NISTIR 5330

Penetration of Proton Beams Through Water II. Three-Dimensional Absorbed Dose Distributions

Martin J. Berger

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

Prepared for:

National Cancer Institute
Bethesda, MD 20892

NIST

NISTIR 5330

Penetration of Proton Beams Through Water II. Three-Dimensional Absorbed Dose Distributions

Martin J. Berger

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

Prepared for:

National Cancer Institute
Bethesda, MD 20892

December 1993

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Arati Prabhakar, Director

Penetration of Proton Beams Through Water
II. Three-Dimensional Absorbed Dose Distributions

Martin J. Berger*

Physics Laboratory**
National Institute of Standards and Technology
Gaithersburg, MD 20899

Abstract

This report describes methods and computer programs for calculating absorbed-dose distributions in a water target irradiated by proton beams. The spatial pattern of absorbed dose from monoenergetic pencil beams is calculated as a function of the depth in the target and of the radial distance from the pencil beam. This calculation uses the Monte Carlo program PTRAN and also Molière's theory of radial multiple-scattering deflections. Such pencil-beam results are then combined linearly to obtain three-dimensional absorbed-dose distributions from beams that irradiate a field with arbitrary shape and size. In general, this requires a double numerical quadrature. Specialized formulas for circular and rectangular fields are also given which require only a single numerical quadrature.

*Work carried out for the National Institute of Standards and Technology under contract 50SBNB3C7583.

**Ionizing Radiation Division, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce, Gaithersburg, MD 20899.

1. Introduction

This is the third report in a series dealing with the transport of proton beams through water. The first report (Berger, 1993a) described the Monte Carlo transport program PTRAN which calculates the penetration, diffusion and slowing down of protons in an extended medium. The second report (Berger, 1993b) presented depth-dose curves, proton spectra and LET distributions as functions of the depth in a water medium.

The present report deals with the calculation of absorbed dose distributions as a function of two or three spatial variables. Section 2 discusses methods for obtaining dose distributions from beams with arbitrary cross sections from the superposition of dose distributions from pencil beams. In general this requires a double numerical integration. However, for beams with circular or rectangular cross sections one of the integrations is done analytically, so that only a single numerical quadrature is required. In section 3 a database of depth-dose distributions is described which was obtained with the Monte Carlo program PTRAN, and which gives the depth-dependence for beams with initial energies from 250 MeV to 50 MeV. In section 4 the radial dependence of the absorbed dose from pencil beams is discussed. It is shown that the radial dependence obtained with the PTRAN program is in good agreement with the dependence that can be obtained more directly and simply with Molière's theory of radial multiple-scattering deflections. However, at depths equal to or greater than the depth where the Bragg peak occurs, it is still necessary to rely on the Monte Carlo method. In section 5, various examples are given of absorbed-dose distributions from beams with circular and rectangular cross sections. In section 6, computer programs are described with which the database of depth-dose distributions can be accessed, and with which the superposition of pencil-beam results can be accomplished.

2. Superposition of Pencil Beam Results

We consider a narrow pencil beam incident along the z axis onto a water medium that occupies the region $z \geq 0$. It is convenient to represent the absorbed-dose distribution from such a beam in terms of two quantities: the energy-deposition distribution dD/dz, and the radial dose distribution $f(\rho,z)$, at depth z. These distributions are defined as follows:

$\frac{dD}{dz}\,dz$ is the amount of energy, per incident proton, which is imparted to the medium at depths between z and z + dz.

$2\pi\rho\, f(\rho,z)\, d\rho$ is the fraction of the energy (dD/dz)dz that is imparted to the medium at radial distances between ρ and $\rho + d\rho$ from the z-axis.

In the present work dD/dz was obtained with the Monte Carlo Program PTRAN, combined with an estimate of energy deposition by secondary charged particles from nuclear reactions (Berger, 1993b). The calculation of dD/dz will be discussed further in section 3, and the calculation of $f(\rho,z)$ in section 4.

We now consider an incident proton beam that consists of a bundle of parallel pencil beams of the same energy that irradiate a specified field on the surface of the phantom. Within

this field, let n(x,y)dxdy be the number of pencil beams incident between x and x + dx and between y and y + dy. Let $D_a(x,y,z)$ denote the absorbed dose at a point (x,y,z), where z indicates the depth and x and y indicate the lateral coordinates. $D_a(x,y,z)$ can be calculated as a linear combination of dose distributions from pencil beams:

$$D_a(x,y,z) = \frac{dD}{dz} \int dx' \int dy' \; n(x',y') \; f(\rho,z) \quad , \tag{1}$$

where

$$\rho = \left[(x-x')^2 + (y-y')^2\right]^{1/2} \quad . \tag{2}$$

The double integral in eq (1) must be extended over the field irradiated by the proton beam. With the density n(x,y) in units of cm^{-2}, and dD/dz in MeV cm^2/g, D_a has units of MeV/g. (Note that 1 MeV/g corresponds to 1.6022×10^{-10} Gy). A computer program FREC2 is described in section 6.6 in which eq (1) is applied to a rectangular field.

It is often advantageous to switch from Cartesian to cylindrical coordinates, especially when one is considering a constant beam density $n(x,y) = n_o$. Depending on the shape of the irradiated field, it may be then be possible to integrate analytically with respect to the angular variable, so that only a single numerical quadrature in the radial variable is required.

Figure 1 shows a curve in the plane z = 0 which represents the boundary of the irradiated field. Also shown is a circle of radius ρ around the point P = (x,y,0). Let $\psi_p(\rho)$ be the fraction of the circular arc that lies within the irradiated field. Assuming a constant density n_o, eq (1) can be restated as

$$D_a = n_o \frac{dD}{dz} F_{red}(z) \quad , \tag{3}$$

where

$$F_{red}(z) = 2\pi \int_o^\infty f(\rho,z) \; \psi_p(\rho) \; \rho \; d\rho \quad . \tag{4}$$

For a uniformly irradiated field F_{red}, is always smaller than unity. We shall call it *reduction factor*, because it represents the reduction of the absorbed dose compared to that which would prevail if the irradiated field were unbounded. The reduction factor can evaluated analytically for simple fields shapes such as a circular or rectangular field.

2.1 Circular Fields.

Assume that the irradiated field is bounded by a circle with radius R, and consider a point P = (x,y,0) located at a distance r from the center of the field. The reduction factor at point P can be shown to be given by the following formulas:

For $r < R$ point (P inside the field),

$$F_{red}(z,R,r) = 2\pi \int_{o}^{R-r} f(\rho,z)\ \rho\ d\rho + 2\pi \int_{R-r}^{R+r} f(\rho,z)\ \psi(\rho,R,r)\ \rho\ d\rho \quad , \tag{5a}$$

and for $r \geq R$

$$F_{red}(z,R,r) = 2\pi \int_{r-R}^{r+R} f(\rho,z)\ \psi(\rho,R,r)\ \rho\ d\rho \quad , \tag{5b}$$

where

$$\psi(\rho,R,r) = \frac{1}{\pi} \cos^{-1} \left[\frac{\rho^2 + r^2 - R^2}{2\rho\ r} \right]^{1/2} \quad . \tag{6}$$

A computer program FCIR is described in section 6.5, which calculates reduction factors and absorbed-dose distributions with eqs (5) and (6).

If the field is not uniform but can be represented by a density $n(r')$, where r' is the distance from the center of the circular field, the absorbed dose must be calculated a double integral. When $r < R$,

$$F_{red}(z,R,r) = \int_{o}^{R-r} f(\rho,z)\ \rho\ d\rho \int_{-\pi}^{\pi} n[r'(\varphi)]\ d\varphi + \int_{R-r}^{R+r} f(\rho,z)\ \rho\ d\rho \int_{-\varphi_1}^{\varphi_1} n[r'(\varphi)]\ d\varphi \quad , \tag{7a}$$

and when $r \geq R$

$$F_{red}(z,R,r) = \int_{r-R}^{r+R} f(\rho,z)\ \rho\ d\rho \int_{-\varphi_1}^{\varphi_1} n[r'(\varphi)]\ d\varphi \quad , \tag{7b}$$

with

$$r' = (r^2 - 2r\rho\ \cos\varphi + \rho^2)^{1/2} \quad , \tag{8}$$

and

$$\varphi_1 = \cos^{-1} \frac{2 + r^2 - R^2}{2\rho\ r} \quad . \tag{9}$$

2.2 Rectangular Fields

As was shown by Meredith and Neary (1944), a point inside or outside a rectangular field can be considered as being at the corner of four equivalent rectangular fields which, when added and/or subtracted, represent the original field (see fig. 2). As a preliminary, we therefore consider a circle with radius ρ centered on a corner of a rectangle with sides s_1 and s_2. Let $a = \max(s_1,s_2)$ and $b = \min(s_1,s_2)$, and let $\psi_c(\rho,s_1,s_2)$ denote the fraction of the circle that lies within the rectangle. It can be shown that this fraction is given by the following expressions:

$$\psi_c(\rho,s_1,s_2) = \frac{1}{4} \qquad \text{if } \rho \le b \ ,$$

$$= \frac{1}{4} - \cos^{-1}\left[\frac{b}{\rho}\right] \qquad \text{if } b \le \rho < a \ ,$$

$$= \frac{1}{4} - \cos^{-1}\left[\frac{b}{\rho}\right] - \cos^{-1}\left[\frac{a}{\rho}\right] \qquad \text{if } a \le \rho < (a^2 + b^2)^{1/2} \ , \tag{10}$$

$$= 0 \qquad \text{if } \rho \ge (a^2 + b^2)^{1/2} \ .$$

Next we consider a uniformly irradiated rectangular field with sides 2A and 2B, occupying the region $-A < x < A$ and $-B < y < B$. The fraction of a circle of radius around the point P = (x,y,0) that lies within the rectangular field can be obtained by adding and/or subtracting the values of ψ_c at the corners of four equivalent rectangles. The four corner functions needed are

$$\psi_{c1} = \psi_c(\rho,A+x,B+y) \ , \qquad \psi_{c2} = \psi_c(\rho,|A-x|,B+y) \ ,$$
$$\psi_{c3} = \psi_c(\rho,A+x,|B-y|) \ , \qquad \psi_{c4} = \psi_c(\rho,|A-x|,|B-y|) \ . \tag{11}$$

Four cases must be considered, depending on the location of P:

1) If $x < A$ and $y < B$ (P inside the rectangle), then the reduction factor is

$$F_{red}(z,A,B,x,y) = 2\pi \int_0^{\rho_1} f(\rho,z)\ \rho\ d\rho + 2\pi \int_{\rho_1}^{\rho_2} f(\rho,z)\ (\psi_{c1} + \psi_{c2} + \psi_{c3} + \psi_{c4})\ \rho\ d\rho \ , \tag{12a}$$

where $\rho_1 = \min(A-x,B-y)$ and $\rho_2 = [(A+x)^2 + (B+y)^2]^{1/2}$.

2) If $x < A$ and $y \ge B$, then

$$F_{red}(z,A,B,x,y) = 2\pi \int_{\rho_1}^{\rho_2} f(\rho,z)\ (\psi_{c1} + \psi_{c2} - \psi_{c3} - \psi_{c4})\ \rho\ d\rho \ , \tag{12b}$$

where $\rho_1 = y-B$ and $\rho_2 = [(A+x)^2 + (B+y)^2]^{1/2}$.

3) If $x \ge A$ and $y < B$, then

$$F_{red}(z,A,B,x,y) = 2\pi \int_{\rho_1}^{\rho_2} f(\rho,z)\ (\psi_{c1} - \psi_{c2} + \psi_{c3} - \psi_{c4})\ \rho\ d\rho \ , \tag{12c}$$

where $\rho_1 = x-A$ and $\rho_2 = [(A+x)^2 + (B+y)^2]^{1/2}$.

4) If $x \geq A$ and $y \geq B$, then

$$F_{red}(z,A,B,x,y) = 2\pi \int_{\rho_1}^{\rho_2} f(\rho,z) \left(\psi_{c1} - \psi_{c2} - \psi_{c3} + \psi_{c4}\right) \rho \, d\rho \quad , \tag{12d}$$

where $\rho_1 = [(x-A)^2 + (y-B)^2]^{1/2}$ and $\rho_2 = [(A+x)^2 + (B+y)^2]^{1/2}$.

A computer program FREC is described in section 6.6 that calculates reduction factors and absorbed-dose distributions for rectangular fields using eqs (10) to (12).

3. Database of Depth-Dose Distributions

The Monte Carlo program PTRAN (Berger, 1993a) was used to calculate the following two quantities that describe the rate of energy loss of the primary protons per unit depth: the loss due to Coulomb interactions, $(dE/dz)_c$, and the energy loss due to nuclear reactions, $(dE/dz)_n$. These were evaluated for monoenergetic beams incident with 25 energies between 250 MeV and 50 MeV, at a grid of 43 scaled depths z/r_o between 0 and 1.04, where z is the actual depth and r_o the CSDA range. By expressing all of the quantities in eq (13) as functions of z/r_o rather than r_o, they become slowly varying functions of T_o, which in facilitates interpolation with respect to T_o. Table 1 gives a set of pertinent range values which were calculated with program PSTAR (Berger, 1992).

Following the procedure discussed in Berger (1993b) the energy deposited in the phantom per unit depth was calculated from the expression

$$\frac{dD}{dz} = \left[\frac{dE}{dz}\right]_c + a\left(z/r_o, T_o\right) \left[\frac{dE}{dz}\right]_n \quad , \tag{13}$$

where T_o is the beam energy and $a(z/r_o,T_o)$ is an absorption factor that takes into account the energy imparted by to the medium by secondary charged particles from nuclear reactions. The values of $a(z/r_o,T_o)$ lie between 0.7 and 0.3 for T_o between 250 MeV and 50 MeV and for z/r_o between 0 and 1.04. Values of $a(z/r_o,T_o)$ were derived from a combination of PTRAN transport results with of calculations of nonelastic nuclear interactions by Seltzer(1993). Tables of $a(z/r_o,T_o)$ can be found in Berger (1993b).

For each energy T_o, a set of 1 million Monte Carlo histories of primary protons was sampled and analyzed. Each set of histories was divided into 10 groups of 100,000 histories, to provide a basis for estimating the statistical error. The relative standard deviation of dD/dz (ratio of the standard deviation to the mean value) at a given value of z/r_o was found to be nearly independent of T_o. The relative standard deviations as functions of the depth are estimated to have the following values:

z/r_o	Relative Standard Deviation of dD/dz
< 0.9	0.01 %
0.95	0.02 %
1.0	0.1 %
1.01	0.3 %
1.02	1 %
1.03	3 to 6%

Except at depths comparable with and beyond the CSDA range, the statistical errors are small compared to the systematic errors of dD/dz. The systematic errors, estimated to be 2 to 3 percent, are due to the uncertainties of the stopping powers and nuclear interactions cross sections, and due to approximations made in the PTRAN Monte Carlo model.

Curves of dD/dz *vs* z/r_o are shown in figure 3 for seven beam energies T_o between 250 MeV and 50 MeV. It can be seen that these curves have rather similar shapes, so that accurate interpolation with respect to T_o is possible. Two computer programs were developed which carry out such an interpolation, using as a database a set of curves of dD/dz *vs* z/r_o for 25 values of T_o. Program PTPOL calculates dD/dz for a monoenergetic beam of specified energy. Program PTGPOL calculates dD/dz for a beam with a Gaussian energy spectrum with specified mean energy and standard deviation. Descriptions of these programs are given in the Sections 6.1 and 6.2.

4. Radial Dose Distributions from Pencil Beams

4.1 Monte Carlo Results

Radial distributions from PTRAN, for T_o = 160 MeV and 70 MeV, are shown in figure 4. Each of this distribution is based on the results from a sample of 10 million proton Monte Carlo histories. It is useful to scale the radial distributions, by plotting the dimensionless quantity $2\pi\rho\ z\ f(\rho,z)$ as a function of the ratio ρ/z. Figure 4a shows scaled radial distributions at depths z = 0.1, 0.3, 0.5 and 0.7 r_o, and figure 4b at z = 0.99, 1, 1.01 and 1.02 r_o, at and beyond the Bragg peak. As a result of scaling, the distributions at 160 MeV (solid curves) are very similar to those at 70 MeV (dotted curves).

