eV>En

(d) photon

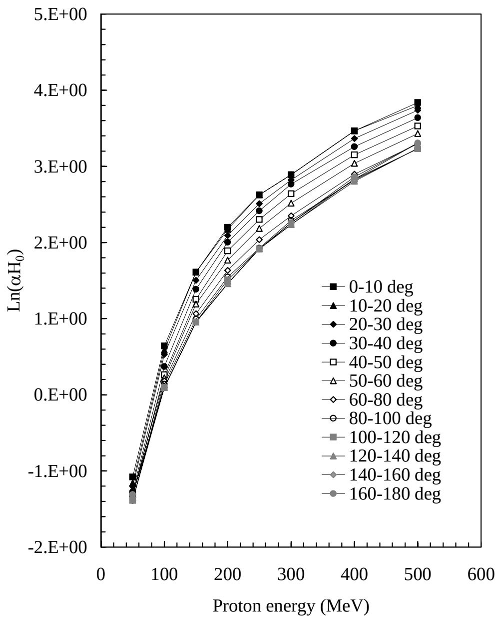
Figure 2-11 Proton energy vs. fitting parameter αH_0 of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 25 cm.



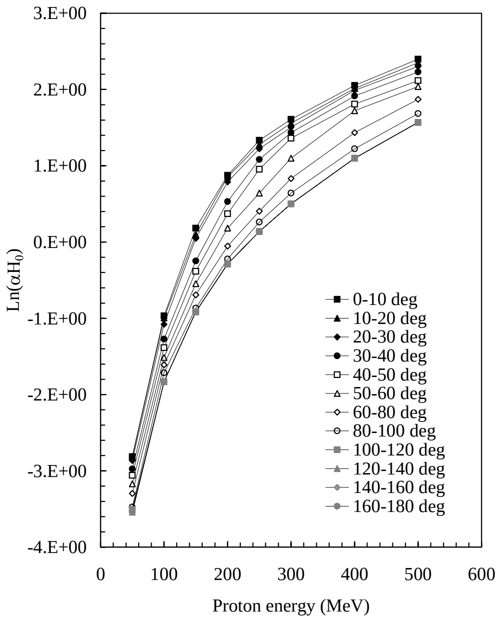
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV



(c) 0.414eV>En



(d) photon

Figure 2-12 Proton energy vs. fitting parameter αH_0 of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 50 cm.

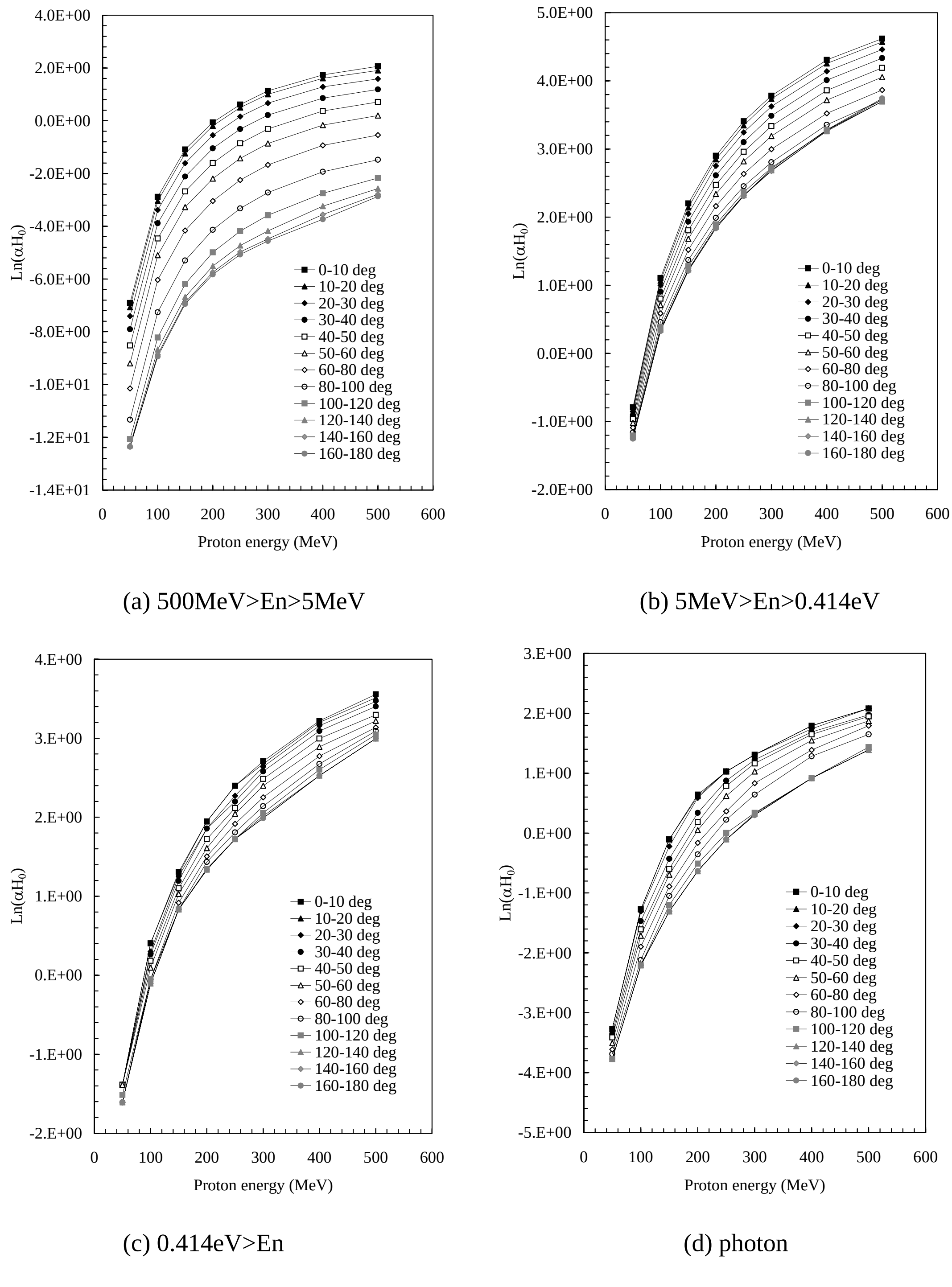
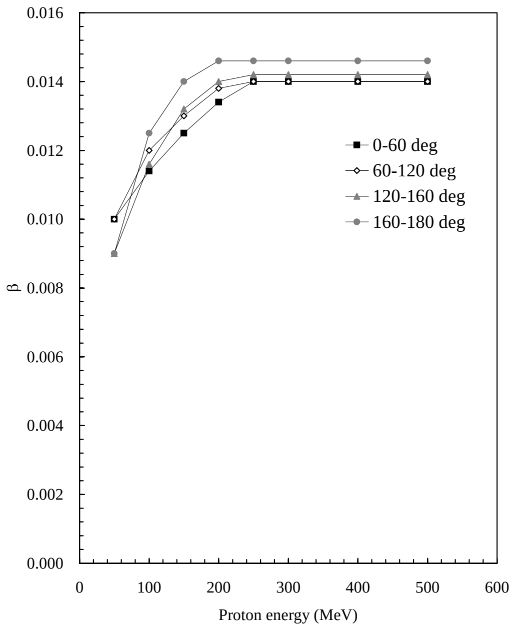
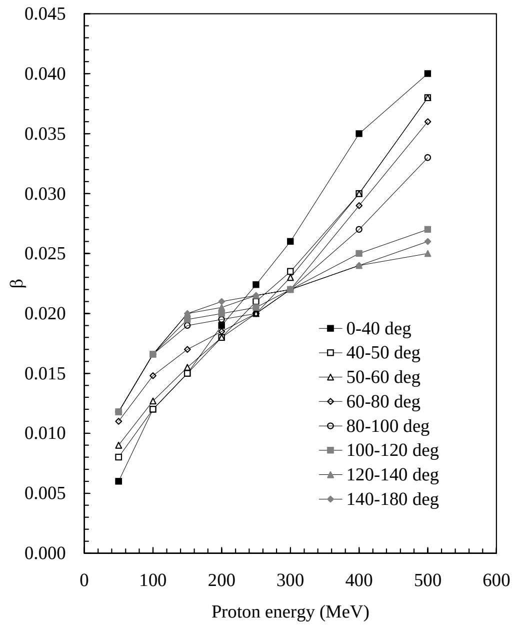


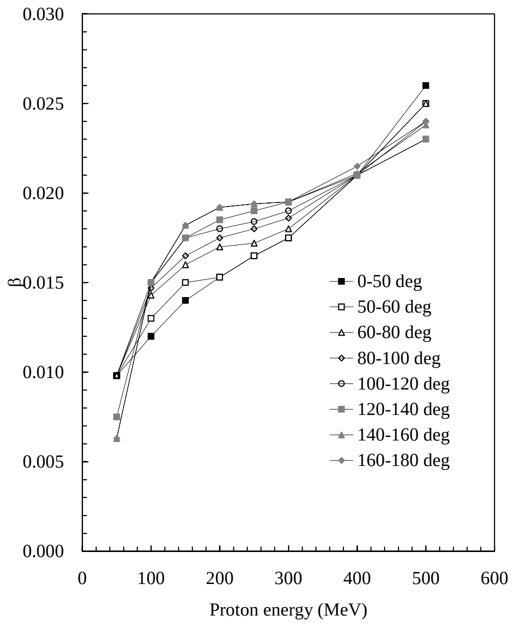
Figure 2-13 Proton energy vs. fitting parameter αH_0 of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 70 cm.



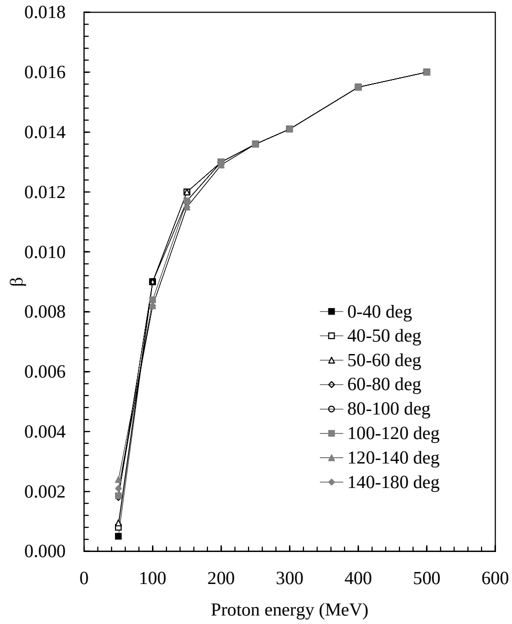
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV



(c) 0.414eV>En



(d) photon

Figure 2-14 Proton energy vs. fitting parameter β of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 0 cm.

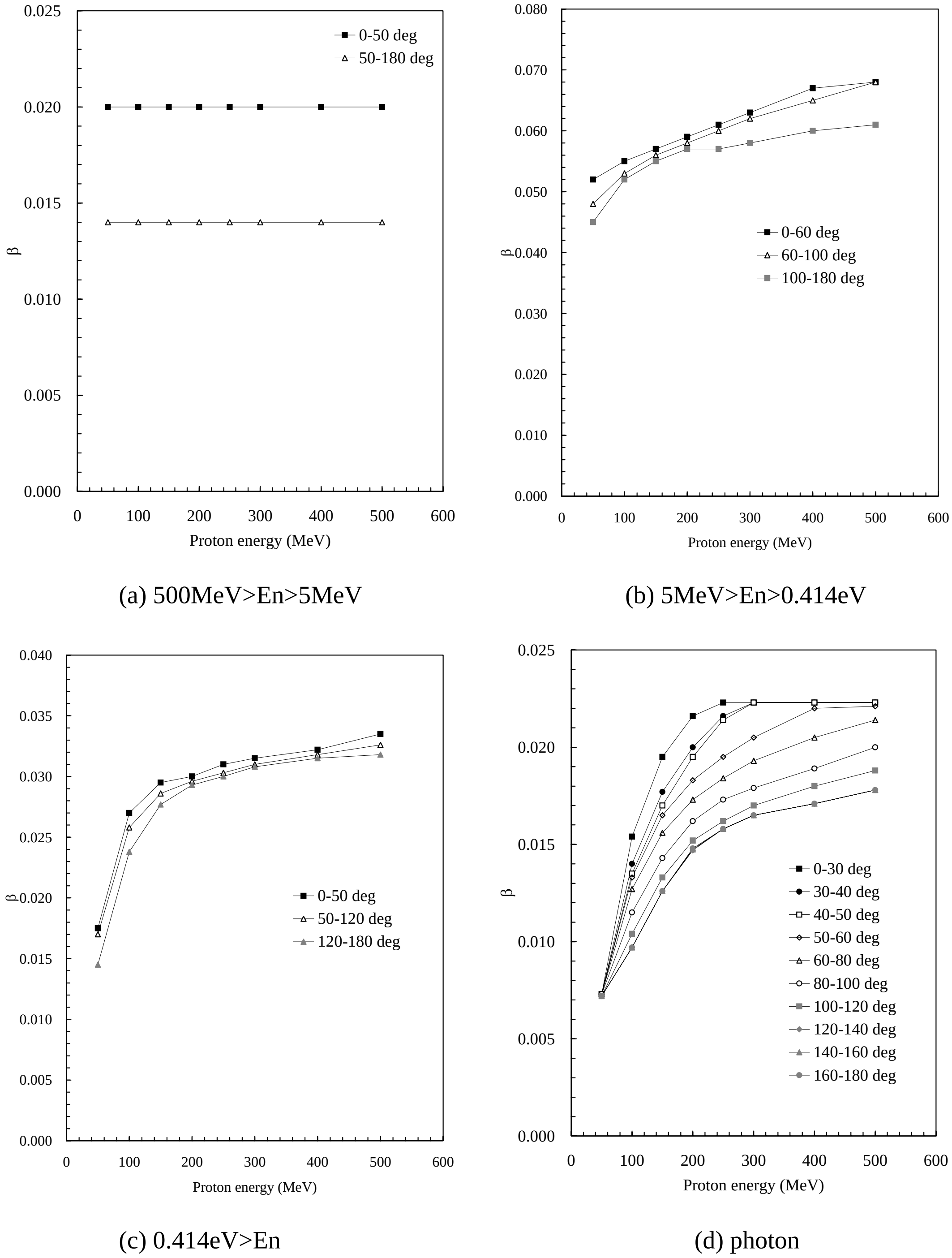
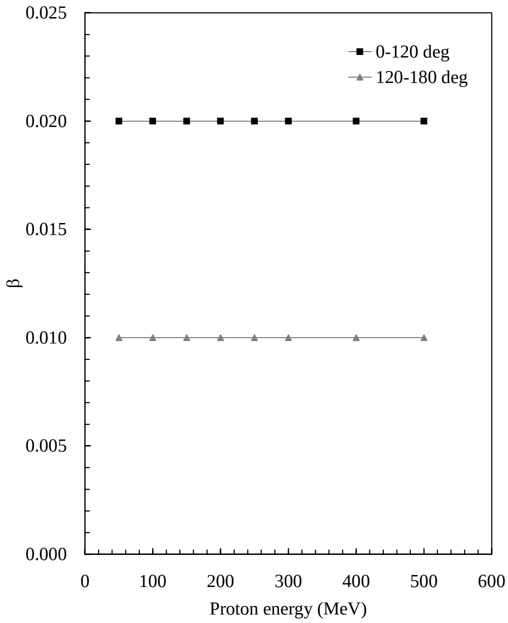
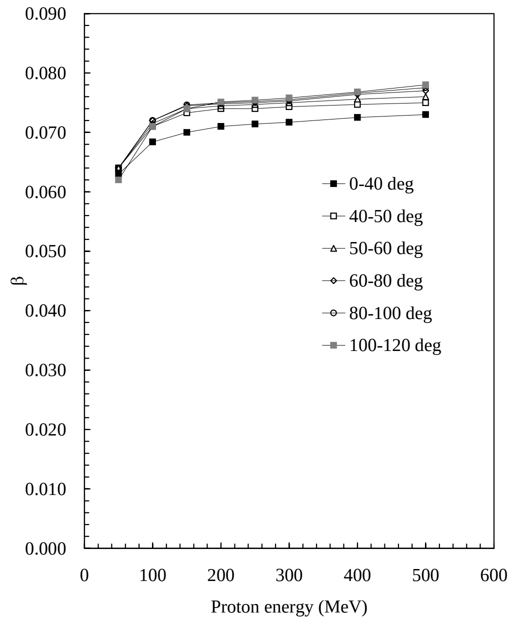