4.2 Results From Other Methods

A simple and convenient theory of the radial distribution of absorbed dose from proton beams was first developed by Preston and Koehler (1968). These authors considered first the mean-squared angular multiple-scattering deflection in a path length s,

$$\langle \theta^2 \rangle = \int_0^s q(s')\, ds' \tag{14}$$

and showed that the corresponding mean-squared value of the radial deflection is

$$\langle \rho^2 \rangle = \int_0^s q(s')\, (s-s')^2\, ds' \quad . \tag{15}$$

The function q(s), common to both formulas, was evaluated by Preston and Koehler according to a prescription given by Bethe and Ashkin (1953). Preston and Koehler then approximated the radial distribution by a Gaussian,

$$f(\rho,s) = \frac{\rho}{\pi \langle \rho^2 \rangle} \exp\left(-\rho^2 / \langle \rho^2 \rangle\right) \quad , \tag{16}$$

and used this Gaussian as a basis for calculating central-axis depth-dose curves for circular and for rectangular fields, using superposition methods equivalent to those described in section 2. The same approach was also used by Carlsson and Rosander (1973), who calculated radial absorbed-dose distributions in water from a 185-MeV proton beam, and obtained good agreement with radial distributions measured by them with a small silicon detector.

Just as the Gaussian approximation for angular multiple-scattering deflections can be replaced by the more accurate distribution of Molière (1948), the Gaussian approximation for the radial distribution $f(\rho,s)$ can be replaced by the radial distribution of Molière (1955). The evaluation of $f(\rho,s)$ thereby becomes somewhat more complicated, but can still be done very quickly with a computer. The relevant equations from Molière's theory are given in section 4.2.

Both with the Gaussian approximation and in Molière's theory the energy loss of the protons can be taken account in the continuous-slowing-down approximation: at every point along the track the energy loss is assumed to be equal to the stopping power. Energy-loss straggling is thus neglected, but this has almost no effect on the shape of the radial distribution. This was verified by comparative calculations with PTRAN, carried out with and without energy-loss straggling. As illustrated in figure 5 for the case of a 160-MeV beam, energy loss straggling changes the radial distribution only slightly at depths $z = 0.1\ r_o$ and $0.99\ r_o$, but practically not at all at depths from $z = 0.2\ r_o$ to $0.98\ r_o$.

Molière's theory provides the radial distribution $f(\rho,s)$ as a function of the path length traversed by the proton, whereas, strictly speaking, one needs $f(\rho,z)$ as a function of the depth z. However, the difference between the path length and depth is exceedingly small. This is illustrated in figure 6, calculated for a 160-MeV beam with a modified version of PTRAN, which shows the percentage amount by which the average path length s_{av} differs from z.

Direct comparisons between radial distributions from Molière's theory and histograms from PTRAN are shown in figure 7a (160 MeV) and in figure 7b (70 MeV), at depths $z = 0.1\ r_o$, $0.5\ r_o$, $0.9\ r_o$ and $0.99\ r_o$. The agreement is generally quite close, except the for the depth $z = 0.1\ r_o$ where a slight difference can be observed near the peak of the radial distribution. The origin of this discrepancy is not well understood. It is suspected to be caused by an approximation made in the PTRAN program in the evaluation of lateral multiple-scattering displacements [eqs (2.7) and (2.8) in Berger, 1993a].

One the basis of the foregoing considerations and comparison, one can conclude that Molière's theory is the preferable tool for calculating the radial distribution $f(\rho,z)$, and should be supplemented by the more costly Monte Carlo method only to obtain results at depths greater than 0.98 r_o. It is expected, however, that the Monte Carlo method will retain its usefulness even at shallow and intermediate depths, for the calculation of proton transport in inhomogeneous media.

4.2 Radial Distribution from Molière's Theory

The equations are listed here which are used in program MORAD to calculate the radial distribution $f(\rho,s)$ according to the theory of Molière. MORAD is further described in section 6.3.

Consider a proton starting out along the z axis. Let θ be the angular multiple-scattering deflection, i.e., the polar angle specifying the direction of motion after the traversal of a path length s. Molière (1948) introduced a scaled angular variable

$$\vartheta = \frac{\theta}{\chi_c \sqrt{B}} \quad , \tag{17}$$

where χ_c and $\sqrt{B}$ depend on the path length s and the proton energy. In terms of this scaled angle, the Molière multiple-scattering distribution is

$$2\pi F_M(\vartheta)\, \vartheta\, d\vartheta = \vartheta\, d\vartheta \left\{ e^{-\vartheta^2} + \frac{1}{B} f^{(1)}(\vartheta) + \frac{1}{B^2} f^{(2)}(\vartheta) + \ldots \right\} \tag{18}$$

with expansion coefficients

$$f^{(n)}(\vartheta) = \frac{1}{n!} \int_o^\infty y\, dy\, J_o(y\vartheta) \exp(-y^2/4) \left[\frac{y^2}{4} \log \frac{y^2}{4} \right]^n \quad , \tag{19}$$

where J_o denotes a Bessel function.

Let ρ be the radial multiple-scattering deflection, i.e., the distance from the z-axis which the particle has reached after traversing a path length s. It was shown by Molière (1955),* that the distribution of ρ is given by the scaled distribution, eq (18), provided one sets

$$\vartheta = \frac{\rho/s}{x_c \sqrt{B_\rho}} \quad . \tag{20}$$

Here x_c and B_ρ are quantities related to, but slightly different from the corresponding quantities χ_c and B used in the distribution of angular multiple-scattering deflections.

---

*Actually Molière showed that the distribution of x/s (where x is the lateral displacement in the x-direction) has the same functional form as the distribution of the scaled projected multiple scattering deflection. An analogous relation holds between the distribution of ρ/s and the distribution of the scaled spatial multiple-scattering deflection.

The evaluation of x_c and B_ρ must be done for path lengths s in which protons lose a considerable fraction of their energy. In Molière's theory this energy loss can be taken account in the continuous-slowing-down approximation. The proton energy is expressed as a function of the path length traveled, according to the relation

$$s = \int_{T_s}^{T_o} \frac{ds'}{-dE/dx} \quad , \tag{21}$$

where T_o is the initial energy, T_s is the energy after the traversal of a path length s, and where -dE/dx is the stopping power.

For a compound

$$x_c^2 = \sum_j w_j \, x_{cj}^2 \quad , \tag{22}$$

where w_j is the fraction by weight of the j^{th} atomic constituent, and where

$$x_{cj}^2 = \int_o^s h(s') \left[\frac{1-s'}{s}\right]^2 ds' \quad , \tag{23}$$

and

$$h(s) = 4\pi N_a \left[r_e \frac{m}{M} \frac{\tau+1}{\tau(\tau+2)}\right]^2 \frac{Z_j^2}{A_j} \quad . \tag{24}$$

N_a is the Avogadro constant, Z_j and A_j are the atomic number and weight of the j^{th} constituent, r_e is the classical electron radius, m/M is the electron-proton mass ratio, and τ is the proton kinetic energy in units of the proton rest mass Mc^2.

The parameter B_ρ is obtained as the solution of the equation

$$B_\rho - \log B_\rho = \log\left(x_c^2/x_a^2\right) + 1 + 2\gamma \quad , \tag{25}$$

where $\gamma = 0.5772156649...$ is Euler's constant, and the screening parameter x_a is given by

$$\log x_a^2 = \frac{1}{x_c^2} \sum_j w_j \int_o^s h(s') \left[\frac{1-s'}{s}\right]^2 \left[\log G_j(s') - F_j(s')/Z_j\right] ds' \quad , \tag{26}$$

where

$$G_j(s) = \frac{m}{M} \frac{\alpha k_{HF}}{0.88534} \left[1.13 + 3.76 \, (Z_j \alpha/\beta)^2\right] \frac{Z_j^{2/3}}{\tau(\tau+2)} \quad , \tag{27}$$

and α is the fine-structure constant and β is the proton speed in units of the speed of light.

The factor k_{HF}, which is a function of $Z_j \alpha/\beta$, converts Molière's result, obtained with a Thomas-Fermi potential, to a corresponding result for a Hartree-Fock potential. Values of k_{HF}

are given in Berger (1993a). Those for hydrogen are smaller than unity by up to 25 percent, and those for oxygen are larger than unity by up to 12 percent.

The term F_j/Z_j in eq (26) is a correction due to Fano (1956) that takes into account the influence of the electrons of the target atoms. F_j is given by

$$F_j = \log\left[1130\ \beta^2\ Z_j^{-4/3}\ (1-\beta^2)^{-1}\right] - u_j - \beta^2/2 \quad , \tag{28}$$

where the constant u_j has the value -3.6 for hydrogen and -5.1 for oxygen.

The factor $(1\text{-}s'/s)^2$ in eqs (23) and (26) is the analog of the factor $(s\text{-}s')^2$ in eq (15). If this factor were omitted, one would obtain instead of x_c and $B\rho$ the corresponding quantities χ_c and B for the distribution of angular multiple-scattering deflections.

Table 2 lists values of B_ρ, and table 3 values of $x_c\sqrt{B_\rho}$, as functions of z/r_o, for seven energies T_o between 250 MeV and 50 MeV. It can be seen that these quantities are very slowly varying functions of T_o.

The width of the Molière distribution can be characterized as a reduced angle $\vartheta_{1/e}$ at which the distribution has fallen to 1/e of its maximum. Hanson *et al.* (1951) found that $\vartheta_{1/e}$ can be approximated as

$$\vartheta_{1/e} = \sqrt{1\ -\ (1.2/B_\rho)} \quad . \tag{29}$$

A more accurate expression is

$$\vartheta_{1/e} = \frac{0.80209\ -\ 0.58365\ B_\rho\ +\ 0.44997\ B_\rho^2}{1\ -\ 0.32791\ B_\rho\ +\ 0.45000\ B_\rho^2} \quad . \tag{30}$$

Equations (29) and (30) can of course also be applied to B_ρ. The value of $\vartheta_{1/e}$ from eq (30) is smaller than that from eq (29) by 1.49 percent for $B_\rho = 4.5$, and by 0.28 percent for $B_\rho = 10$, and is larger by 0.43 percent for $B_\rho = 20$. The Gaussian approximation to the Molière distribution as function of the reduced angle is

$$2\pi\ f_{MG}(\vartheta) = \left(\vartheta/\vartheta_{1/e}^2\right) \exp\left(-\vartheta^2/\vartheta_{1/e}^2\right) \quad . \tag{31}$$

In figure 8, the Molière distribution is compared with the Gaussian approximation for four values of B_ρ (or B) between 20 and 4.5 (the lowest value for which Molière's theory remains accurate). The peak value of the Gaussian approximation is too high and its tail too low. The greater the value of B_ρ (or B), the better is the Gaussian approximation.

The radial deflection $\rho_{1/e}$ where the radial distribution has fallen to 1/e of its maximum is

$$\rho_{1/e} = s\ x_c\ \sqrt{B_\rho}\ \vartheta_{1/e} \quad . \tag{32}$$

Values of $\rho_{1/e}$ in water were measured by Preston and Koehler (1968). Table 4 lists these results, together with the theoretical values calculated by these authors in the Gaussian approximation, and with values from the Molière theory. A substantial correction was applied by Preston and Koehler to take into account the radial spread of the beam incident on the scattering target. With this correction, there is good agreement between the measured and calculated results.

4.3 Database of Radial Distributions from PTRAN

The results of calculations with PTRAN, for energies T_o = 250, 200, 160, 130, 100, 70 and 50 MeV, obtained with a sample of 1 million proton histories in each case, were used to prepare a database of the scaled radial distribution $2\pi\rho$ zf(ρ,z) as function of ρ/z. This was done for depths at depths at which Molière's theory can no longer be used. The database is used by a program called PTRAD which generates, by linear interpolation with respect to log T_o, radial distributions f(ρ,z) at scaled depths z/r_o = 0.985, 0.99, 0.995, 1.0, 1.005, 1.01, 1.015, 1.020 and 1.025 r_o. More information about PTRAD is given in section 6.4.

5. Reduction Factors and Absorbed-Dose Distributions

This section contains illustrative results pertaining to an incident 160-MeV proton beam (r_o = 17.65 cm of water). The reduction factors and absorbed-dose distributions were obtained with depth-dose distributions dD/dz from program PTPOL, and with radial distributions f(ρ,z) from programs MORAD and PTRAD. The reduction factors for circular fields were generated with program FCIR, and those for rectangular fields with program FREC. Unless the contrary is stated, the density of pencil beams is assumed to constant over the field area. Absorbed-dose values are given in units of MeV/g, normalized to one incident proton per cm^2.

5.1 Circular Fields

Figures 9a-d show the reduction factors [defined by eqs (5a,b)] at depths z = 0.1 r_o, 0.5 r_o and 0.99 r_o, as functions of the distance r from the center of circular fields with radii R = 8, 4, 2 and 1 mm, respectively. Figure 10 shows the reduction factors as function of depth along the central axis, again for field radii R = 8, 4, 2, and 1 mm.

Central-axis absorbed-dose distributions for field radii R = 4, 2 and 1 mm are plotted in figure 11. Also plotted for comparison is the absorbed dose from an unbounded field. This figure shows how the reduction of the field radius reduces the magnitude of the Bragg peak, in agreement with earlier findings of Preston and Koehler (1968).

Figures 12a,b,c shows absorbed dose distributions as functions of depth, along lines parallel to the z axis, for various distances r between these lines and the z axis, for circular fields with radii R = 4, 2 and 1 mm, respectively.

Figure 13 shows the average absorbed dose as a function of depth, for circular fields with radius R = 8, 4, 2 and 1 mm. The absorbed dose is averaged over thin disks of radius R centered on the z axis.

Figures 14a,b,c show reduction factors at depths $z = 0.1\ r_o$, $0.5\ r_o$, and $0.9\ r_o$ for a circular field (radius $R = 4$ mm) calculated for a field density that is not constant but is given by $n(r) = \exp(-Qr^2)$, where r is the distance from the center of the field. These results were calculated from eqs (7a,b), for parameter values $Q = 2$, 1, and 0 (constant density).

5.2 Rectangular Fields

Figures 15a,b,c compare reduction factors for circular fields with reduction factors for square fields, at depths $z = 0.1\ r_o$, $0.5\ r_o$ and $0.9\ r_o$, respectively. The circular fields and square fields have the same area (64 mm^2). Two sets of curves are shown for the square field. In one case (indicated as 0 deg), the reduction factors are plotted along a line that starts at the center of the field and is parallel to an edge of the square. In the other case (indicated as 45 deg) the line that starts at the center of the field and passes though a corner of the square.

Figure 16 shows the absorbed dose along the central axis, for square fields with sides equal to 8, 4, 2 or 1 mm. Figure 17 shows similar results for a field in the form of a slit, i.e., with one side of the rectangular field effectively unbounded, and with the other side having a width equal to 8, 4, 2 or 1 mm.

Figures 18a,b,c show reduction factors and absorbed-dose distributions for a rectangular 1 mm × 10 mm field. Figure 18a shows this quantities as a function of depth, along the central field axis. Figure 18b shown them at a depth $z = 0.5\ r_o$, as a function of radial distance r from the field axis, where the radial distance is measured along a line that goes through the center, and is parallel to the long side, of the rectangle. Figure 18c is similar to 18b, except that the radial distance is measured along a line that is parallel to the sort side of the rectangle.

6. Computer Programs

The program files, data file and sample output files supplied with this report are stored on a single 3.5" 1.44-Mb disk. The program files include Fortran source code as well as executable code for use with an IBM-compatible personal computer. The source code, data files, and sample output files are written in ASCII format, and can be transferred to other types of computers. A listing of all files can be found in Appendix 1, and the source code for all the Fortran programs in Appendix 2.

The programs prompt the user to supply input data and/or to indicate the names of files which contain the required input data. The output files are supplied with headings and descriptions, so that they are practically self-explanatory.

6.1 Program PTPOL

PTPOL calculates the energy deposition distribution dD/dz in water for a monoenergetic proton beam. The user must supply the beam energy (in MeV) and the name of the output file. If the desired energy is smaller than 50 MeV or greater than 250 MeV, the program halts and tells the user that the energy is out of bounds. The output file includes a list of depths, the values of dD/dz at these depths, in units of MeV/g, and the corresponding relative depth-dose

values (with unit peak height). Also included in the output are the depth at which the peak occurs, and the peak value of dD/dz. The sample output file PTPOL.160, shown in table 5, is for a beam energy of 160 MeV.