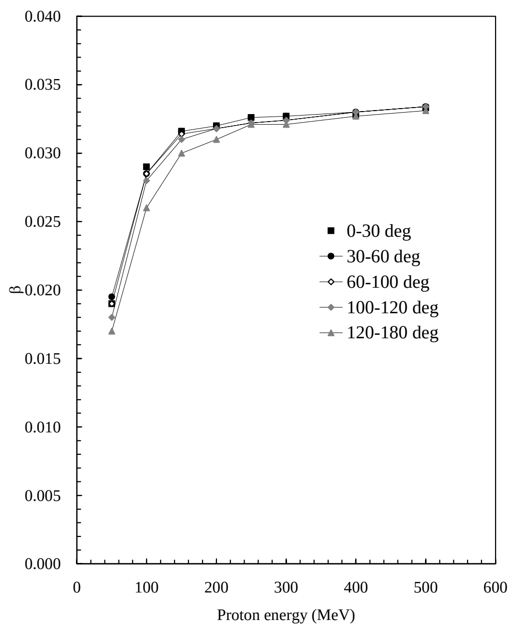
Figure 2-15 Proton energy vs. fitting parameter β of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 25 cm.



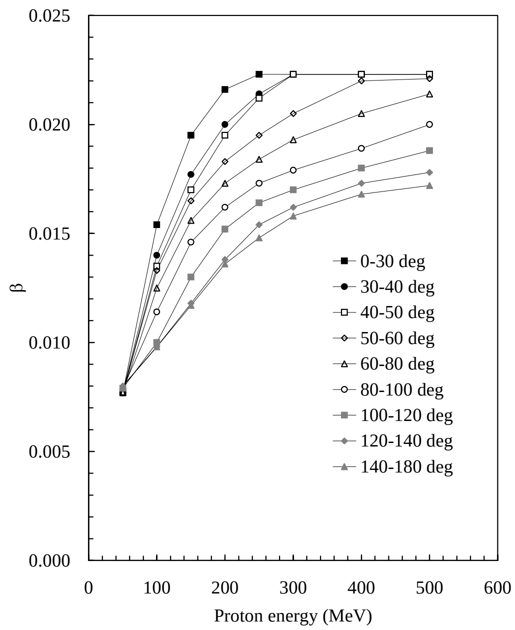
(a) 500MeV>En>5MeV



(b) 5MeV>En>0.414eV



(c) 0.414eV>En



(d) photon

Figure 2-16 Proton energy vs. fitting parameter β of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 50 cm.

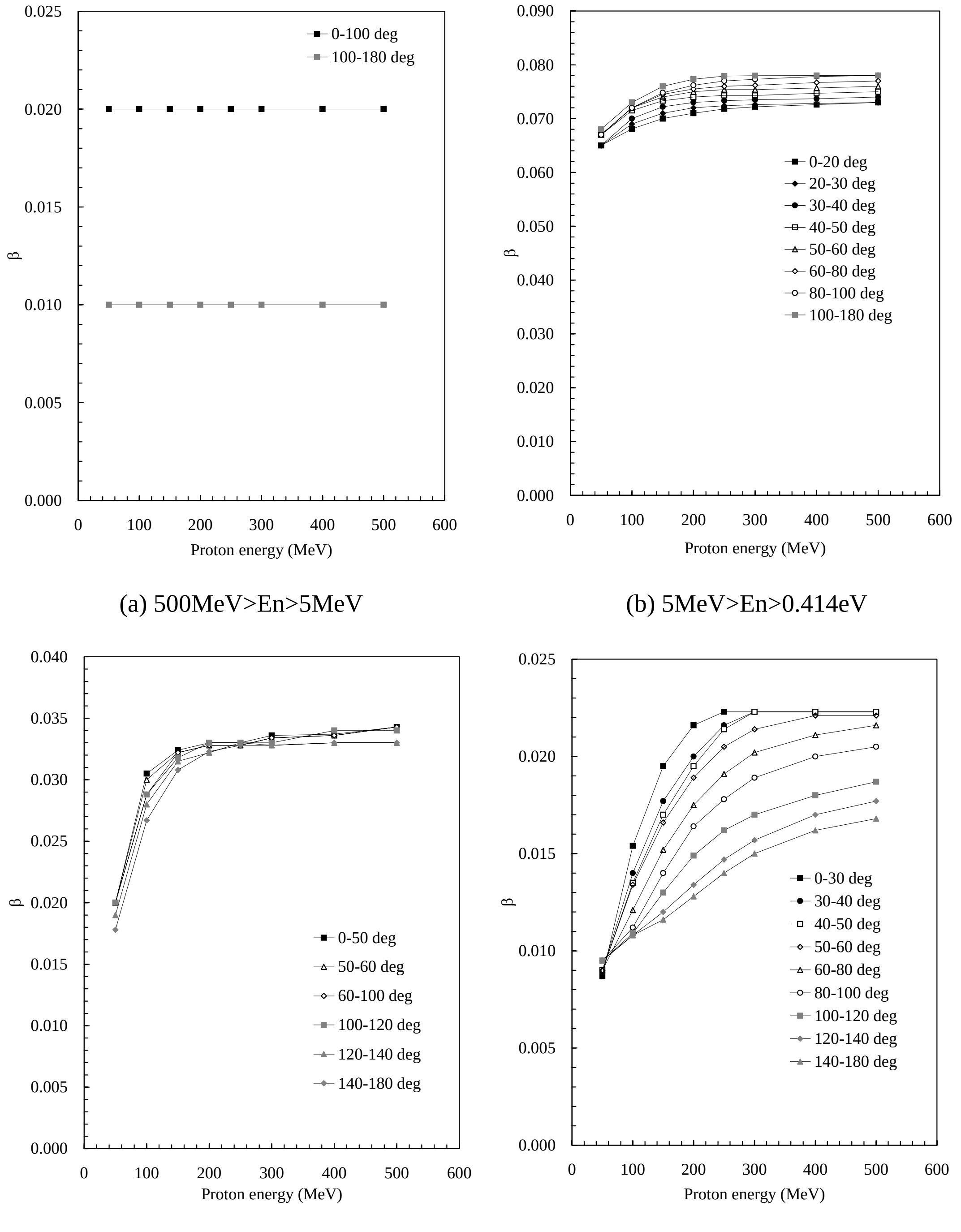


Figure 2-17 Proton energy vs. fitting parameter β of concrete for each emission angle range relative to proton beam direction where thickness of additional iron shield is 70 cm.