6.2 Program PTGPOL

PTGPOL calculates the energy deposition distribution dD/dz in water for a proton beam with a Gaussian energy spectrum. The user must specify the average energy T_{av} and the standard deviation σ_T of the spectrum. The latter must be entered in terms of a relative standard deviation $P = 100\ \sigma_T/T_{av}$. The Gaussian distribution is truncated at the energies $T_{1,2} = T_{av} \pm q\,\sigma_T$. The cut-off parameter q (recommended value 4) must be specified by the user. If either T_1 or T_2 are smaller than 50 MeV or greater than 250 MeV, the program halts and informs the user that these energies are out of bounds.

The set of depths at which dD/dz is to be evaluated must be supplied in a previously-prepared file. The first entry in this file must be the number of depths (no greater than 201), and the other entries must be depth-values expressed in units of the CSDA range at energy T_{av}. A default file ZRLIST, supplied with the program, has 52 depth-values.

The output file from PTGPOL contains similar information as the output file from PTPOL, and in addition lists the range at energy T_{av}, and the parameters of the Gaussian beam spectrum. A sample output file PTGPOL.OUT, shown in table 6, pertains to a beam with a mean energy of 160 MeV and a relative standard deviation of P = 1 percent.

6.3 Program MORAD

MORAD calculates the radial distribution $f(\rho,s)$ according to the theory of Molière, using the equations listed in section 4.2. In response to prompts, the user must specify a) the beam energy (in MeV), b) a set of path lengths, and c) the set of radial distances at which the radial distributions are to be evaluated for each path length.

The path lengths (in units of the CSDA range) can be read from a previously prepared file. The first line of such file should contain NMAX, the number of path lengths, and subsequent lines should contain the path lengths, separated by blanks or other delimeter. Alternatively, the path lengths can be specified in terms of a maximum value ZRMAX and a number NMAX, from which MORAD computes the path lengths n(ZRMAX/NMAX), n = 1, 2, ..., NMAX. It is also possible to specify that ZRMAX should have the default value 0.98, and NMAX the default value 98.

The Molière distribution, as a function of the reduced angle ϑ, extends from zero to infinity. This is unrealistic and is due to an approximation made in the theory. In MORAD the distribution is truncated at $\vartheta_{max} = 10$, and is then renormalized to unity. Prior to renormalization, the integral over the distribution up to ϑ_{max} is smaller than unity by a fraction of a percent, and is printed out as part of the output of MORAD. The corresponding truncation value of the radial deflection is

$$\rho_{max} = s\, x_c \sqrt{B_\rho}\ \vartheta_{max} \quad . \tag{33}$$

The radial distribution is tabulated by MORAD at KMAX equidistant value of between 0 and ρ_{max}. KMAX is an input parameter. Table 7 shows an excerpt from a sample output file MORAD.160 for 98 depths (path lengths), and table 8 an output file MORAD160.050 for a single depth ($z = 0.5\ r_o$).

6.4 Program PTRAD

PTRAD calculates the radial distribution $f(\rho,z)$ using Monte Carlo results from PTRAN stored in a database prepared as described in section 4.3. There are 9 files in this database, called RADF.n, n = 32, 33,...,40, which contain scaled radial distributions at 9 depths ($z = 0.985$, 0.99, 0.995, 1.0, 1.005, 1.01, 1.015, 1.020 and 1.025 r_o). The distributions are generated at 201 equidistant values of ρ which are listed in the output file. In order to run PTRAD, the user merely has to specify the beam energy, in MeV, and the name of the output file. A sample output file PTRAD.160 is shown in table 9.

6.5 Program FCIR

FCIR uses the equations given in section 2.1 to calculate reduction factors and absorbed-dose values as functions of the depth z and of the radial distance r from the center of a circular field. The user must specify the field radius, in cm, and the set of distances r for which the calculation is to be done. The radial distances can be read from a prepared file, entered from the keyboard, or specified in terms of a maximum radial distance r_{max} and a number LMAX of radial distances. With the third choice, FCIR computes a set of LMAX+1 distances $\ell(r_{max}/LMAX)\cdot\ell$, $\ell = 0, 1, 2, \ldots,$ LMAX. If LMAX is 1, calculations are made only for $r = 0$, along the central axis of the field.

The user is queried whether the requested path lengths are all smaller than 0.98 r_o. If the answer is yes, input has to be supplied only from a file generated by MORAD. If the answer is no, input must in addition be supplied from a file generated by PTRAD. The beam energy and path lengths, and the radial distributions for pencil beams, are supplied to FCIR via the files from MORAD and PTRAD. Finally, the user must supply the name of the output file.

Sample output files FCIR.1 and FCIR.2 , for a circular field with a radius of 2 mm, are shown in tables 10 and 11, respectively. FCIR.1 contains reduction factors and absorbed-dose values, as a function of depth, along the central axis. FCIR.2 contains reduction factors and absorbed-dose values as a function of the radial distance r, at a depth $z = 0.5\ r_o$.

6.6 Programs FREC, FREC1, and FREC2

FREC uses the equations given in section 2.2 to calculate reduction factors and absorbed-dose values as functions of the depth z and of the distance r from the center of a rectangular field. The field is assumed to extend from -A to A in x, and from -B to B in y, with the origin at the center of the rectangular field. The user must specify the parameters A and B, and also

the angle α with respect to the x-axis of a line starting at the center of the field along which reduction factors and absorbed-dose values are to be calculated. The user can also indicate that the line should pass through a corner of the field, in which case FREC computes α.

The remaining input data, including the radial distances r along the chosen line, and the input files from MORAD and PTRAD, with beam energy, path lengths and radial distributions from pencil beams, must be supplied in the same manner as described in section 6.5 for FCIR.

Sample output files FREC.1, FREC.2A and FREC.2B are shown in tables 12, 13, and 14, which pertain to a rectangular 1 mm $\times$ 10 mm field. FREC.1 contains reduction factors and absorbed-dose values as a function of depth, along the central axis. FREC.2A and FREC.2B contain reduction factors and absorbed-dose values at a depth 0.5 r_o, along lines that pass through the center of the field and are parallel to the short, respectively, the long side of the rectangular field.

Program FREC1 is similar to FREC, but provides reduction factors and absorbed-dose values not along a specified line, but for a set of specified points (x,y). Table 15 shows a sample output file for a rectangular 5 mm $\times$ 2 mm field.

Program FREC2 performs the same function as FREC1, but evaluates eq (1) with a double numerical quadrature, with respect to x from -A to A, and with respect to y from y from -B to B. The integration limits are specified by the external functions FUN1 and FUN2. The pencil-beam density, n(x,y) = 1, is specified by the external function FUN3. Program FREC2 could easily be modified so as to apply to a field of different size and shape, by changing the functions FUN1 and FUN2. Any pencil-beam density n(x,y) could be used by the choice of an appropriate function FUN3.

6.7 Programs AXPLOT and RADPLOT

AXPLOT plots reduction factors and absorbed-dose values along the central axis of a circular or rectangular field, using input files generated by FCIR or FREC. RADPLOT plots reduction factors and absorbed-dose values at a fixed depth, as functions of the radial distance from the center of a circular or rectangular field. These programs must be compiled and linked with a library from a graphics program by Kahaner and Anderson (1990). Figure 18 of this report was produced with AXPLOT, and figures 19 and 20 with RADPLOT.

References

Berger, M. J. (1992). ESTAR, PSTAR and ASTAR: Computer programs for calculating stopping-power and range tables for electrons, protons and helium ions, National Institute of Standards and Technology Report NISTIR 1499.

Berger, M. J. (1993a). Proton Monte Carlo transport program PTRAN, National Institute of Standards and Technology Report NSTIR 5113.

Berger, M. J. (1993b). Penetration of proton beams through water. I. Depth-dose distributions, spectra and LET distributions, National Institute of Standards Report NISTIR 5226.

Bethe, H. A. and Ashkin, J. (1953). Penetration of beta-rays through matter, p. 252, *Experimental Nuclear Physics*, Vol. I, Ed. E. Segre, Wiley, N.Y.

Carlsson, J. and Rosander, K. (1973). Effects of multiple scattering on proton beams in radiotherapy, Phys. Med. Biol. **18**, 633.

Fano, U. (1956). Inelastic collisions and the Molière theory of multiple scattering, Phys. Rev. **93**, 117.

Hanson, A. O., Lanzl, L. H., Lyman, E. M. and Scott, M. B. (1951). Measurement of multiple scattering of 15.7-MeV electrons, Phys. Rev. **84**, 634.

Kahaner, D. K. and Anderson, W. E. (1990). Volksgrapher: A Fortran plotting package user;s guide, version 3.0, National Institute of Standards and Technology Report NISTIR 90-4238.

Meredith, W. J. and Neary, G. J. (1944). The production of isodose curves and the calculation of energy absorption from standard depth dose data, Br. J. Radiol. **17**, 75.

Molière, G. (1948). Theorie der Streuung schneller geladener Teilchen. II. Mehrfach-und Vielfachstreuung. Z. f. Naturforschung, **3a**, 78.

Molière, G. (1955). Theorie der Streuung schneller geladener Teilchen. III. Die Vielfachstreuung von Bahnspuren unter Berücksichtigung der statistischen Kupplung, Z. f. Naturforschung, **10a**, 177.

Preston, W. M. and Koehler, A. M. (1968). The effects of scattering on small proton beams, Harvard Cyclotron Laboratory Internal Report.

Seltzer, S. M. (1993). An assessment of the role of charged secondaries from nonelastic nuclear interactions by therapy proton beams in water, National Institute of Standards and Technology Report NISTIR 5221.

Table 1. Stopping powers and CSDA ranges for protons in water. Calculated with program PSTAR (Berger, 1992).

T (MeV)	dE/dx (MeV cm^2/g)	r_o g/cm^2
250.0	3.910	37.94
237.5	4.032	34.79
225.0	4.169	31.74
212.5	4.320	28.80
200.0	4.491	25.96
190.0	4.642	23.77
180.0	4.810	21.65
170.0	4.997	19.614
160.0	5.207	17.653
152.5	5.381	16.237
145.0	5.573	14.867
137.5	5.784	13.546
130.0	6.018	12.275
122.5	6.280	11.055
115.0	6.574	9.888
107.5	6.907	8.775
100.0	7.286	7.718
92.5	7.723	6.718
85.0	8.233	5.777
77.5	8.834	4.897
70.0	9.555	4.080
65.0	10.121	3.572
60.0	10.775	3.093
55.0	11.539	2.644
50.0	12.443	2.227

Table 2. Parameter B_ρ in Molière's radial distribution (for water), as a function of s/r_o, where s is the path length and r_o is the CSDA range path length, for various values of the initial proton energy T_o.

T_o (MeV)	250.0	200.0	160.0	130.0	100.0	70.0	50.0
r_o (g/cm^2)	37.94	25.95	17.65	12.28	7.718	4.080	2.227
s/r_o							
0.00006	6.284	5.979	5.674	5.391	5.032	4.536	4.055
0.00008	6.624	6.322	6.022	5.742	5.388	4.901	4.431
0.00010	6.886	6.586	6.288	6.011	5.660	5.180	4.717
0.00015	7.358	7.061	6.767	6.494	6.148	5.677	5.225
0.00020	7.690	7.395	7.103	6.832	6.490	6.024	5.578
0.00030	8.154	7.862	7.573	7.304	6.967	6.506	6.067
0.0004	8.481	8.191	7.903	7.637	7.301	6.845	6.410
0.0005	8.733	8.444	8.158	7.893	7.559	7.105	6.674
0.0006	8.939	8.651	8.365	8.101	7.769	7.317	6.887
0.0008	9.262	8.975	8.691	8.429	8.098	7.649	7.223
0.0010	9.512	9.226	8.943	8.681	8.352	7.905	7.481
0.0015	9.964	9.680	9.398	9.138	8.811	8.368	7.947
0.002	10.283	10.000	9.720	9.461	9.135	8.694	8.275
0.003	10.732	10.450	10.171	9.913	9.589	9.150	8.735
0.004	11.049	10.768	10.489	10.233	9.910	9.473	9.059
0.005	11.294	11.014	10.736	10.480	10.158	9.722	9.310
0.006	11.494	11.214	10.937	10.681	10.360	9.926	9.514
0.008	11.809	11.530	11.254	10.999	10.679	10.245	9.836
0.010	12.053	11.775	11.499	11.245	10.925	10.493	10.084
0.015	12.496	12.218	11.943	11.690	11.372	10.941	10.535
0.020	12.809	12.532	12.258	12.006	11.688	11.259	10.853
0.030	13.251	12.975	12.702	12.450	12.133	11.706	11.302
0.040	13.564	13.289	13.016	12.765	12.449	12.022	11.619
0.050	13.807	13.532	13.260	13.009	12.694	12.268	11.866
0.06	14.006	13.731	13.460	13.209	12.895	12.469	12.068
0.08	14.320	14.046	13.775	13.525	13.211	12.787	12.386
0.10	14.565	14.291	14.021	13.771	13.458	13.034	12.634
0.15	15.013	14.740	14.470	14.221	13.909	13.486	13.088
0.20	15.334	15.061	14.792	14.544	14.232	13.811	13.413
0.30	15.795	15.524	15.256	15.008	14.698	14.278	13.881
0.4	16.132	15.862	15.595	15.348	15.039	14.620	14.224
0.5	16.404	16.135	15.868	15.623	15.314	14.896	14.501
0.6	16.636	16.368	16.103	15.858	15.550	15.133	14.738
0.8	17.040	16.774	16.511	16.267	15.961	15.546	15.152
0.9	17.234	16.970	16.708	16.466	16.160	15.746	15.352
0.99999	17.461	17.199	16.939	16.698	16.394	15.980	15.587

Table 3. Scale parameter $x_c \sqrt{B_\rho}$ in Molière's radial distribution (for water) as function of s/r_o, where s is the path length and r_o is the CSDA range, for various values of the initial proton energy T_o.

T_o (MeV)	250.0	200.0	160.0	130.0	100.0	70.0	50.0
r_o (g/cm^2)	37.94	25.95	17.65	12.28	7.718	4.080	2.227
s/r_o							
0.00006	1.511	1.495	1.477	1.458	1.433	1.394	1.350
0.00008	1.551	1.537	1.521	1.505	1.483	1.449	1.411
0.00010	1.581	1.569	1.554	1.540	1.520	1.489	1.456
0.00015	1.635	1.624	1.613	1.601	1.584	1.559	1.532
0.00020	1.671	1.662	1.652	1.642	1.627	1.606	1.583
0.00030	1.721	1.714	1.706	1.698	1.686	1.669	1.651
0.0004	1.755	1.750	1.743	1.736	1.726	1.712	1.697
0.0005	1.781	1.776	1.771	1.765	1.756	1.744	1.732
0.0006	1.802	1.798	1.793	1.788	1.781	1.770	1.759
0.0008	1.834	1.832	1.828	1.824	1.818	1.810	1.801
0.0010	1.859	1.857	1.854	1.851	1.846	1.840	1.833
0.0015	1.903	1.902	1.901	1.899	1.897	1.893	1.890
0.0020	1.933	1.934	1.933	1.932	1.931	1.930	1.929
0.0030	1.975	1.977	1.978	1.978	1.979	1.980	1.982
0.0040	2.004	2.007	2.009	2.010	2.012	2.015	2.018
0.0050	2.027	2.030	2.033	2.035	2.037	2.042	2.046
0.0060	2.045	2.049	2.052	2.054	2.058	2.063	2.069
0.0080	2.073	2.078	2.082	2.085	2.090	2.097	2.104
0.010	2.095	2.100	2.105	2.109	2.114	2.122	2.131
0.010	2.135	2.141	2.147	2.152	2.159	2.169	2.180
0.020	2.163	2.170	2.176	2.182	2.190	2.201	2.214
0.030	2.203	2.211	2.218	2.225	2.234	2.248	2.262
0.040	2.232	2.240	2.249	2.256	2.266	2.281	2.297
0.050	2.255	2.264	2.273	2.281	2.292	2.307	2.325
0.06	2.274	2.284	2.293	2.302	2.313	2.330	2.348
0.08	2.306	2.316	2.326	2.335	2.348	2.366	2.385
0.10	2.332	2.343	2.354	2.363	2.376	2.395	2.416
0.15	2.385	2.397	2.408	2.419	2.433	2.454	2.477
0.20	2.428	2.441	2.453	2.464	2.480	2.502	2.526
0.30	2.503	2.517	2.530	2.543	2.560	2.585	2.611
0.4	2.573	2.588	2.602	2.615	2.633	2.660	2.688
0.5	2.643	2.658	2.673	2.688	2.707	2.735	2.765
0.6	2.716	2.732	2.748	2.763	2.783	2.813	2.845
0.8	2.885	2.903	2.921	2.938	2.960	2.994	3.030
0.9	2.993	3.012	3.031	3.049	3.073	3.110	3.148
0.99999	3.143	3.163	3.184	3.204	3.230	3.271	3.313

Table 4. Comparison of the calculated radial spread of proton beams in water with experimental results of Preston and Koehler (1968). The radial spread is defined as the radial distance from the beam axis at which intensity has fallen to a fraction 1/e of the peak intensity.

Beam Energy	Depth	Radial Spread (mm), $\rho_{1/e}$				
(MeV)	(cm)	ρ_m	ρ_a	ρ_c	ρ_{PK}	ρ_M
127	5.7	1.90	1.51	1.15 ± 0.15	1.08	1.02
127	8.7	2.70	1.60	2.18 ± 0.10	2.17	2.07
127	11.4	3.85	1.68	3.46 ± 0.09	3.50	3.40
134	12.4	3.80	0.94	3.68 ± 0.10	3.69	3.65

ρ_m measured

ρ_a measured in absence of scattering material

$\rho_c = (\rho_m^2 - \rho_a^2)^{1/2}$ corrected experimental value

ρ_{PK} calculated by Preston and Koehler, using Gaussian approximation

ρ_M calculated from Molière's theory.

Table 5. Output file from program PTPOL.

```
Program PTPOL, output file PTPOL.160

  EBEAM = average beam energy, MeV
  RANGE = CSDA range at energy EBEAM, g/cm²
     ZM = depth (in units of RANGE) at which energy-deposition curve peaks
   DMAX = energy deposition per unit depth at peak, MeV cm²/g
   NMAX = number of depths

      EBEAM        RANGE         ZM          DMAX        NMAX
      152.00      16.1474      0.9903      31.2816          44

Depths, in units of RANGE

     0.000     0.100     0.200     0.300     0.400     0.450
     0.500     0.550     0.600     0.650     0.700     0.720
     0.740     0.760     0.780     0.800     0.820     0.840
     0.860     0.880     0.900     0.910     0.920     0.930
     0.940     0.950     0.955     0.960     0.965     0.970
     0.975     0.980     0.985     0.990     0.995     1.000
     1.005     1.010     1.015     1.020     1.025     1.030
     1.035     1.040

dD/dz, energy-deposition distribution, MeV cm²/g, per incident proton

     6.379316    6.443711    6.545821    6.693469    6.904040    7.041533
     7.207235    7.408860    7.656943    7.967148    8.364057    8.555535
     8.771009    9.015185    9.294683    9.617826    9.996713   10.449075
    10.998257   11.686963   12.582426   13.143499   13.813137   14.630116
    15.659860   17.021864   17.898077   18.979285   20.356806   22.178840
    24.537248   27.325106   29.988105   31.277747   29.860523   25.003223
    17.941608   10.807292    5.297353    2.073649    0.639564    0.164671
     0.031402    0.004889

Relative energy-deposition distribution (peak value unity)

     0.203932    0.205991    0.209255    0.213975    0.220706    0.225102
     0.230399    0.236844    0.244775    0.254692    0.267380    0.273501
     0.280389    0.288195    0.297130    0.307460    0.319572    0.334033
     0.351589    0.373606    0.402231    0.420168    0.441574    0.467691
     0.500610    0.544150    0.572161    0.606724    0.650761    0.709007
     0.784400    0.873521    0.958651    0.999878    0.954573    0.799296
     0.573552    0.345484    0.169344    0.066290    0.020445    0.005264
     0.001004    0.000156
```

Table 6. Output file from program PTGPOL.

```
Program PTGPOL, output file PTGPOL.160
List of depths from file ZRFILE

       EAV = average beam energy, MeV
     SIGMA = standard deviation of beam spectrum, MeV
         P = 100*SIGMA/EAV, relative standard deviation
       CUT = cut-off for Gaussian beam (in units of SIGMA)
     RGREF = CSDA range at energy EAV
        ZM = depth (in units of RANGE) at which energy-deposition curve peaks
      DMAX = energy deposition per unit depth at peak, MeV cm^2/g
     NRMAX = number of depths

    EAV     SIGMA      P      CUT      RGREF       ZM       DMAX      NRMAX
  160.00     1.60    1.00     4.00    17.6500    0.9813   22.5506      52

Depths, in units of RGREF

     0.000000    0.100000    0.200000    0.300000    0.400000    0.450000
     0.500000    0.550000    0.600000    0.650000    0.700000    0.720000
     0.740000    0.760000    0.780000    0.800000    0.820000    0.840000
     0.860000    0.880000    0.900000    0.910000    0.920000    0.930000
     0.940000    0.950000    0.955000    0.960000    0.965000    0.970000
     0.975000    0.980000    0.985000    0.990000    0.995000    1.000000
     1.005000    1.010000    1.015000    1.020000    1.025000    1.030000
     1.035000    1.040000    1.045000    1.050000    1.055000    1.060000
     1.065000    1.070000    1.075000    1.080000

dD/dz, energy-deposition distribution, MeV cm^2/g, per incident proton

     6.245952    6.290157    6.370409    6.493944    6.677337    6.799634
     6.948656    7.131837    7.359206    7.645930    8.015577    8.194778
     8.396866    8.626770    8.890688    9.197047    9.557862    9.990335
    10.521089   11.192994   12.083185   12.654453   13.354994   14.249679
    15.445681   17.075772   18.072508   19.162411   20.280644   21.318145
    22.125494   22.531537   22.376124   21.549951   20.029351   17.893136
    15.313623   12.523026    9.765560    7.250373    5.118912    3.433616
     2.186644    1.321339    0.757280    0.411389    0.211664    0.102985
     0.047249    0.020323    0.008121    0.002974

Relative energy-deposition distribution (peak value unity)

     0.276974    0.278935    0.282493    0.287972    0.296104    0.301527
     0.308136    0.316259    0.326341    0.339056    0.355448    0.363394
     0.372356    0.382551    0.394254    0.407840    0.423840    0.443018
     0.466554    0.496349    0.535824    0.561157    0.592222    0.631897
     0.684933    0.757219    0.801419    0.849750    0.899338    0.945345
     0.981147    0.999153    0.992261    0.955625    0.888194    0.793465
     0.679077    0.555329    0.433050    0.321515    0.226996    0.152262
     0.096966    0.058594    0.033581    0.018243    0.009386    0.004567
     0.002095    0.000901    0.000360    0.000132
```

Table 7. Excerpt from output file MORAD.160 from program MORAD.

```
Program MORAD, output file MORAD.160

   98 depths
  201 radial distances

        TIN   =  energy of incident proton beam, MeV
       RGIN   =  CSDA range at energy TIN, g/cm2
         ZR   =  depth, in units of RGIN
       RMAX   =  largest radial distance
        SUM   =  cumulative integral of Molière distribution up to RMAX

         TIN            RGIN            ZR            RMAX           SUM
  160.000000       17.653381       0.010000       0.003716       0.999108
```

Radial distances, ρ, cm

0.00000E+00	1.85799E-05	3.71597E-05	5.57396E-05	7.43194E-05	9.28993E-05	1.11479E-04	1.30059E-04
1.48639E-04	1.67219E-04	1.85799E-04	2.04378E-04	2.22958E-04	2.41538E-04	2.60118E-04	2.78698E-04
2.97278E-04	3.15858E-04	3.34437E-04	3.53017E-04	3.71597E-04	3.90177E-04	4.08757E-04	4.27337E-04
4.45917E-04	4.64496E-04	4.83076E-04	5.01656E-04	5.20236E-04	5.38816E-04	5.57396E-04	5.75976E-04
5.94555E-04	6.13135E-04	6.31715E-04	6.50295E-04	6.68875E-04	6.87455E-04	7.06035E-04	7.24615E-04
7.43194E-04	7.61774E-04	7.80354E-04	7.98934E-04	8.17514E-04	8.36094E-04	8.54674E-04	8.73253E-04
8.91833E-04	9.10413E-04	9.28993E-04	9.47573E-04	9.66153E-04	9.84733E-04	1.00331E-03	1.02189E-03
1.04047E-03	1.05905E-03	1.07763E-03	1.09621E-03	1.11479E-03	1.13337E-03	1.15195E-03	1.17053E-03
1.18911E-03	1.20769E-03	1.22627E-03	1.24485E-03	1.26343E-03	1.28201E-03	1.30059E-03	1.31917E-03
1.33775E-03	1.35633E-03	1.37491E-03	1.39349E-03	1.41207E-03	1.43065E-03	1.44923E-03	1.46781E-03
1.48639E-03	1.50497E-03	1.52355E-03	1.54213E-03	1.56071E-03	1.57929E-03	1.59787E-03	1.61645E-03
1.63503E-03	1.65361E-03	1.67219E-03	1.69077E-03	1.70935E-03	1.72793E-03	1.74651E-03	1.76509E-03
1.78367E-03	1.80225E-03	1.82083E-03	1.83941E-03	1.85799E-03	1.87657E-03	1.89515E-03	1.91373E-03
1.93231E-03	1.95089E-03	1.96947E-03	1.98804E-03	2.00662E-03	2.02520E-03	2.04378E-03	2.06236E-03
2.08094E-03	2.09952E-03	2.11810E-03	2.13668E-03	2.15526E-03	2.17384E-03	2.19242E-03	2.21100E-03
2.22958E-03	2.24816E-03	2.26674E-03	2.28532E-03	2.30390E-03	2.32248E-03	2.34106E-03	2.35964E-03
2.37822E-03	2.39680E-03	2.41538E-03	2.43396E-03	2.45254E-03	2.47112E-03	2.48970E-03	2.50828E-03
2.52686E-03	2.54544E-03	2.56402E-03	2.58260E-03	2.60118E-03	2.61976E-03	2.63834E-03	2.65692E-03
2.67550E-03	2.69408E-03	2.71266E-03	2.73124E-03	2.74982E-03	2.76840E-03	2.78698E-03	2.80556E-03
2.82414E-03	2.84272E-03	2.86130E-03	2.87988E-03	2.89846E-03	2.91704E-03	2.93562E-03	2.95420E-03
2.97278E-03	2.99136E-03	3.00994E-03	3.02852E-03	3.04710E-03	3.06568E-03	3.08426E-03	3.10284E-03
3.12142E-03	3.14000E-03	3.15858E-03	3.17716E-03	3.19574E-03	3.21432E-03	3.23290E-03	3.25148E-03
3.27006E-03	3.28864E-03	3.30721E-03	3.32579E-03	3.34437E-03	3.36295E-03	3.38153E-03	3.40011E-03
3.41869E-03	3.43727E-03	3.45585E-03	3.47443E-03	3.49301E-03	3.51159E-03	3.53017E-03	3.54875E-03
3.56733E-03	3.58591E-03	3.60449E-03	3.62307E-03	3.64165E-03	3.66023E-03	3.67881E-03	3.69739E-03
3.71597E-03							

Radial distribution, f(ρ,z), cm^{-2}

2.41382E+06	2.40689E+06	2.38624E+06	2.35222E+06	2.30544E+06	2.24671E+06	2.17705E+06	2.09763E+06
2.00973E+06	1.91476E+06	1.81415E+06	1.70937E+06	1.60188E+06	1.49306E+06	1.38425E+06	1.27665E+06
1.17136E+06	1.06934E+06	9.71393E+05	8.78184E+05	7.90219E+05	7.07863E+05	6.31341E+05	5.60757E+05
4.96100E+05	4.37265E+05	3.84066E+05	3.36252E+05	2.93522E+05	2.55541E+05	2.21951E+05	1.92384E+05
1.66472E+05	1.43854E+05	1.24181E+05	1.07126E+05	9.23815E+04	7.96666E+04	6.87240E+04	5.93224E+04
5.12552E+04	4.43393E+04	3.84139E+04	3.33382E+04	2.89903E+04	2.52645E+04	2.20699E+04	1.93285E+04
1.69736E+04	1.49480E+04	1.32033E+04	1.16981E+04	1.03971E+04	9.27032E+03	8.29237E+03	7.44156E+03
6.69948E+03	6.05048E+03	5.48126E+03	4.98051E+03	4.53862E+03	4.14741E+03	3.79995E+03	3.49032E+03
3.21352E+03	2.96526E+03	2.74190E+03	2.54033E+03	2.35791E+03	2.19237E+03	2.04175E+03	1.90437E+03
1.77879E+03	1.66375E+03	1.55816E+03	1.46105E+03	1.37161E+03	1.28908E+03	1.21282E+03	1.14226E+03
1.07687E+03	1.01620E+03	9.59841E+02	9.07423E+02	8.58615E+02	8.13118E+02	7.70663E+02	7.31004E+02
6.93920E+02	6.59210E+02	6.26691E+02	5.96196E+02	5.67573E+02	5.40684E+02	5.15402E+02	4.91611E+02
4.69204E+02	4.48086E+02	4.28165E+02	4.09361E+02	3.91597E+02	3.74804E+02	3.58917E+02	3.43879E+02
3.29633E+02	3.16130E+02	3.03323E+02	2.91169E+02	2.79627E+02	2.68660E+02	2.58233E+02	2.48315E+02
2.38876E+02	2.29887E+02	2.21323E+02	2.13160E+02	2.05375E+02	1.97946E+02	1.90855E+02	1.84082E+02
1.77611E+02	1.71426E+02	1.65510E+02	1.59850E+02	1.54434E+02	1.49247E+02	1.44278E+02	1.39517E+02
1.34953E+02	1.30576E+02	1.26377E+02	1.22346E+02	1.18477E+02	1.14762E+02	1.11192E+02	1.07761E+02
1.04463E+02	1.01291E+02	9.82393E+01	9.53031E+01	9.24767E+01	8.97552E+01	8.71340E+01	8.46085E+01
8.21747E+01	7.98284E+01	7.75660E+01	7.53838E+01	7.32784E+01	7.12465E+01	6.92852E+01	6.73913E+01
6.55622E+01	6.37952E+01	6.20878E+01	6.04375E+01	5.88421E+01	5.72993E+01	5.58071E+01	5.43635E+01
5.29665E+01	5.16145E+01	5.03056E+01	4.90382E+01	4.78107E+01	4.66216E+01	4.54695E+01	4.43529E+01
4.32706E+01	4.22214E+01	4.12039E+01	4.02171E+01	3.92598E+01	3.83310E+01	3.74297E+01	3.65548E+01
3.57055E+01	3.48808E+01	3.40799E+01	3.33021E+01	3.25464E+01	3.18121E+01	3.10985E+01	3.04049E+01
2.97307E+01	2.90751E+01	2.84375E+01	2.78175E+01	2.72143E+01	2.66275E+01	2.60565E+01	2.55007E+01
2.49598E+01	2.44332E+01	2.39205E+01	2.34212E+01	2.29350E+01	2.24613E+01	2.19999E+01	2.15503E+01
2.11121E+01							