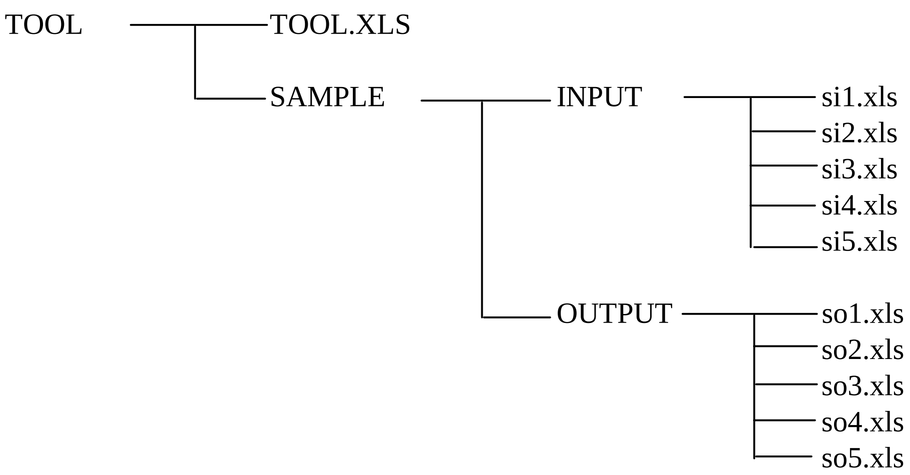
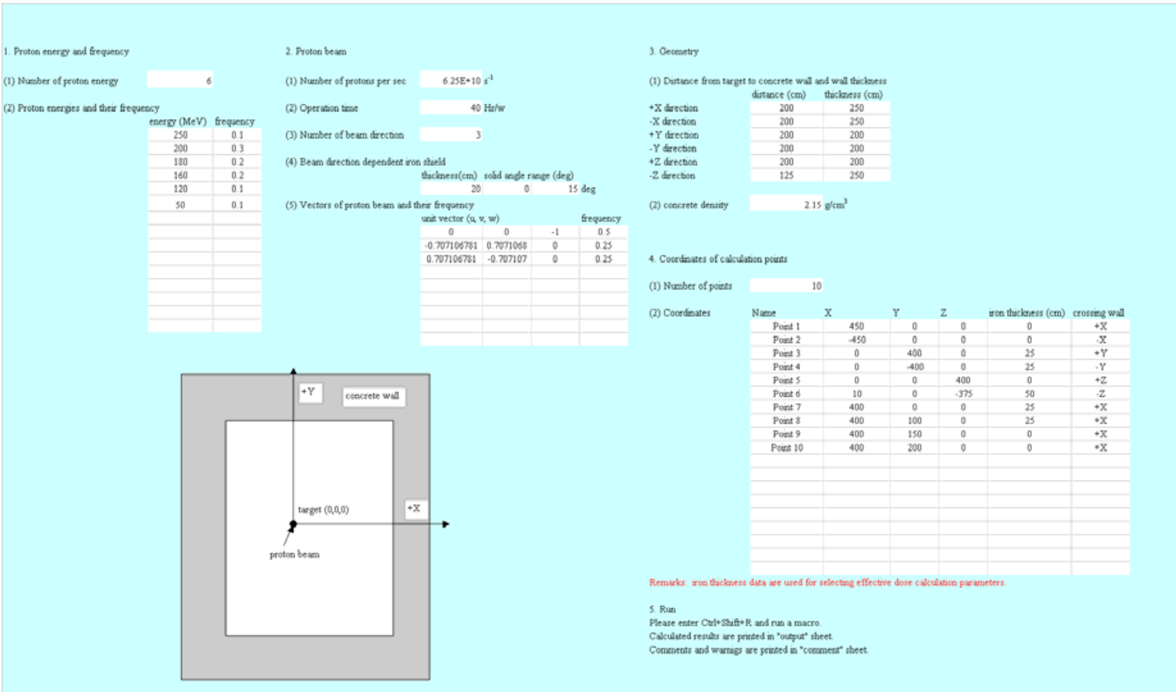


Figure 3-1 Directory structure of the package



1. Proton energy and frequency

(1) Number of proton energy 6

(2) Proton energies and their frequency

energy (MeV)	frequency
250	0.1
200	0.3
180	0.2
160	0.2
120	0.1
50	0.1

2. Proton beam

(1) Number of protons per sec 6.25E+10 s^{-1}

(2) Operation time 40 Hr/w

(3) Number of beam direction 3

(4) Beam direction dependent iron shield

thickness(cm)	solid angle range (deg)		
20	0	15	deg

(5) Vectors of proton beam and their frequency

unit vector (u, v, w)			frequency
0	0	-1	0.5
-0.707106781	0.7071068	0	0.25
0.707106781	-0.707107	0	0.25

3. Geometry

(1) Distance from target to concrete wall and wall thickness

	distance (cm)	thickness (cm)
+X direction	200	250
-X direction	200	250
+Y direction	200	200
-Y direction	200	200
+Z direction	200	200
-Z direction	125	250

(2) concrete density 2.15 g/cm^3

4. Coordinates of calculation points

(1) Number of points 10

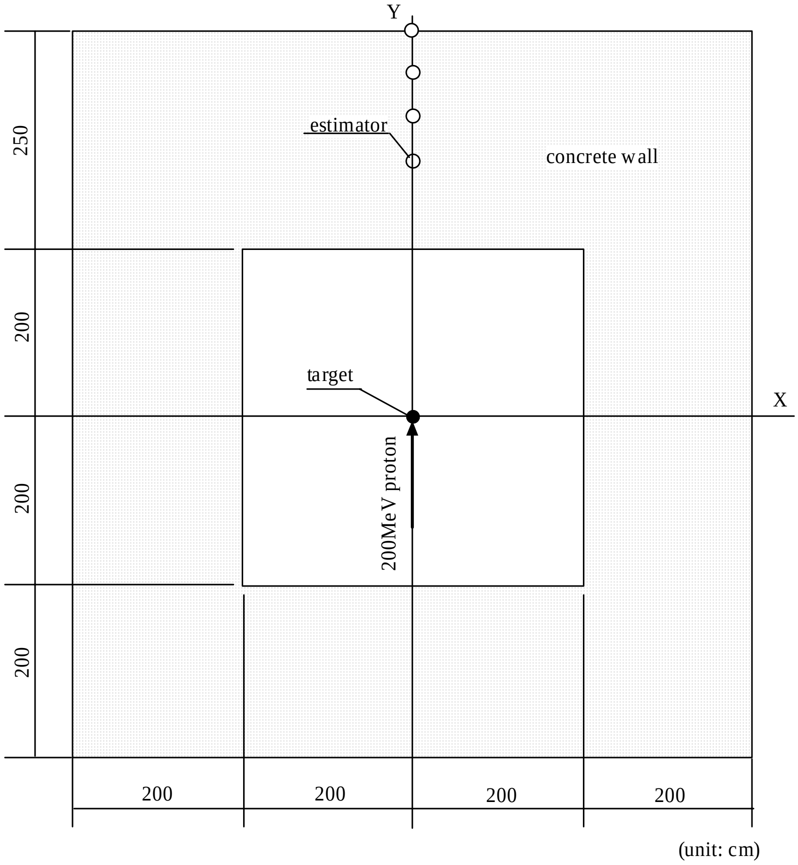
(2) Coordinates

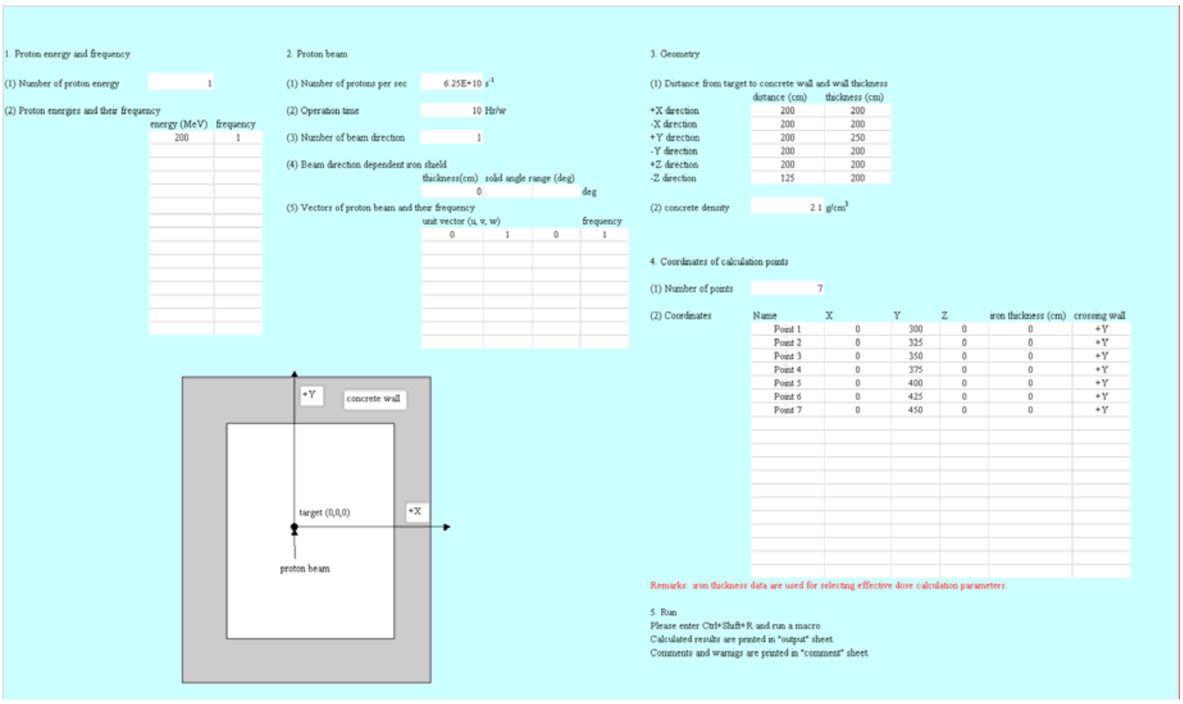
Name	X	Y	Z	iron thickness (cm)	crossing wall
Point 1	450	0	0	0	+X
Point 2	-450	0	0	0	-X
Point 3	0	400	0	25	+Y
Point 4	0	-400	0	25	-Y
Point 5	0	0	400	0	+Z
Point 6	10	0	-375	50	-Z
Point 7	400	0	0	25	+X
Point 8	400	100	0	25	+X
Point 9	400	150	0	0	+X
Point 10	400	200	0	0	+X

Remarks: iron thickness data are used for selecting effective dose calculation parameters.

5. Run
Please enter Ctrl+Shift+R and run a macro.
Calculated results are printed in "output" sheet.
Comments and warnigs are printed in "comment" sheet.

Figure 3-2 Input sheet of the program





1. Proton energy and frequency

(1) Number of proton energy: 1

(2) Proton energies and their frequency

energy (MeV)	frequency
200	1

2. Proton beam

(1) Number of protons per sec: 6.25E+10 s^{-1}

(2) Operation time: 10 Hr/w

(3) Number of beam direction: 1

(4) Beam direction dependent iron shield

thickness(cm)	solid angle range (deg)		
0			deg

(5) Vectors of proton beam and their frequency

unit vector (u, v, w)			frequency
0	1	0	1

3. Geometry

(1) Distance from target to concrete wall and wall thickness

	distance (cm)	thickness (cm)
+X direction	200	200
-X direction	200	200
+Y direction	200	250
-Y direction	200	200
+Z direction	200	200
-Z direction	125	200

(2) concrete density: 2.1 g/cm^3

4. Coordinates of calculation points

(1) Number of points: 7

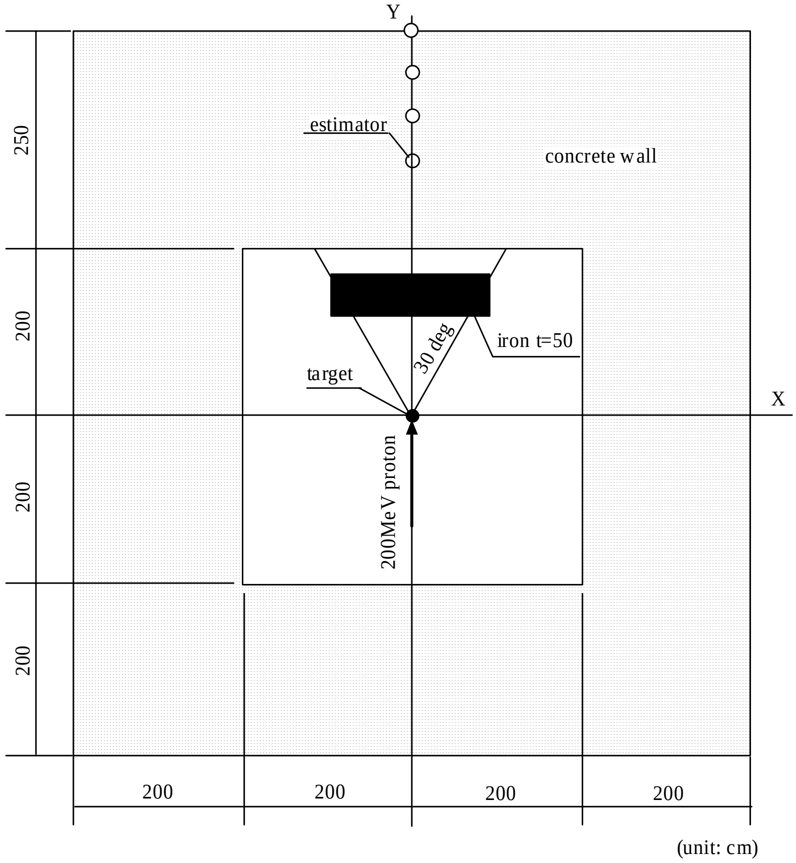
(2) Coordinates

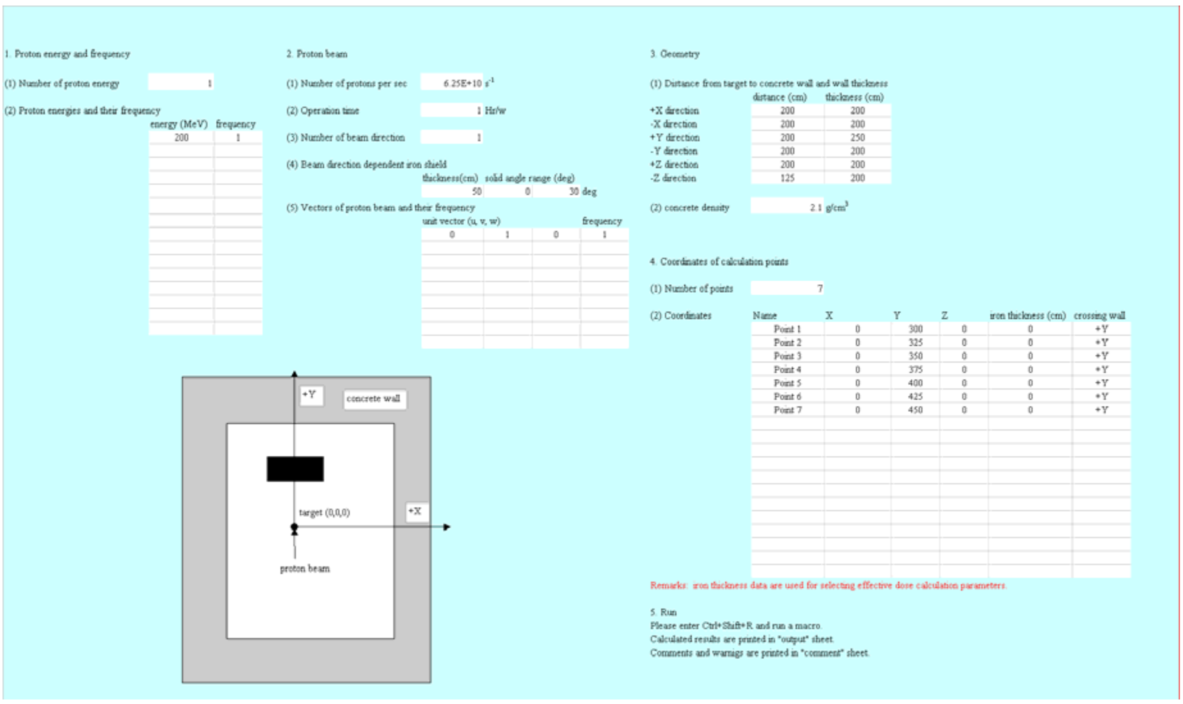
Name	X	Y	Z	iron thickness (cm)	crossing wall
Point 1	0	300	0	0	+Y
Point 2	0	325	0	0	+Y
Point 3	0	350	0	0	+Y
Point 4	0	375	0	0	+Y
Point 5	0	400	0	0	+Y
Point 6	0	425	0	0	+Y
Point 7	0	450	0	0	+Y

Remarks: iron thickness data are used for selecting effective dose calculation parameters.

5. Run
Please enter Ctrl+Shift+R and run a macro.
Calculated results are printed in "output" sheet.
Comments and warnigs are printed in "comment" sheet.