Table 8. Output file MORAD160.050 from program MORAD.

```
Program MORAD, output file MORAD160.050

    0 depths
  201 radial distances

        TIN  =  energy of incident proton beam, MeV
       RGIN  =  CSDA range at energy TIN, g/cm^2
         ZR  =  depth, in units of RGIN
       RMAX  =  largest radial distance
        SUM  =  cumulative integral of Molière distribution up to RMAX

        TIN          RGIN          ZR          RMAX          SUM
  160.000000     17.653381     0.500000     1.668557     0.999355

Radial distances, ρ, cm

0.00000E+00  8.34279E-03  1.66856E-02  2.50284E-02  3.33711E-02  4.17139E-02  5.00567E-02  5.83995E-02
6.67423E-02  7.50851E-02  8.34279E-02  9.17707E-02  1.00113E-01  1.08456E-01  1.16799E-01  1.25142E-01
1.33485E-01  1.41827E-01  1.50170E-01  1.58513E-01  1.66856E-01  1.75199E-01  1.83541E-01  1.91884E-01
2.00227E-01  2.08570E-01  2.16912E-01  2.25255E-01  2.33598E-01  2.41941E-01  2.50284E-01  2.58626E-01
2.66969E-01  2.75312E-01  2.83655E-01  2.91998E-01  3.00340E-01  3.08683E-01  3.17026E-01  3.25369E-01
3.33711E-01  3.42054E-01  3.50397E-01  3.58740E-01  3.67083E-01  3.75425E-01  3.83768E-01  3.92111E-01
4.00454E-01  4.08797E-01  4.17139E-01  4.25482E-01  4.33825E-01  4.42168E-01  4.50511E-01  4.58853E-01
4.67196E-01  4.75539E-01  4.83882E-01  4.92224E-01  5.00567E-01  5.08910E-01  5.17253E-01  5.25596E-01
5.33938E-01  5.42281E-01  5.50624E-01  5.58967E-01  5.67310E-01  5.75652E-01  5.83995E-01  5.92338E-01
6.00681E-01  6.09023E-01  6.17366E-01  6.25709E-01  6.34052E-01  6.42395E-01  6.50737E-01  6.59080E-01
6.67423E-01  6.75766E-01  6.84109E-01  6.92451E-01  7.00794E-01  7.09137E-01  7.17480E-01  7.25822E-01
7.34165E-01  7.42508E-01  7.50851E-01  7.59194E-01  7.67536E-01  7.75879E-01  7.84222E-01  7.92565E-01
8.00908E-01  8.09250E-01  8.17593E-01  8.25936E-01  8.34279E-01  8.42622E-01  8.50964E-01  8.59307E-01
8.67650E-01  8.75993E-01  8.84335E-01  8.92678E-01  9.01021E-01  9.09364E-01  9.17707E-01  9.26049E-01
9.34392E-01  9.42735E-01  9.51078E-01  9.59421E-01  9.67763E-01  9.76106E-01  9.84449E-01  9.92792E-01
1.00113E+00  1.00948E+00  1.01782E+00  1.02616E+00  1.03451E+00  1.04285E+00  1.05119E+00  1.05953E+00
1.06788E+00  1.07622E+00  1.08456E+00  1.09291E+00  1.10125E+00  1.10959E+00  1.11793E+00  1.12628E+00
1.13462E+00  1.14296E+00  1.15130E+00  1.15965E+00  1.16799E+00  1.17633E+00  1.18468E+00  1.19302E+00
1.20136E+00  1.20970E+00  1.21805E+00  1.22639E+00  1.23473E+00  1.24308E+00  1.25142E+00  1.25976E+00
1.26810E+00  1.27645E+00  1.28479E+00  1.29313E+00  1.30147E+00  1.30982E+00  1.31816E+00  1.32650E+00
1.33485E+00  1.34319E+00  1.35153E+00  1.35987E+00  1.36822E+00  1.37656E+00  1.38490E+00  1.39325E+00
1.40159E+00  1.40993E+00  1.41827E+00  1.42662E+00  1.43496E+00  1.44330E+00  1.45164E+00  1.45999E+00
1.46833E+00  1.47667E+00  1.48502E+00  1.49336E+00  1.50170E+00  1.51004E+00  1.51839E+00  1.52673E+00
1.53507E+00  1.54342E+00  1.55176E+00  1.56010E+00  1.56844E+00  1.57679E+00  1.58513E+00  1.59347E+00
1.60182E+00  1.61016E+00  1.61850E+00  1.62684E+00  1.63519E+00  1.64353E+00  1.65187E+00  1.66021E+00
1.66856E+00

Radial distribution, f(ρ,z), cm^-2

1.18020E+01  1.17695E+01  1.16725E+01  1.15127E+01  1.12927E+01  1.10163E+01  1.06878E+01  1.03127E+01
9.89674E+00  9.44622E+00  8.96775E+00  8.46803E+00  7.95373E+00  7.43134E+00  6.90705E+00  6.38660E+00
5.87524E+00  5.37761E+00  4.89772E+00  4.43889E+00  4.00380E+00  3.59445E+00  3.21220E+00  2.85784E+00
2.53162E+00  2.23332E+00  1.96229E+00  1.71759E+00  1.49796E+00  1.30198E+00  1.12804E+00  9.74488E-01
8.39604E-01  7.21677E-01  6.19036E-01  5.30071E-01  4.53259E-01  3.87176E-01  3.30508E-01  2.82055E-01
2.40732E-01  2.05568E-01  1.75700E-01  1.50369E-01  1.28907E-01  1.10737E-01  9.53589E-02  8.23421E-02
7.13191E-02  6.19764E-02  5.40481E-02  4.73094E-02  4.15705E-02  3.66719E-02  3.24797E-02  2.88817E-02
2.57839E-02  2.31077E-02  2.07876E-02  1.87685E-02  1.70049E-02  1.54582E-02  1.40965E-02  1.28930E-02
1.18252E-02  1.08742E-02  1.00242E-02  9.26176E-03  8.57557E-03  7.95604E-03  7.39504E-03  6.88559E-03
6.42174E-03  5.99836E-03  5.61104E-03  5.25594E-03  4.92972E-03  4.62947E-03  4.35264E-03  4.09696E-03
3.86046E-03  3.64136E-03  3.43811E-03  3.24929E-03  3.07366E-03  2.91010E-03  2.75759E-03  2.61523E-03
2.48220E-03  2.35774E-03  2.24120E-03  2.13196E-03  2.02945E-03  1.93319E-03  1.84271E-03  1.75758E-03
1.67742E-03  1.60188E-03  1.53064E-03  1.46340E-03  1.39989E-03  1.33985E-03  1.28307E-03  1.22931E-03
1.17840E-03  1.13014E-03  1.08437E-03  1.04093E-03  9.99688E-04  9.60500E-04  9.23243E-04  8.87805E-04
8.54076E-04  8.21959E-04  7.91359E-04  7.62191E-04  7.34373E-04  7.07830E-04  6.82492E-04  6.58293E-04
6.35171E-04  6.13068E-04  5.91930E-04  5.71707E-04  5.52350E-04  5.33816E-04  5.16061E-04  4.99047E-04
4.82736E-04  4.67093E-04  4.52086E-04  4.37683E-04  4.23855E-04  4.10574E-04  3.97814E-04  3.85552E-04
3.73763E-04  3.62425E-04  3.51518E-04  3.41022E-04  3.30918E-04  3.21189E-04  3.11818E-04  3.02790E-04
2.94088E-04  2.85700E-04  2.77611E-04  2.69809E-04  2.62281E-04  2.55015E-04  2.48002E-04  2.41230E-04
2.34689E-04  2.28370E-04  2.22264E-04  2.16362E-04  2.10656E-04  2.05139E-04  1.99802E-04  1.94638E-04
1.89642E-04  1.84806E-04  1.80124E-04  1.75590E-04  1.71199E-04  1.66945E-04  1.62824E-04  1.58829E-04
1.54957E-04  1.51204E-04  1.47563E-04  1.44033E-04  1.40607E-04  1.37284E-04  1.34059E-04  1.30928E-04
1.27889E-04  1.24938E-04  1.22072E-04  1.19289E-04  1.16584E-04  1.13956E-04  1.11403E-04  1.08920E-04
1.06507E-04  1.04161E-04  1.01879E-04  9.96594E-05  9.75004E-05  9.53999E-05  9.33558E-05  9.13665E-05
8.94301E-05  8.75450E-05  8.57096E-05  8.39221E-05  8.21813E-05  8.04856E-05  7.88335E-05  7.72238E-05
7.56552E-05
```

Table 9. Excerpt from output file PTRAD.160 from program PTRAD.

```
Program PTRAD, output file PTRAD.160

    9 depths
  201 radial distances

        TIN  =  energy of incident proton beam, MeV
         BR  =  depth, in units of CSDA range at energy TIN
       RTOP  =  Maximum radial distance

          TIN             ZR            RTOP
   160.000000       0.985000       2.648007

Radial distances, ρ, cm

0.00000E+00  1.32400E-02  2.64801E-02  3.97201E-02  5.29601E-02  6.62002E-02  7.94402E-02  9.26803E-02
1.05920E-01  1.19160E-01  1.32400E-01  1.45640E-01  1.58880E-01  1.72120E-01  1.85361E-01  1.98601E-01
2.11841E-01  2.25081E-01  2.38321E-01  2.51561E-01  2.64801E-01  2.78041E-01  2.91281E-01  3.04521E-01
3.17761E-01  3.31001E-01  3.44241E-01  3.57481E-01  3.70721E-01  3.83961E-01  3.97201E-01  4.10441E-01
4.23681E-01  4.36921E-01  4.50161E-01  4.63401E-01  4.76641E-01  4.89881E-01  5.03121E-01  5.16361E-01
5.29601E-01  5.42841E-01  5.56082E-01  5.69322E-01  5.82562E-01  5.95802E-01  6.09042E-01  6.22282E-01
6.35522E-01  6.48762E-01  6.62002E-01  6.75242E-01  6.88482E-01  7.01722E-01  7.14962E-01  7.28202E-01
7.41442E-01  7.54682E-01  7.67922E-01  7.81162E-01  7.94402E-01  8.07642E-01  8.20882E-01  8.34122E-01
8.47362E-01  8.60602E-01  8.73842E-01  8.87082E-01  9.00322E-01  9.13562E-01  9.26803E-01  9.40043E-01
9.53283E-01  9.66523E-01  9.79763E-01  9.93003E-01  1.00624E+00  1.01948E+00  1.03272E+00  1.04596E+00
1.05920E+00  1.07244E+00  1.08568E+00  1.09892E+00  1.11216E+00  1.12540E+00  1.13864E+00  1.15188E+00
1.16512E+00  1.17836E+00  1.19160E+00  1.20484E+00  1.21808E+00  1.23132E+00  1.24456E+00  1.25780E+00
1.27104E+00  1.28428E+00  1.29752E+00  1.31076E+00  1.32400E+00  1.33724E+00  1.35048E+00  1.36372E+00
1.37696E+00  1.39020E+00  1.40344E+00  1.41668E+00  1.42992E+00  1.44316E+00  1.45640E+00  1.46964E+00
1.48288E+00  1.49612E+00  1.50936E+00  1.52260E+00  1.53584E+00  1.54908E+00  1.56232E+00  1.57556E+00
1.58880E+00  1.60204E+00  1.61528E+00  1.62852E+00  1.64176E+00  1.65500E+00  1.66824E+00  1.68148E+00
1.69472E+00  1.70796E+00  1.72120E+00  1.73444E+00  1.74768E+00  1.76092E+00  1.77416E+00  1.78740E+00
1.80064E+00  1.81388E+00  1.82712E+00  1.84036E+00  1.85361E+00  1.86685E+00  1.88009E+00  1.89333E+00
1.90657E+00  1.91981E+00  1.93305E+00  1.94629E+00  1.95953E+00  1.97277E+00  1.98601E+00  1.99925E+00
2.01249E+00  2.02573E+00  2.03897E+00  2.05221E+00  2.06545E+00  2.07869E+00  2.09193E+00  2.10517E+00
2.11841E+00  2.13165E+00  2.14489E+00  2.15813E+00  2.17137E+00  2.18461E+00  2.19785E+00  2.21109E+00
2.22433E+00  2.23757E+00  2.25081E+00  2.26405E+00  2.27729E+00  2.29053E+00  2.30377E+00  2.31701E+00
2.33025E+00  2.34349E+00  2.35673E+00  2.36997E+00  2.38321E+00  2.39645E+00  2.40969E+00  2.42293E+00
2.43617E+00  2.44941E+00  2.46265E+00  2.47589E+00  2.48913E+00  2.50237E+00  2.51561E+00  2.52885E+00
2.54209E+00  2.55533E+00  2.56857E+00  2.58181E+00  2.59505E+00  2.60829E+00  2.62153E+00  2.63477E+00
2.64801E+00

Radial distribution, f(ρ,z), cm-2

1.12791E+00  1.12028E+00  1.11265E+00  1.10621E+00  1.09929E+00  1.09155E+00  1.08288E+00  1.07324E+00
1.06259E+00  1.05094E+00  1.03826E+00  1.02455E+00  1.00982E+00  9.94053E-01  9.77252E-01  9.59416E-01
9.40544E-01  9.20641E-01  8.99821E-01  8.78278E-01  8.56168E-01  8.33618E-01  8.10733E-01  7.87599E-01
7.64288E-01  7.40859E-01  7.17364E-01  6.93846E-01  6.70343E-01  6.46886E-01  6.23504E-01  6.00220E-01
5.77056E-01  5.54049E-01  5.31264E-01  5.08762E-01  4.86597E-01  4.64818E-01  4.43467E-01  4.22585E-01
4.02205E-01  3.82360E-01  3.63078E-01  3.44385E-01  3.26304E-01  3.08857E-01  2.92064E-01  2.75942E-01
2.60501E-01  2.45723E-01  2.31586E-01  2.18070E-01  2.05155E-01  1.92824E-01  1.81061E-01  1.69851E-01
1.59180E-01  1.49034E-01  1.39402E-01  1.30272E-01  1.21634E-01  1.13479E-01  1.05796E-01  9.85758E-02
9.17983E-02  8.54384E-02  7.94735E-02  7.38813E-02  6.86417E-02  6.37352E-02  5.91438E-02  5.48501E-02
5.08381E-02  4.70924E-02  4.35986E-02  4.03428E-02  3.73121E-02  3.44944E-02  3.18775E-02  2.94502E-02
2.72004E-02  2.51173E-02  2.31902E-02  2.14092E-02  1.97645E-02  1.82472E-02  1.68483E-02  1.55598E-02
1.43736E-02  1.32823E-02  1.22784E-02  1.13552E-02  1.05060E-02  9.72443E-03  9.00519E-03  8.34346E-03
7.73540E-03  7.17674E-03  6.66382E-03  6.19304E-03  5.76070E-03  5.36350E-03  4.99818E-03  4.66172E-03
4.35092E-03  4.06304E-03  3.79517E-03  3.54485E-03  3.30926E-03  3.08637E-03  2.87545E-03  2.67619E-03
2.48815E-03  2.31097E-03  2.14431E-03  1.98796E-03  1.84146E-03  1.70457E-03  1.57698E-03  1.45847E-03
1.34862E-03  1.24735E-03  1.15422E-03  1.06913E-03  9.91735E-04  9.21571E-04  8.58035E-04  8.00594E-04
7.48788E-04  7.01956E-04  6.59722E-04  6.21460E-04  5.86822E-04  5.55318E-04  5.26418E-04  4.99814E-04
4.74953E-04  4.51549E-04  4.29126E-04  4.07368E-04  3.86018E-04  3.65165E-04  3.44797E-04  3.25000E-04
3.05761E-04  2.87117E-04  2.69102E-04  2.51748E-04  2.35043E-04  2.19066E-04  2.03801E-04  1.89279E-04
1.75531E-04  1.62586E-04  1.50473E-04  1.39131E-04  1.28633E-04  1.18833E-04  1.09717E-04  1.01316E-04
9.34881E-05  8.63074E-05  7.96359E-05  7.35059E-05  6.78660E-05  6.26659E-05  5.78979E-05  5.35132E-05
4.95051E-05  4.58266E-05  4.24317E-05  3.93554E-05  3.65129E-05  3.39395E-05  3.15913E-05  2.94258E-05
2.74783E-05  2.57067E-05  2.40699E-05  2.26036E-05  2.12292E-05  1.99830E-05  1.88627E-05  1.77918E-05
1.68067E-05  1.58690E-05  1.49780E-05  1.41330E-05  1.33332E-05  1.25418E-05  1.18305E-05  1.11623E-05
1.05011E-05  9.88199E-06  9.30439E-06  8.73271E-06  8.20162E-06  7.71050E-06  7.22434E-06  6.74306E-06
6.30065E-06
```