Figure 4-1 Geometry and input sheet of sample No.1





1. Proton energy and frequency

(1) Number of proton energy: 1

(2) Proton energies and their frequency

energy (MeV)	frequency
200	1

2. Proton beam

(1) Number of protons per sec: 6.25E+10 s^{-1}

(2) Operation time: 1 Hr/w

(3) Number of beam direction: 1

(4) Beam direction dependent iron shield

thickness(cm)	solid angle range (deg)		
50	0	30	deg

(5) Vectors of proton beam and their frequency

unit vector (u, v, w)			frequency
0	1	0	1

3. Geometry

(1) Distance from target to concrete wall and wall thickness

	distance (cm)	thickness (cm)
+X direction	200	200
-X direction	200	200
+Y direction	200	250
-Y direction	200	200
+Z direction	200	200
-Z direction	125	200

(2) concrete density: 2.1 g/cm^3

4. Coordinates of calculation points

(1) Number of points: 7

(2) Coordinates

Name	X	Y	Z	iron thickness (cm)	crossing wall
Point 1	0	300	0	0	+Y
Point 2	0	325	0	0	+Y
Point 3	0	350	0	0	+Y
Point 4	0	375	0	0	+Y
Point 5	0	400	0	0	+Y
Point 6	0	425	0	0	+Y
Point 7	0	450	0	0	+Y

Remarks: iron thickness data are used for selecting effective dose calculation parameters.

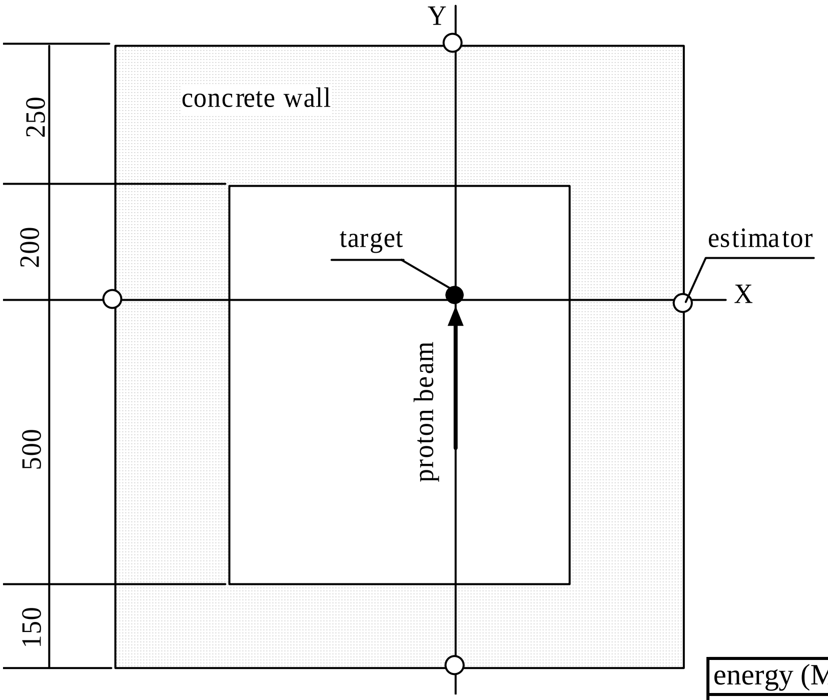
5. Run

Please enter Ctrl+Shift+R and run a macro.

Calculated results are printed in "output" sheet.

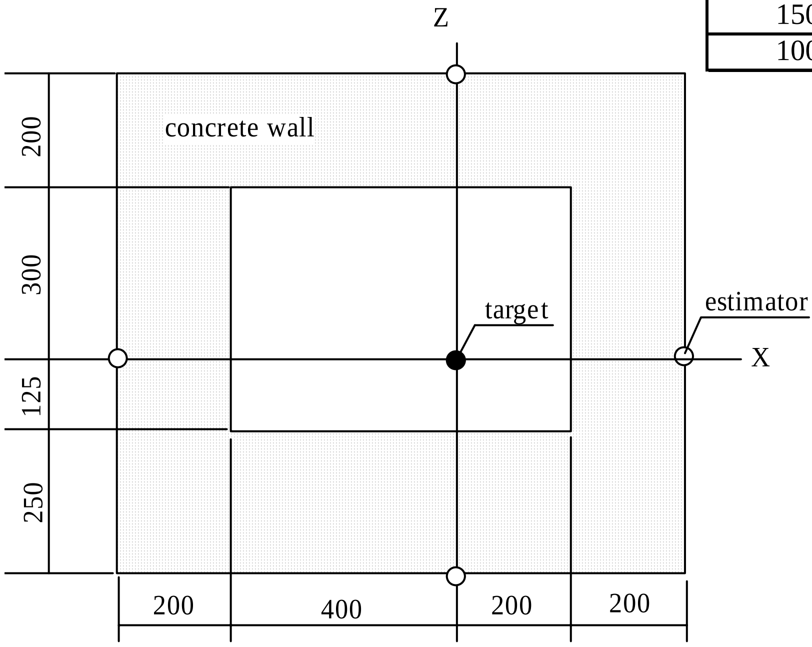
Comments and warnigs are printed in "comment" sheet.

Figure 4-2 Geometry and input sheet of sample No.2



energy (MeV)	frequency
250	0.2
200	0.3
150	0.3
100	0.2

horizontal cross-section



(unit: cm)

vertical cross-section

Figure 4-3 Geometry and input sheet of sample No.3

1. Proton energy and frequency

(1) Number of proton energy: 4

(2) Proton energies and their frequency

energy (MeV)	frequency
250	0.2
200	0.3
150	0.3
100	0.2

2. Proton beam

(1) Number of protons per sec: 6.25E+10 s^{-1}

(2) Operation time: 1 Hr/w

(3) Number of beam direction: 1

(4) Beam direction dependent iron shield

thickness(cm)	solid angle range (deg)		
0	0	0	deg

(5) Vectors of proton beam and their frequency

unit vector (u, v, w)			frequency
0	1	0	1

3. Geometry

(1) Distance from target to concrete wall and wall thickness

	distance (cm)	thickness (cm)
+X direction	200	200
-X direction	400	200
+Y direction	200	250
-Y direction	500	150
+Z direction	300	200
-Z direction	125	250

(2) concrete density: 2.1 g/cm^3

4. Coordinates of calculation points

(1) Number of points: 6

(2) Coordinates

Name	X	Y	Z	iron thickness (cm)	crossing wall
Point 1	0	450	0	0	+Y
Point 2	0	-650	0	0	-Y
Point 3	400	0	0	0	+X
Point 4	-600	0	0	0	-X
Point 5	0	0	500	0	+Z
Point 6	0	0	-375	0	-Z

Remarks: iron thickness data are used for selecting effective dose calculation parameters.

5. Run

Please enter Ctrl+Shift+R and run a macro.

Calculated results are printed in "output" sheet.

Comments and warnigs are printed in "comment" sheet.