Table 10. Output file FCIR.1 from program FCIR.

```
Program FCIR, output file FCIR.1
Input file MORAD.160
Input file PTRAD.160
Input file PTPOL.160

      TIN  =  energy of incident proton beam, MeV
     RGIN  =  CSDA range at energy TIN, g/cm2
   RADIUS  =  radius of circular field, cm
     LMAX  =  number of radial distances from center of field
    NCASE  =  number of depths

        TIN          RGIN         RADIUS         LMAX        NCASE
  160.00000      17.65338       0.20000            1          107

Radial distance (cm) from center of field = 0.000

Depths, in units of RGIN

0.010000  0.020000  0.030000  0.040000  0.050000  0.060000  0.070000  0.080000
0.090000  0.100000  0.110000  0.120000  0.130000  0.140000  0.150000  0.160000
0.170000  0.180000  0.190000  0.200000  0.210000  0.220000  0.230000  0.240000
0.250000  0.260000  0.270000  0.280000  0.290000  0.300000  0.310000  0.320000
0.330000  0.340000  0.350000  0.360000  0.370000  0.380000  0.390000  0.400000
0.410000  0.420000  0.430000  0.440000  0.450000  0.460000  0.470000  0.480000
0.490000  0.500000  0.510000  0.520000  0.530000  0.540000  0.550000  0.560000
0.570000  0.580000  0.590000  0.600000  0.610000  0.620000  0.630000  0.640000
0.650000  0.660000  0.670000  0.680000  0.690000  0.700000  0.710000  0.720000
0.730000  0.740000  0.750000  0.760000  0.770000  0.780000  0.790000  0.800000
0.810000  0.820000  0.830000  0.840000  0.850000  0.860000  0.870000  0.880000
0.890000  0.900000  0.910000  0.920000  0.930000  0.940000  0.950000  0.960000
0.970000  0.980000  0.985000  0.990000  0.995000  1.000000  1.005000  1.010000
1.015000  1.020000  1.025000

Reduction factors

1.000000  1.000000  1.000000  1.000000  1.000000  1.000000  1.000000  1.000000
1.000000  1.000000  1.000000  1.000000  1.000000  0.999832  0.999614  0.999361
0.999070  0.998734  0.998350  0.997912  0.997409  0.996836  0.996181  0.995431
0.994569  0.993575  0.992419  0.991062  0.989448  0.987506  0.985141  0.982245
0.978695  0.974354  0.969090  0.962774  0.955300  0.946574  0.936539  0.925168
0.912465  0.898469  0.883240  0.866869  0.849459  0.831132  0.812014  0.792238
0.771932  0.751228  0.730247  0.709103  0.687904  0.666744  0.645713  0.624881
0.604320  0.584085  0.564225  0.544779  0.525781  0.507255  0.489221  0.471694
0.454684  0.438194  0.422227  0.406782  0.391855  0.377439  0.363525  0.350105
0.337167  0.324700  0.312691  0.301126  0.289991  0.279274  0.268961  0.259035
0.249485  0.240295  0.231453  0.222944  0.214755  0.206874  0.199286  0.191981
0.184944  0.178166  0.171632  0.165332  0.159254  0.153386  0.147717  0.142232
0.136919  0.131760  0.129551  0.128709  0.127830  0.128633  0.130434  0.133959
0.133396  0.139213  0.139700

Absorbed dose, MeV/g, from a beam of 1 proton/cm2

6.249280  6.253005  6.256818  6.260764  6.264886  6.269230  6.273839  6.278757
6.284030  6.289700  6.295804  6.302346  6.309319  6.315659  6.322102  6.328735
6.335532  6.342449  6.349453  6.356497  6.363521  6.370490  6.377352  6.384037
6.390450  6.396480  6.401947  6.406600  6.410099  6.411972  6.411624  6.408335
6.401297  6.389614  6.372371  6.348702  6.317856  6.279141  6.232118  6.176513
6.112279  6.039575  5.958720  5.870231  5.774710  5.672882  5.565526  5.453476
5.337544  5.218554  5.097287  4.974484  4.850840  4.726976  4.603480  4.480829
4.359514  4.239927  4.122427  4.007289  3.894760  3.785048  3.678329  3.574723
3.474328  3.377211  3.283452  3.193109  3.106209  3.022755  2.942734  2.866135
2.792947  2.723197  2.656898  2.594047  2.534628  2.478673  2.426200  2.377294
2.332048  2.290564  2.252980  2.219541  2.190535  2.166381  2.147519  2.134632
2.128588  2.131040  2.143681  2.168993  2.211883  2.279476  2.385033  2.558756
2.877361  3.413780  3.686637  3.824325  3.620271  3.064799  2.216462  1.356335
0.655387  0.267163  0.082841
```

Table 11. Output file FCIR.2 from program FCIR.

```
Program FCIR, output file FCIR.2
Input file MORAD160.050
Input file PTPOL.160

      TIN  =  energy of incident proton beam, MeV
     RGIN  =  CSDA range at energy TIN, g/cm2
   RADIUS  =  radius of circular field, cm
     LMAX  =  number of radial distances from center of field
    NCASE  =  number of depths

        TIN          RGIN         RADIUS          LMAX         NCASE
  160.00000      17.65338         0.20000           101             1

Radial distances from center of field (cm)

0.000000  0.005000  0.010000  0.015000  0.020000  0.025000  0.030000  0.035000
0.040000  0.045000  0.050000  0.055000  0.060000  0.065000  0.070000  0.075000
0.080000  0.085000  0.090000  0.095000  0.100000  0.105000  0.110000  0.115000
0.120000  0.125000  0.130000  0.135000  0.140000  0.145000  0.150000  0.155000
0.160000  0.165000  0.170000  0.175000  0.180000  0.185000  0.190000  0.195000
0.200000  0.205000  0.210000  0.215000  0.220000  0.225000  0.230000  0.235000
0.240000  0.245000  0.250000  0.255000  0.260000  0.265000  0.270000  0.275000
0.280000  0.285000  0.290000  0.295000  0.300000  0.305000  0.310000  0.315000
0.320000  0.325000  0.330000  0.335000  0.340000  0.345000  0.350000  0.355000
0.360000  0.365000  0.370000  0.375000  0.380000  0.385000  0.390000  0.395000
0.400000  0.405000  0.410000  0.415000  0.420000  0.425000  0.430000  0.435000
0.440000  0.445000  0.450000  0.455000  0.460000  0.465000  0.470000  0.475000
0.480000  0.485000  0.490000  0.495000  0.500000

Depth as fraction of RGIN = 0.500
Reduction factors

0.751228  0.750933  0.750050  0.748579  0.746523  0.743882  0.740661  0.736862
0.732492  0.727554  0.722055  0.716003  0.709404  0.702268  0.694606  0.686427
0.677744  0.668571  0.658922  0.648812  0.638258  0.627279  0.615892  0.604120
0.591983  0.579504  0.566707  0.553617  0.540258  0.526659  0.512845  0.498846
0.484689  0.470403  0.456019  0.441564  0.427070  0.412564  0.398075  0.383632
0.369254  0.354992  0.340867  0.326899  0.313114  0.299535  0.286184  0.273083
0.260252  0.247708  0.235468  0.223548  0.211960  0.200716  0.189826  0.179298
0.169139  0.159354  0.149947  0.140918  0.132269  0.123998  0.116102  0.108578
0.101421  0.094625  0.088182  0.082085  0.076324  0.070891  0.065774  0.060965
0.056450  0.052219  0.048261  0.044563  0.041113  0.037899  0.034911  0.032134
0.029560  0.027175  0.024968  0.022930  0.021049  0.019315  0.017718  0.016250
0.014901  0.013663  0.012528  0.011488  0.010535  0.009664  0.008868  0.008140
0.007476  0.006869  0.006316  0.005811  0.005350

Absorbed dose, MeV/g, from a beam of 1 proton/cm2

5.218554  5.216508  5.210374  5.200157  5.185868  5.167525  5.145148  5.118762
5.088400  5.054099  5.015901  4.973855  4.928016  4.878447  4.825216  4.768401
4.708086  4.644363  4.577331  4.507100  4.433787  4.357516  4.278420  4.196642
4.112331  4.025644  3.936746  3.845810  3.753013  3.658541  3.562582  3.465332
3.366988  3.267751  3.167826  3.067416  2.966725  2.865957  2.765311  2.664979
2.565095  2.466025  2.367898  2.270869  2.175107  2.080778  1.988036  1.897029
1.807892  1.720754  1.635728  1.552919  1.472419  1.394311  1.318661  1.245529
1.174960  1.106987  1.041636  0.978917  0.918832  0.861374  0.806526  0.754259
0.704541  0.657329  0.612572  0.570216  0.530200  0.492457  0.456916  0.423503
0.392142  0.362752  0.335253  0.309563  0.285598  0.263275  0.242513  0.223229
0.205342  0.188773  0.173446  0.159285  0.146218  0.134173  0.123084  0.112885
0.103515  0.094915  0.087028  0.079802  0.073187  0.067135  0.061602  0.056547
0.051931  0.047717  0.043872  0.040366  0.037168
```

Table 12. Output file FREC.1 from program FREC.

```
Program FREC, output file FREC.1
Input file = MORAD.160
Input file = PTRAD.160
Input file = PTPOL.160

      TIN  =  energy of incident proton beam, MeV
     RGIN  =  CSDA range at energy TIN, g/cm2
       2A  =  side of rectangular field, cm
       2B  =  side of rectangular field, cm
    ALPHA  =  angle (deg) defined below
     LMAX  =  number of radial distances from center of field
    NCASE  =  number of depths

Rectangular field extends from -A to A in x, and from -B to B in y.  Line along which reduction factor is
calculated starts at the origin and makes angle ALPHA (deg) with respect to x-axis.
```

TIN	RGIN	A	B	ALPHA	LMAX	NCASE
160.00000	17.65338	0.05000	0.50000	0.00000	1	107

Radial distance (cm) from center of field = 0.000
Depths, in units of RGIN

0.010000	0.020000	0.030000	0.040000	0.050000	0.060000	0.070000	0.080000
0.090000	0.100000	0.110000	0.120000	0.130000	0.140000	0.150000	0.160000
0.170000	0.180000	0.190000	0.200000	0.210000	0.220000	0.230000	0.240000
0.250000	0.260000	0.270000	0.280000	0.290000	0.300000	0.310000	0.320000
0.330000	0.340000	0.350000	0.360000	0.370000	0.380000	0.390000	0.400000
0.410000	0.420000	0.430000	0.440000	0.450000	0.460000	0.470000	0.480000
0.490000	0.500000	0.510000	0.520000	0.530000	0.540000	0.550000	0.560000
0.570000	0.580000	0.590000	0.600000	0.610000	0.620000	0.630000	0.640000
0.650000	0.660000	0.670000	0.680000	0.690000	0.700000	0.710000	0.720000
0.730000	0.740000	0.750000	0.760000	0.770000	0.780000	0.790000	0.800000
0.810000	0.820000	0.830000	0.840000	0.850000	0.860000	0.870000	0.880000
0.890000	0.900000	0.910000	0.920000	0.930000	0.940000	0.950000	0.960000
0.970000	0.980000	0.985000	0.990000	0.995000	1.000000	1.005000	1.010000
1.015000	1.020000	1.025000					

Reduction factors

1.000000	1.000000	1.000000	1.000000	1.000000	0.999921	0.999655	0.999228
0.998628	0.997801	0.996676	0.995124	0.992895	0.989566	0.984554	0.977221
0.967035	0.953648	0.937119	0.917651	0.895618	0.871597	0.846089	0.819596
0.792565	0.765385	0.738368	0.711759	0.685743	0.660457	0.635995	0.612418
0.589760	0.568035	0.547274	0.527396	0.508415	0.490302	0.473025	0.456551
0.440844	0.425868	0.411586	0.397963	0.384966	0.372560	0.360713	0.349395
0.338577	0.328230	0.318328	0.308880	0.299792	0.291077	0.282713	0.274680
0.266957	0.259528	0.252373	0.245476	0.238822	0.232395	0.226183	0.220170
0.214347	0.208700	0.203220	0.197897	0.192722	0.187686	0.182783	0.178006
0.173349	0.168805	0.164371	0.160041	0.155811	0.151678	0.147638	0.143689
0.139828	0.136051	0.132358	0.128745	0.125210	0.121752	0.118369	0.115058
0.111818	0.108648	0.105544	0.102504	0.099528	0.096611	0.093752	0.090946
0.088189	0.085475	0.084419	0.083850	0.083572	0.083792	0.084856	0.086104
0.086641	0.089510	0.089876					

Absorbed dose, MeV/g, from a beam of 1 proton/cm^2

6.249280	6.253005	6.256818	6.260764	6.264886	6.268737	6.271671	6.273911
6.275405	6.275869	6.274878	6.271616	6.264490	6.250812	6.226854	6.188526
6.132385	6.056129	5.960025	5.845253	5.714090	5.570127	5.416494	5.256345
5.092504	4.927431	4.763102	4.601079	4.442557	4.288415	4.139266	3.995518
3.857411	3.725052	3.598672	3.477744	3.362391	3.252439	3.147705	3.047982
2.953055	2.862714	2.776737	2.694915	2.617036	2.542902	2.472319	2.405110
2.341098	2.280117	2.222005	2.166848	2.114020	2.063629	2.015546	1.969641
1.925807	1.883934	1.843924	1.805674	1.769091	1.734095	1.700610	1.668556
1.637865	1.608474	1.580340	1.553424	1.527691	1.503105	1.479631	1.457249
1.435945	1.415736	1.396639	1.378669	1.361842	1.346202	1.331793	1.318707
1.307033	1.296881	1.288378	1.281729	1.277162	1.274987	1.275548	1.279330
1.286955	1.299533	1.318240	1.344756	1.382343	1.435740	1.513715	1.636112
1.853288	2.214559	2.402326	2.491435	2.366847	1.996419	1.441960	0.871803
0.425676	0.171778	0.053296					

Table 13. Output file FREC.2A from program FREC.

```
Program FREC, output file FREC.2A
Input file = MORAD160.050
Input file = PTPOL.160

      TIN  =  energy of incident proton beam, MeV
     RGIN  =  CSDA range at energy TIN, g/cm2
       2A  =  side of rectangular field, cm
       2B  =  side of rectangular field, cm
    ALPHA  =  angle (deg) defined below
     LMAX  =  number of radial distances from center of field
    NCASE  =  number of depths

Rectangular field extends from -A to A in x, and from -B to B in y.  Line along which reduction factor is
calculated starts at the origin and makes angle ALPHA (deg) with respect to x-axis.
```

TIN	RGIN	A	B	ALPHA	LMAX	NCASE
160.00000	17.65338	0.05000	0.50000	0.00000	101	1

Radial distances from center of field (cm)

0.00000	0.00500	0.01000	0.01500	0.02000	0.02500
0.03000	0.03500	0.04000	0.04500	0.05000	0.05500
0.06000	0.06500	0.07000	0.07500	0.08000	0.08500
0.09000	0.09500	0.10000	0.10500	0.11000	0.11500
0.12000	0.12500	0.13000	0.13500	0.14000	0.14500
0.15000	0.15500	0.16000	0.16500	0.17000	0.17500
0.18000	0.18500	0.19000	0.19500	0.20000	0.20500
0.21000	0.21500	0.22000	0.22500	0.23000	0.23500
0.24000	0.24500	0.25000	0.25500	0.26000	0.26500
0.27000	0.27500	0.28000	0.28500	0.29000	0.29500
0.30000	0.30500	0.31000	0.31500	0.32000	0.32500
0.33000	0.33500	0.34000	0.34500	0.35000	0.35500
0.36000	0.36500	0.37000	0.37500	0.38000	0.38500
0.39000	0.39500	0.40000	0.40500	0.41000	0.41500
0.42000	0.42500	0.43000	0.43500	0.44000	0.44500
0.45000	0.45500	0.46000	0.46500	0.47000	0.47500
0.48000	0.48500	0.49000	0.49500	0.50000	