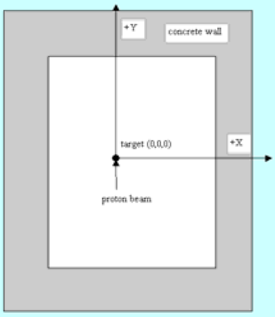
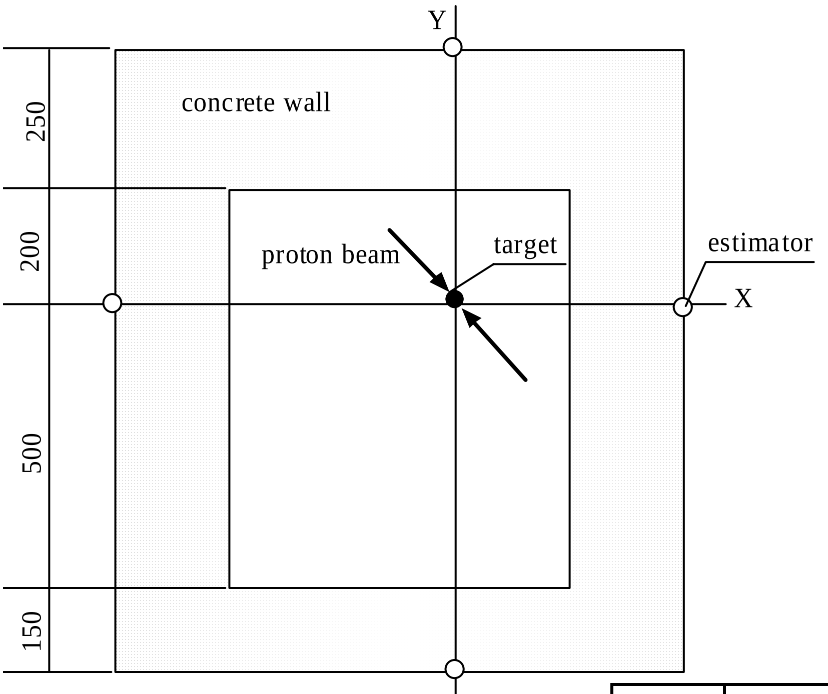
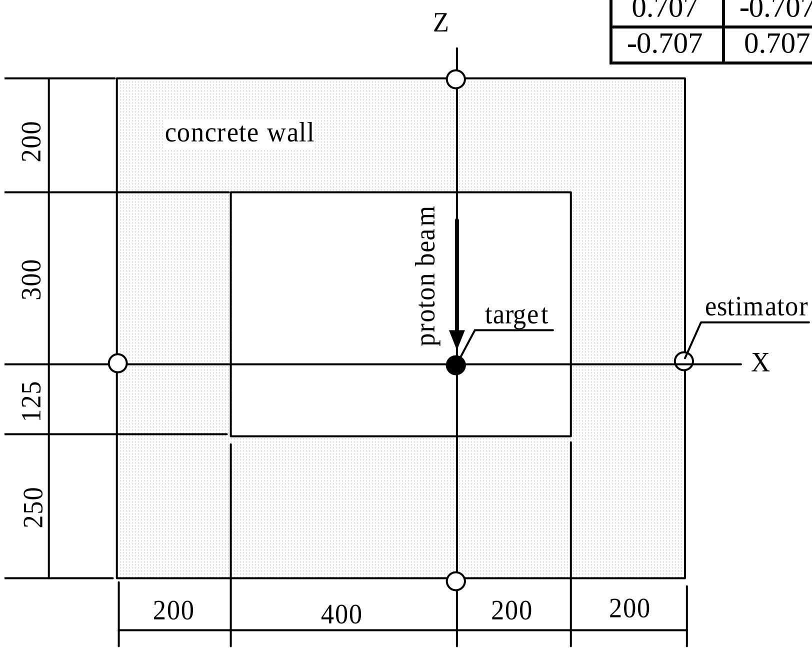


Figure 4-3 Geometry and input sheet of sample No.3 (continued)



horizontal cross-section

u	v	w	frequency
0	0	-1	0.5
0.707	-0.707	0	0.25
-0.707	0.707	0	0.25



(unit: cm)

vertical cross-section

Figure 4-4 Geometry and input sheet of sample No.4

1. Proton energy and frequency

(1) Number of proton energy: 1

(2) Proton energies and their frequency

energy (MeV)	frequency
250	1

2. Proton beam

(1) Number of protons per sec: 6.25E+10 s^{-1}

(2) Operation time: 1 Hr/w

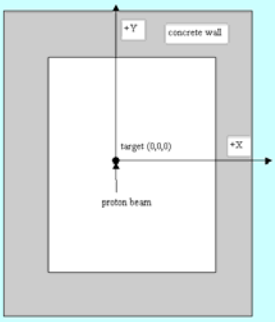
(3) Number of beam direction: 3

(4) Beam direction dependent iron shield

thickness(cm)	solid angle range (deg)	
0	0	0 deg

(5) Vectors of proton beam and their frequency

unit vector (u, v, w)			frequency
0	0	-1	0.5
0.707106781	-0.707107	0	0.25
-0.707106781	0.7071068	0	0.25



3. Geometry

(1) Distance from target to concrete wall and wall thickness

	distance (cm)	thickness (cm)
+X direction	200	200
-X direction	400	200
+Y direction	200	250
-Y direction	500	150
+Z direction	300	200
-Z direction	125	250

(2) concrete density: 2.1 g/cm^3

4. Coordinates of calculation points

(1) Number of points: 6

(2) Coordinates

Name	X	Y	Z	iron thickness (cm)	crossing wall
Point 1	0	450	0	0	+Y
Point 2	0	-650	0	0	-Y
Point 3	400	0	0	0	+X
Point 4	-600	0	0	0	-X
Point 5	0	0	500	0	+Z
Point 6	0	0	-375	0	-Z

Remarks: iron thickness data are used for selecting effective dose calculation parameters.

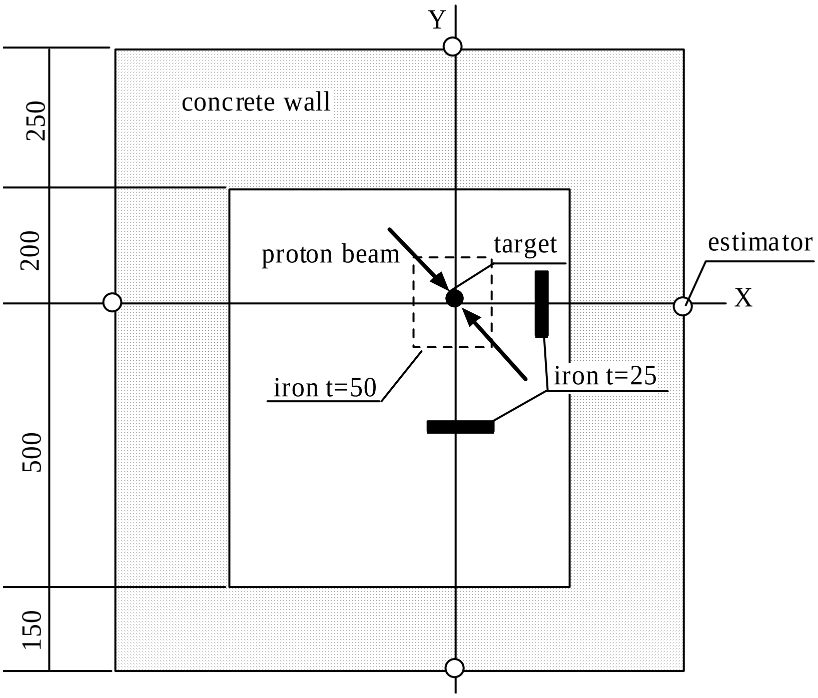
5. Run

Please enter Ctrl+Shift+R and run a macro.

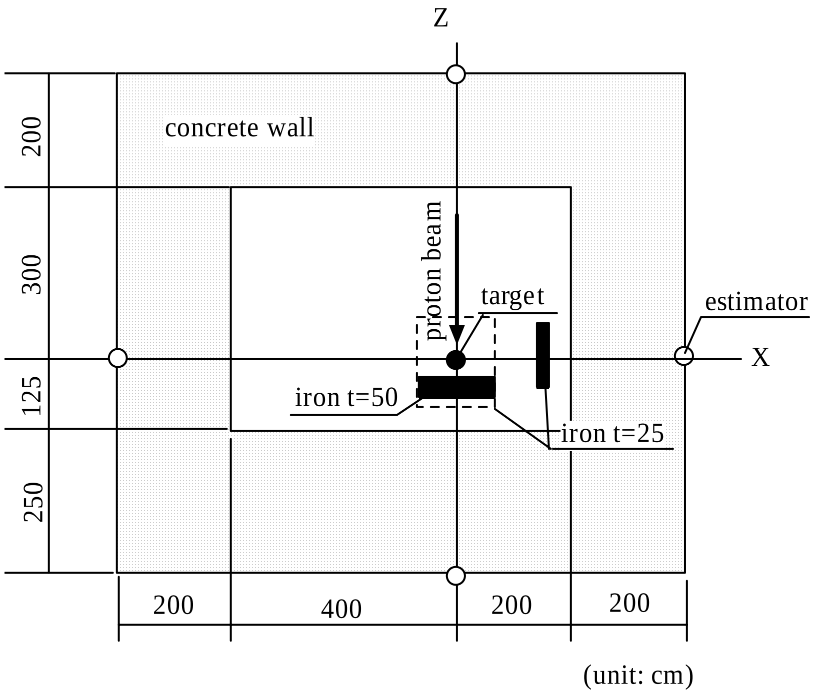
Calculated results are printed in "output" sheet.

Comments and warnigs are printed in "comment" sheet.