Depth as fraction of RGIN = 0.500
Reduction factors

0.328230	0.328015	0.327025	0.325536	0.323571	0.320883	0.317758	0.314051
0.309860	0.305112	0.299950	0.294321	0.288282	0.281896	0.275192	0.268123
0.260767	0.253223	0.245407	0.237490	0.229369	0.221173	0.212943	0.204630
0.196290	0.187997	0.179778	0.171636	0.163557	0.155617	0.147874	0.140275
0.132826	0.125571	0.118607	0.111781	0.105230	0.098903	0.092867	0.087030
0.081471	0.076161	0.071123	0.066311	0.061760	0.057458	0.053395	0.049559
0.045951	0.042581	0.039398	0.036431	0.033654	0.031077	0.028664	0.026427
0.024348	0.022426	0.020641	0.018993	0.017471	0.016070	0.014775	0.013586
0.012493	0.011488	0.010565	0.009719	0.008946	0.008235	0.007585	0.006990
0.006448	0.005949	0.005494	0.005078	0.004699	0.004351	0.004034	0.003743
0.003478	0.003235	0.003012	0.002808	0.002622	0.002451	0.002293	0.002149
0.002017	0.001894	0.001782	0.001678	0.001583	0.001494	0.001412	0.001336
0.001266	0.001200	0.001140	0.001083	0.001031			

Absorbed dose, MeV/g, from a beam of 1 proton/cm^2

2.280117	2.278619	2.271747	2.261404	2.247748	2.229079	2.207372	2.181619
2.152504	2.119521	2.083663	2.044559	2.002610	1.958250	1.911678	1.862573
1.811469	1.759064	1.704766	1.649769	1.593355	1.536425	1.479250	1.421505
1.363570	1.305958	1.248861	1.192306	1.136179	1.081023	1.027233	0.974447
0.922699	0.872304	0.823928	0.776506	0.731002	0.687053	0.645118	0.604571
0.565955	0.529069	0.494071	0.460646	0.429029	0.399142	0.370917	0.344270
0.319210	0.295801	0.273686	0.253077	0.233786	0.215884	0.199118	0.183578
0.169135	0.155790	0.143384	0.131938	0.121367	0.111632	0.102640	0.094375
0.086782	0.079804	0.073395	0.067516	0.062145	0.057206	0.052693	0.048556
0.044789	0.041326	0.038168	0.035277	0.032645	0.030227	0.028022	0.026003
0.024163	0.022471	0.020926	0.019510	0.018216	0.017023	0.015932	0.014928
0.014009	0.013159	0.012377	0.011656	0.010993	0.010377	0.009809	0.009281
0.008794	0.008340	0.007918	0.007525	0.007160			

Table 14. Output file FREC.2B from program FREC.

```
Program FREC, output file FREC.2B
Input file = MORAD160.050
Input file = PTPOL.160

      TIN  =  energy of incident proton beam, MeV
     RGIN  =  CSDA range at energy TIN, g/cm2
       2A  =  side of rectangular field, cm
       2B  =  side of rectangular field, cm
    ALPHA  =  angle (deg) defined below
     LMAX  =  number of radial distances from center of field
    NCASE  =  number of depths

Rectangular field extends from -A to A in x, and from -B to B in y.  Line along which reduction factor is
calculated starts at the origin and makes angle ALPHA (deg) with respect to x-axis.
```

TIN	RGIN	A	B	ALPHA	LMAX	NCASE
160.00000	17.65338	0.05000	0.50000	90.00000	101	1

Radial distances from center of field (cm)

0.00000	0.01000	0.02000	0.03000	0.04000	0.05000
0.06000	0.07000	0.08000	0.09000	0.10000	0.11000
0.12000	0.13000	0.14000	0.15000	0.16000	0.17000
0.18000	0.19000	0.20000	0.21000	0.22000	0.23000
0.24000	0.25000	0.26000	0.27000	0.28000	0.29000
0.30000	0.31000	0.32000	0.33000	0.34000	0.35000
0.36000	0.37000	0.38000	0.39000	0.40000	0.41000
0.42000	0.43000	0.44000	0.45000	0.46000	0.47000
0.48000	0.49000	0.50000	0.51000	0.52000	0.53000
0.54000	0.55000	0.56000	0.57000	0.58000	0.59000
0.60000	0.61000	0.62000	0.63000	0.64000	0.65000
0.66000	0.67000	0.68000	0.69000	0.70000	0.71000
0.72000	0.73000	0.74000	0.75000	0.76000	0.77000
0.78000	0.79000	0.80000	0.81000	0.82000	0.83000
0.84000	0.85000	0.86000	0.87000	0.88000	0.89000
0.90000	0.91000	0.92000	0.93000	0.94000	0.95000
0.96000	0.97000	0.98000	0.99000	1.00000	

Depth as fraction of RGIN = 0.500
Reduction factors

0.328230	0.328229	0.328224	0.328214	0.328201	0.328181	0.328157	0.328126
0.328088	0.328042	0.327983	0.327914	0.327828	0.327724	0.327600	0.327447
0.327261	0.327035	0.326762	0.326433	0.326030	0.325545	0.324967	0.324250
0.323385	0.322377	0.321203	0.319782	0.318102	0.316329	0.313851	0.311203
0.308151	0.304881	0.300708	0.296197	0.291230	0.285829	0.279344	0.272575
0.265176	0.257154	0.249037	0.239656	0.229853	0.219617	0.209126	0.198160
0.187044	0.175709	0.164298	0.152863	0.141542	0.130401	0.119521	0.108981
0.098760	0.089171	0.080033	0.071431	0.063425	0.056034	0.049222	0.043032
0.037428	0.032406	0.027856	0.023889	0.020404	0.017362	0.014718	0.012431
0.010471	0.008800	0.007382	0.006186	0.005180	0.004337	0.003634	0.003049
0.002563	0.002160	0.001826	0.001550	0.001321	0.001132	0.000975	0.000844
0.000735	0.000644	0.000567	0.000502	0.000447	0.000400	0.000360	0.000325
0.000295	0.000269	0.000246	0.000226	0.000208			

Absorbed dose, MeV/g, from a beam of 1 proton/cm2

2.280117	2.280109	2.280071	2.280007	2.279913	2.279778	2.279610	2.279393
2.279131	2.278807	2.278399	2.277919	2.277326	2.276600	2.275738	2.274677
2.273386	2.271815	2.269919	2.267633	2.264832	2.261464	2.257448	2.252464
2.246455	2.239459	2.231304	2.221432	2.209758	2.197440	2.180229	2.161835
2.140632	2.117918	2.088932	2.057592	2.023090	1.985567	1.940517	1.893495
1.842101	1.786369	1.729988	1.664815	1.596716	1.525617	1.452736	1.376558
1.299340	1.220600	1.141332	1.061892	0.983249	0.905858	0.830274	0.757059
0.686054	0.619443	0.555968	0.496207	0.440593	0.389252	0.341930	0.298928
0.260002	0.225114	0.193507	0.165949	0.141741	0.120609	0.102243	0.086355
0.072739	0.061130	0.051284	0.042971	0.035982	0.030129	0.025243	0.021177
0.017801	0.015002	0.012685	0.010767	0.009179	0.007864	0.006772	0.005864
0.005107	0.004473	0.003940	0.003489	0.003106	0.002781	0.002501	0.002261
0.002053	0.001871	0.001712	0.001572	0.001448			

Table 15. Output file FREC1.1 from program FREC1.

```
Program FREC1, output file FREC1.1
Input file = MORAD50.160
Input file = PTPOL.160

Rectangular field extends from -A to A in x, and from -B to B in y.

       TIN  =  energy of incident proton beam, MeV
      RGIN  =  CSDA range at energy TIN, g/cm2
        2A  =  side of rectangular field, cm
        2B  =  side of rectangular field, cm
         X  =  x-distance from center of field, cm
         Y  =  y-distance from center of field, cm
      LMAX  =  number of (X,Y) values
     NCASE  =  number of depths
     REDUC  =  reduction factor
      DRAD  =  absorbed dose, MeV/g

       TIN          RGIN           A           B        LMAX       NCASE
    160.00000    17.65338     0.50000     0.20000        9           1

Depths as fraction of RGIN = 0.500

         X           Y         REDUC        DRAD
   0.40000     0.00000     0.72156     5.01246
   0.40000     0.20000     0.39753     2.76153
   0.40000     0.40000     0.03857     0.26795
   0.50000     0.00000     0.44855     3.11596
   0.50000     0.20000     0.24801     1.72282
   0.50000     0.40000     0.02505     0.17402
   0.60000     0.00000     0.17550     1.21915
   0.60000     0.20000     0.09838     0.68339
   0.60000     0.40000     0.01153     0.08007
```

Figure Captions

Fig. 1. Diagram illustrating the calculation of the reduction factor. The solid line is the boundary of the irradiated field. The fraction of the circle of radius ρ around point P that lies inside the irradiated field is equal to the sum of the arc lengths AB and CD, divided by $2\pi\rho$.

Fig. 2. Diagram illustrating the calculation of the reduction factor for a rectangular field. The irradiated field is the rectangle ABCD. The absorbed dose at point P_1 inside the rectangle can be calculated as the sum of the contributions from the rectangles P_1AEF, P_1FBG, P_1GCH and P_1HDE. The absorbed dose at point P_2 outside the rectangle can be calculated as the sum of the contributions from the rectangles P_2KAI and P_2JDK, minus the contributions from the rectangles P_2LBI and P_2LCJ. (adapted from Meredith and Neary, 1944).

Fig. 3. Energy deposition distribution dD/dz for proton beams with energies between 250 MeV and 50 MeV. (From Berger, 1993b).

Fig. 4. Scaled radial distributions calculated with PTRAN. The solid curves are for a beam energy of 160 MeV, and the dotted curves for 70 MeV.
   a. Results at shallow and intermediate depths.
   b. Results at great depths, at and beyond the Bragg peak.

Fig. 5. Effect of energy-loss straggling on the radial distributions calculated with PTRAN. The solid curves represent results that take into account energy-loss straggling, whereas the points (o) represent results calculated in the continuous-slowing-down approximation.

Fig. 6. Percentage amount by which the average path length s_{av} exceeds the penetration depth, when a proton has reach depth z. The squares represent Monte Carlo results from PTRAN, and the curve is from a least-squares cubic-spline fit.

Fig. 7. Radial dose distribution, $2\pi\rho\ f(\rho,z)$, as a function of the radial distance from the axis of a narrow pencil beam. The histograms were calculated with PTRAN, and the curves were obtained from the theory of Molière (1955). The distributions shown are normalized to unity, when integrated with respect to ρ.
   a. Beam energy T_o = 160 MeV
   b. Beam energy T_o = 70 MeV

Fig. 8. Molière distribution $f_M(\vartheta)$ as function of function of the scaled angular variable ϑ, for selected values of the parameter B. The solid curves represent the Molière theory, and the dotted curves represent the Gaussian approximation.

Fig. 9. Reductions factors for a circular field, at depth z/r_o = 0.1, 0.5 and 0.9, for a beam energy of 160 MeV.
   a. Field radius 8 mm
   b. Field radius 4 mm
   c. Field radius 2 mm
   d. Field radius 1 mm

Fig. 10. Reduction factors along the central axis, for a beam energy of 160 MeV and a circular field with radii of 1, 2, 4 and 8 mm.

Fig. 11. Absorbed-dose values along the central axis, for a beam energy of 160 MeV and a circular field with radii of 1, 2 and 4 mm. The dotted curve pertains to a laterally unbounded broad beam.

Fig. 12. Absorbed-dose values along lines that are parallel to the z axis and at distances of 0,2, 3.98, 4.02, 6 and 8 mm from the z axis, for a beam energy of 160 MeV.
- a. Field radius 4 mm
- b. Field radius 2 mm
- c. Field radius 1 mm

Fig. 13. Average absorbed dose as a function of depth, for circular fields with radii of 8, 4, 2 and 1 mm. The absorbed dose is averaged over thin disks with radii equal to the field radii.

Fig. 14. Reduction factors for a circular filed, with a pencil beam density $n(r) = \exp(-Qr^2)$, where r is the radial distance from the center of the field. The results are for a 160-MeV beam and a field radius of 4 mm.
- a. Depth $z = 0.1\ r_o$
- b. Depth $z = 0.5\ r_o$
- c. Depth $z = 0.9\ r_o$

Fig. 15. Comparison of reduction factors for circular and square fields with the same area ($64\ mm^2$), for a 160-MeV beam. The curves with the label "0 deg" pertain to reduction factors from a square field along a line that starts a the center is parallel to an edge of the field. The label "45 deg" pertains to a line starting at the center that passes through a corner of the field.
- a. Depth $z = 0.1\ r_o$
- b. Depth $z = 0.5\ r_o$
- c. Depth $z = 0.9\ r_o$

Fig. 16. Absorbed dose along the central axis of a square fields with sides of 1, 2, 4, and 8 mm, for a 160-MeV beam. The dotted curve is for a laterally unbounded broad beam.

Fig. 17. Absorbed dose along the central axis of rectangular fields that are unbounded in one dimension and have widths of 1, 2, 4, and 8 mm in the other dimension, for a 160-MeV beam. The dotted curve is for a laterally unbounded broad beam.

Fig. 18. Reduction factors and absorbed-dose values for a rectangular 1 mm $\times$ 10 mm field, for a 160-MeV beam.
- a. Central-axis depth dose
- b. At depth $z = 0.5\ r_o$, as a function of radial distance along a line that starts at the center of the field and is parallel to the long side of the field
- c. Similar to b, but for a line that is parallel to the short side of the field.