Figure 4-4 Geometry and input sheet of sample No.4 (continued)

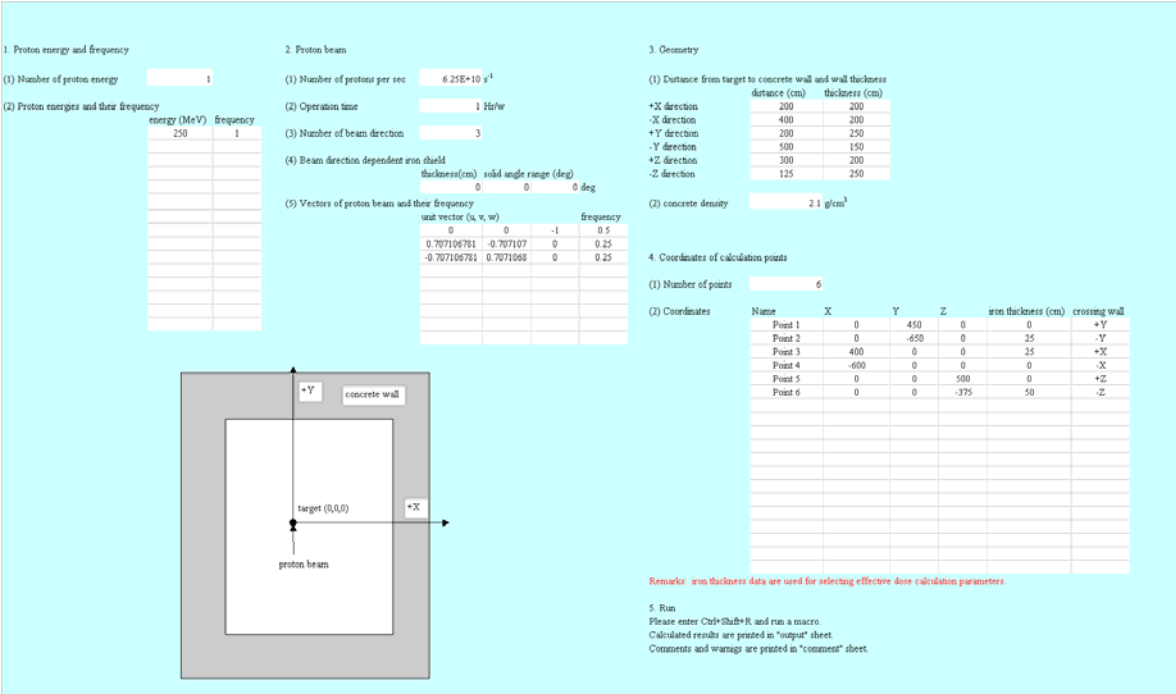


horizontal cross-section



vertical cross-section

Figure 4-5 Geometry and input sheet of sample No.5



1. Proton energy and frequency

(1) Number of proton energy: 1

(2) Proton energies and their frequency

energy (MeV)	frequency
250	1

2. Proton beam

(1) Number of protons per sec: 6.25E+10 s^{-1}

(2) Operation time: 1 Hr/w

(3) Number of beam direction: 3

(4) Beam direction dependent iron shield

thickness(cm)	solid angle range (deg)	
0	0	0 deg

(5) Vectors of proton beam and their frequency

unit vector (u, v, w)			frequency
0	0	-1	0.5
0.707106781	-0.707107	0	0.25
-0.707106781	0.7071068	0	0.25

3. Geometry

(1) Distance from target to concrete wall and wall thickness

	distance (cm)	thickness (cm)
+X direction	200	200
-X direction	400	200
+Y direction	200	250
-Y direction	500	150
+Z direction	300	200
-Z direction	125	250

(2) concrete density: 2.1 g/cm^3

4. Coordinates of calculation points

(1) Number of points: 6

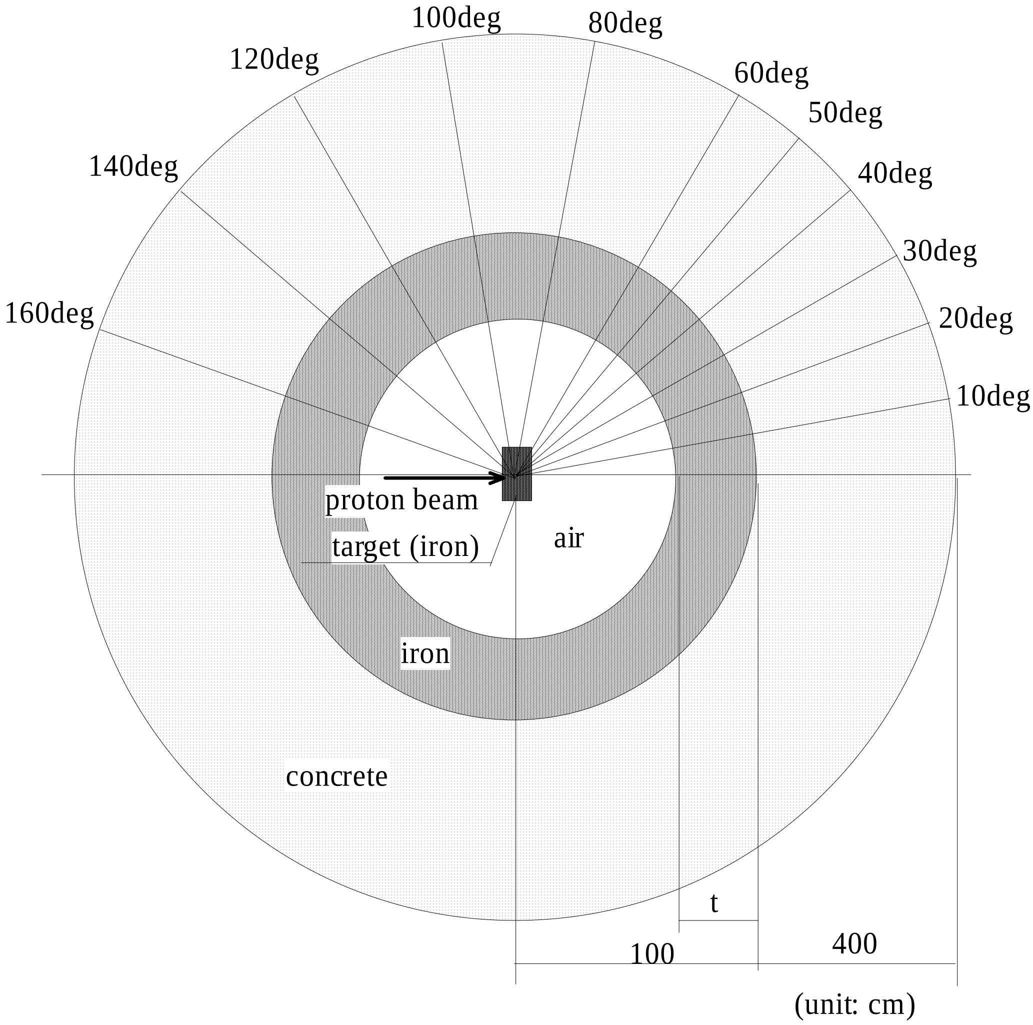
(2) Coordinates

Name	X	Y	Z	iron thickness (cm)	crossing wall
Point 1	0	450	0	0	+Y
Point 2	0	-650	0	25	-Y
Point 3	400	0	0	25	+X
Point 4	-600	0	0	0	-X
Point 5	0	0	500	0	+Z
Point 6	0	0	-375	50	-Z

Remarks: iron thickness data are used for selecting effective dose calculation parameters

5. Run
Please enter Ctrl+Shift+R and run a macro.
Calculated results are printed in "output" sheet.
Comments and warnigs are printed in "comment" sheet.

Figure 4-5 Geometry and input sheet of sample No.5 (continued)



Proton energy (MeV)	Target thickness (cm)
50	4.32E-01
100	1.44E+00
150	2.90E+00
200	4.78E+00
250	7.00E+00
300	9.70E+00
400	1.60E+01
500	2.36E+01

iron thickness t (cm)
0.0
25.0
50.0
70.0

Figure A-1 MCNPX model for calculating effective dose distribution in concrete