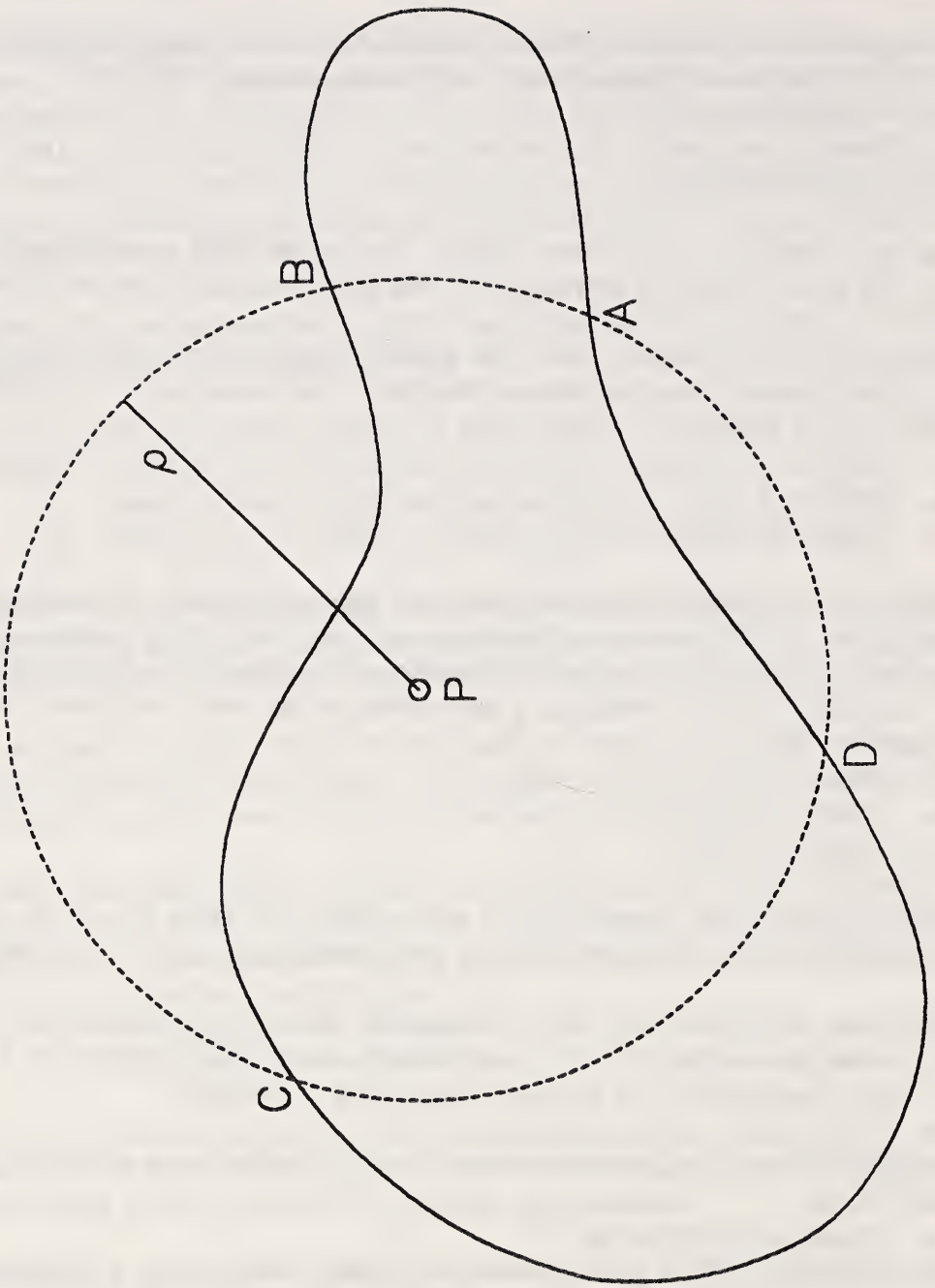

Fig.1

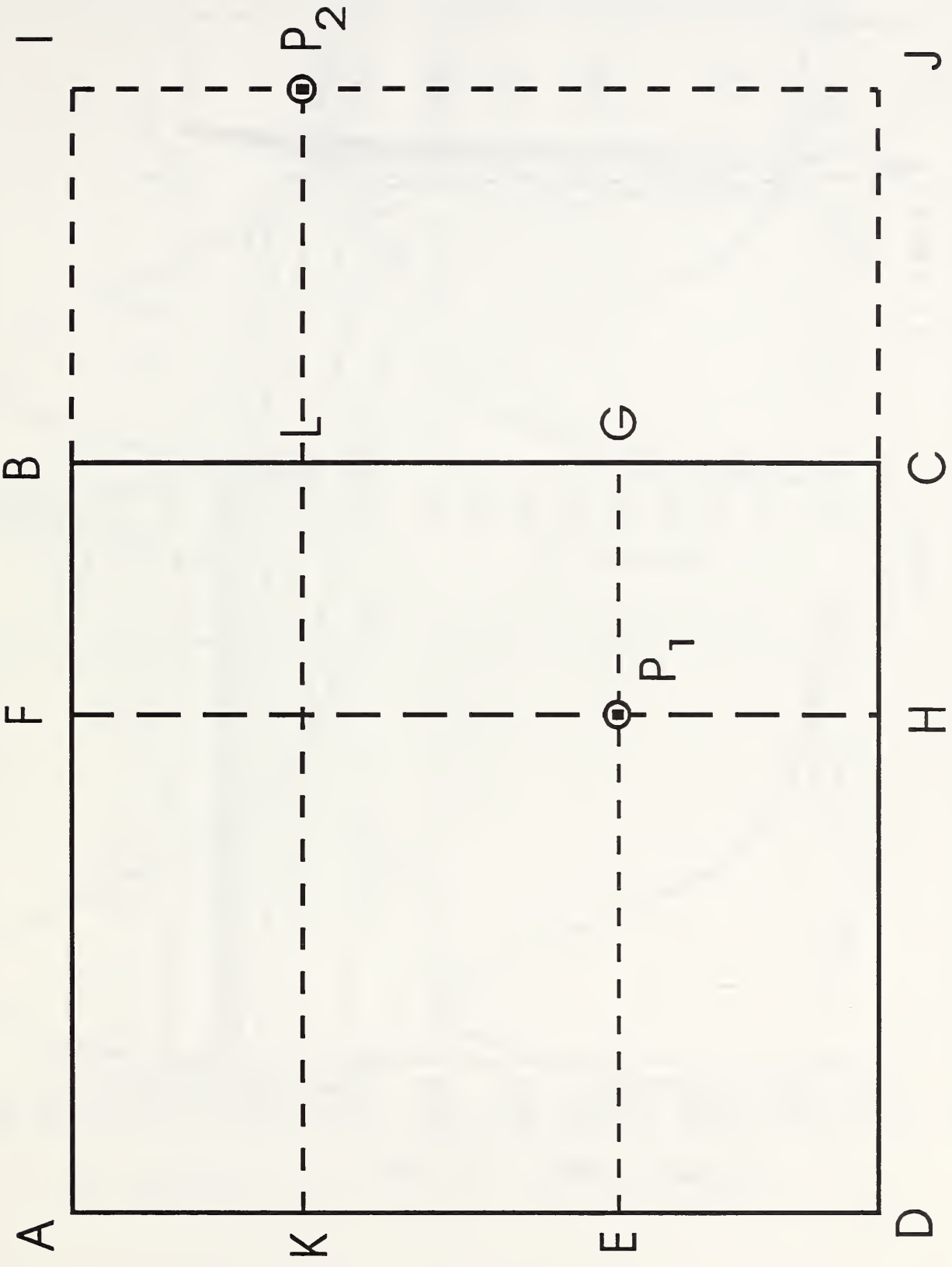

Fig. 2

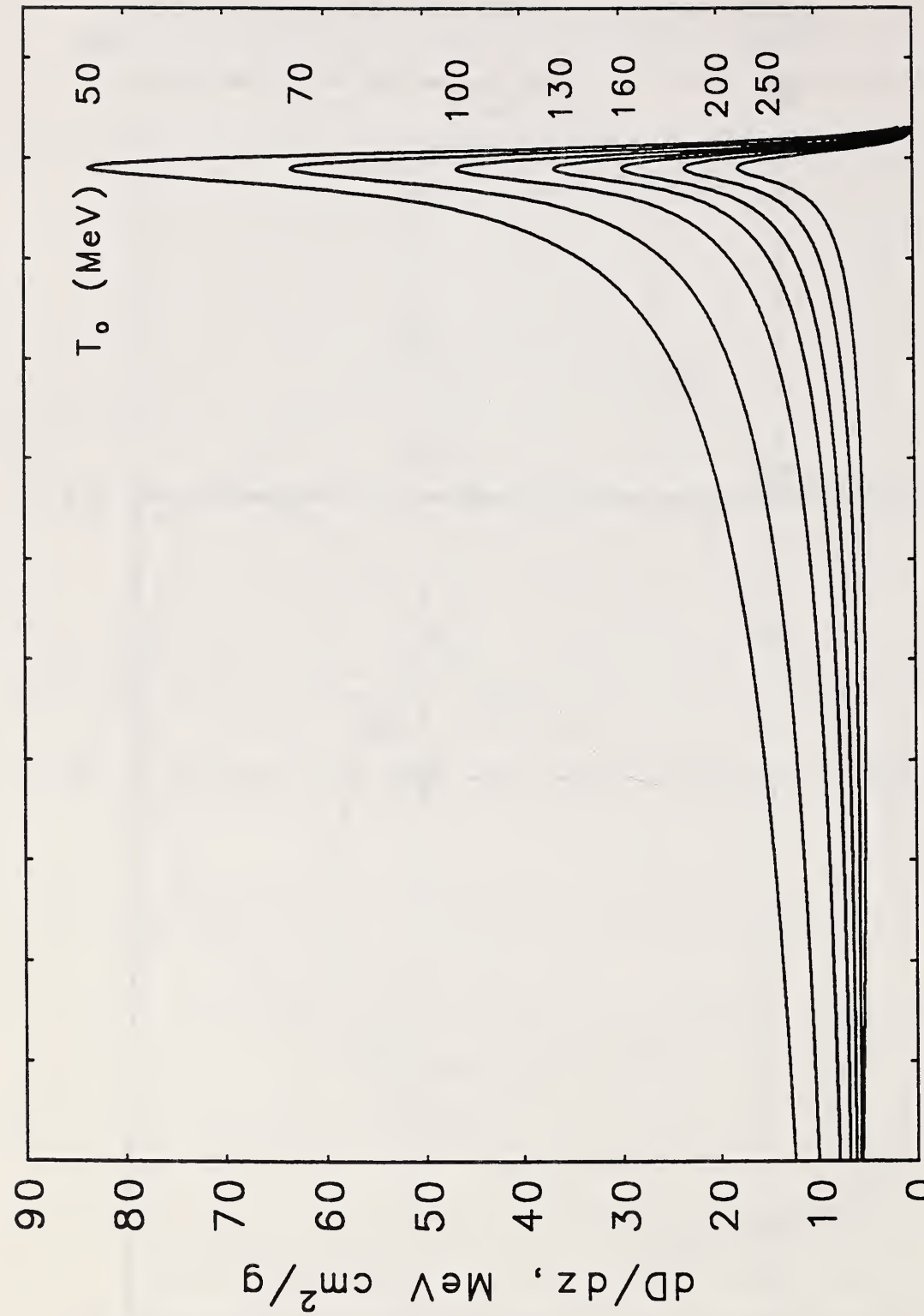
dD/dz, MeV cm²/g
z/r₀
T₀ (MeV)
50
70
100
130
160
200
250
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
60
70
80
90

Fig.3

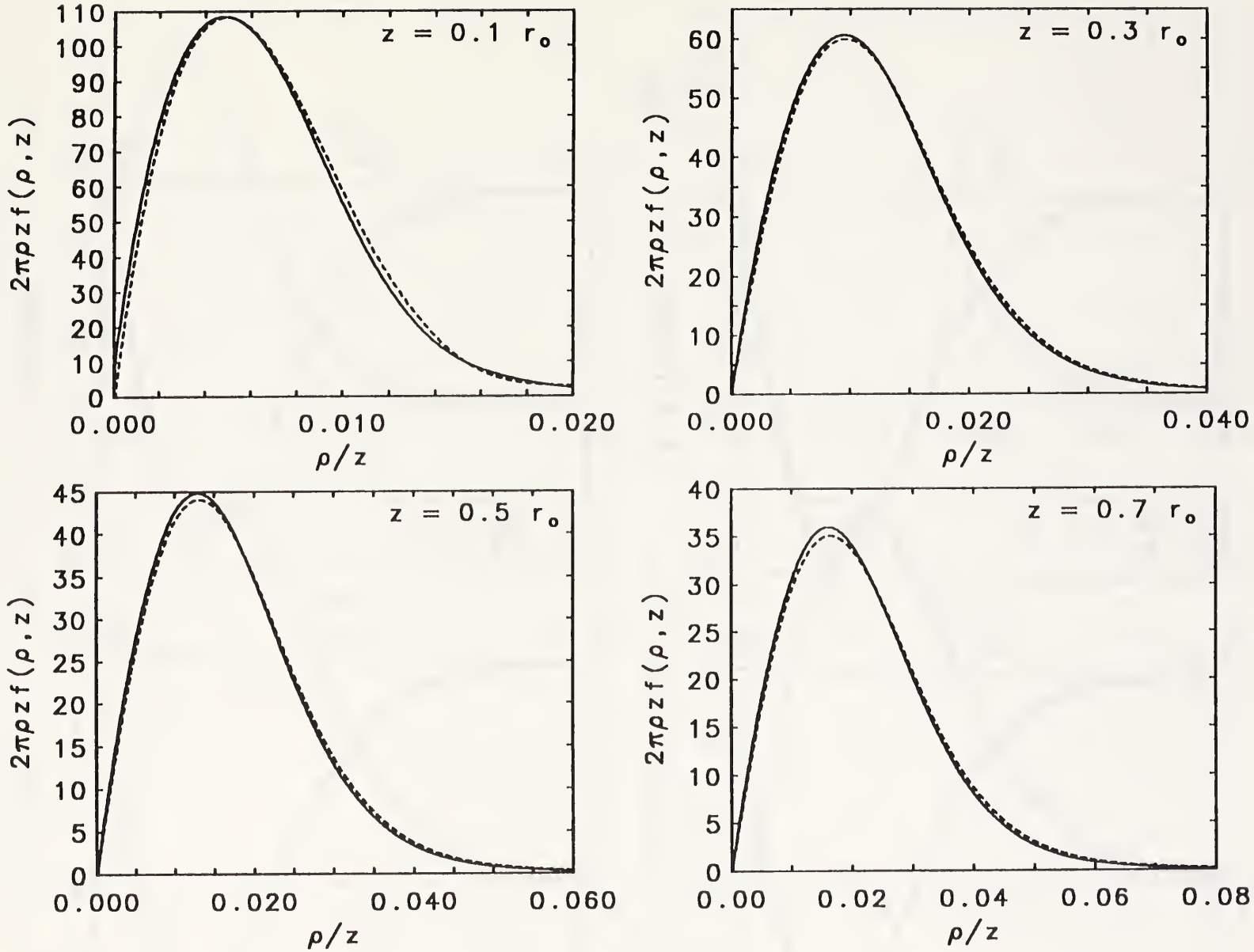
z = 0.1 r₀
z = 0.3 r₀
z = 0.5 r₀
z = 0.7 r₀
2πρzf(ρ,z)
ρ/z
0.000
0.010
0.020
0.040
0.060
0.00
0.02
0.04
0.06
0.08

Fig.4a

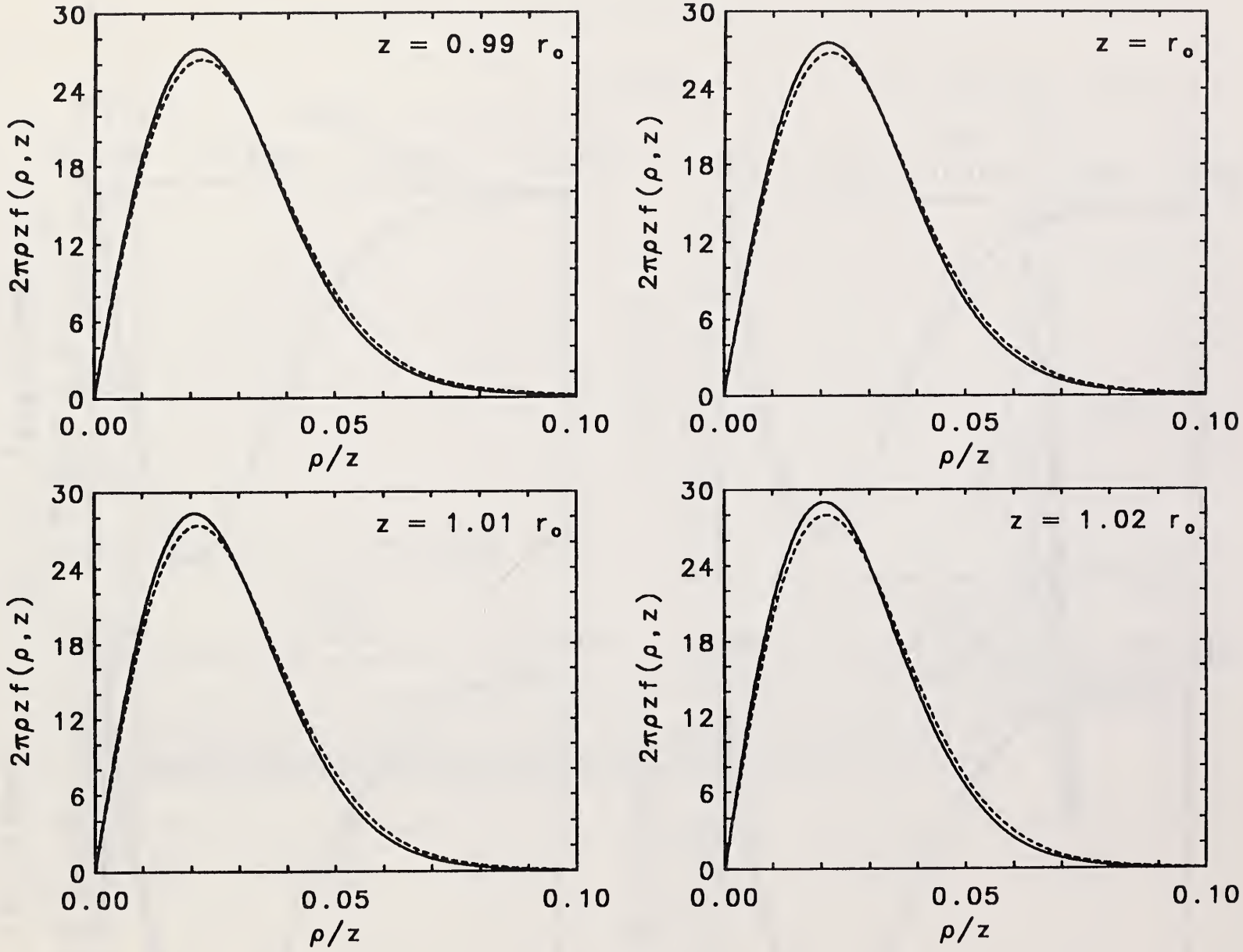

Fig.4b

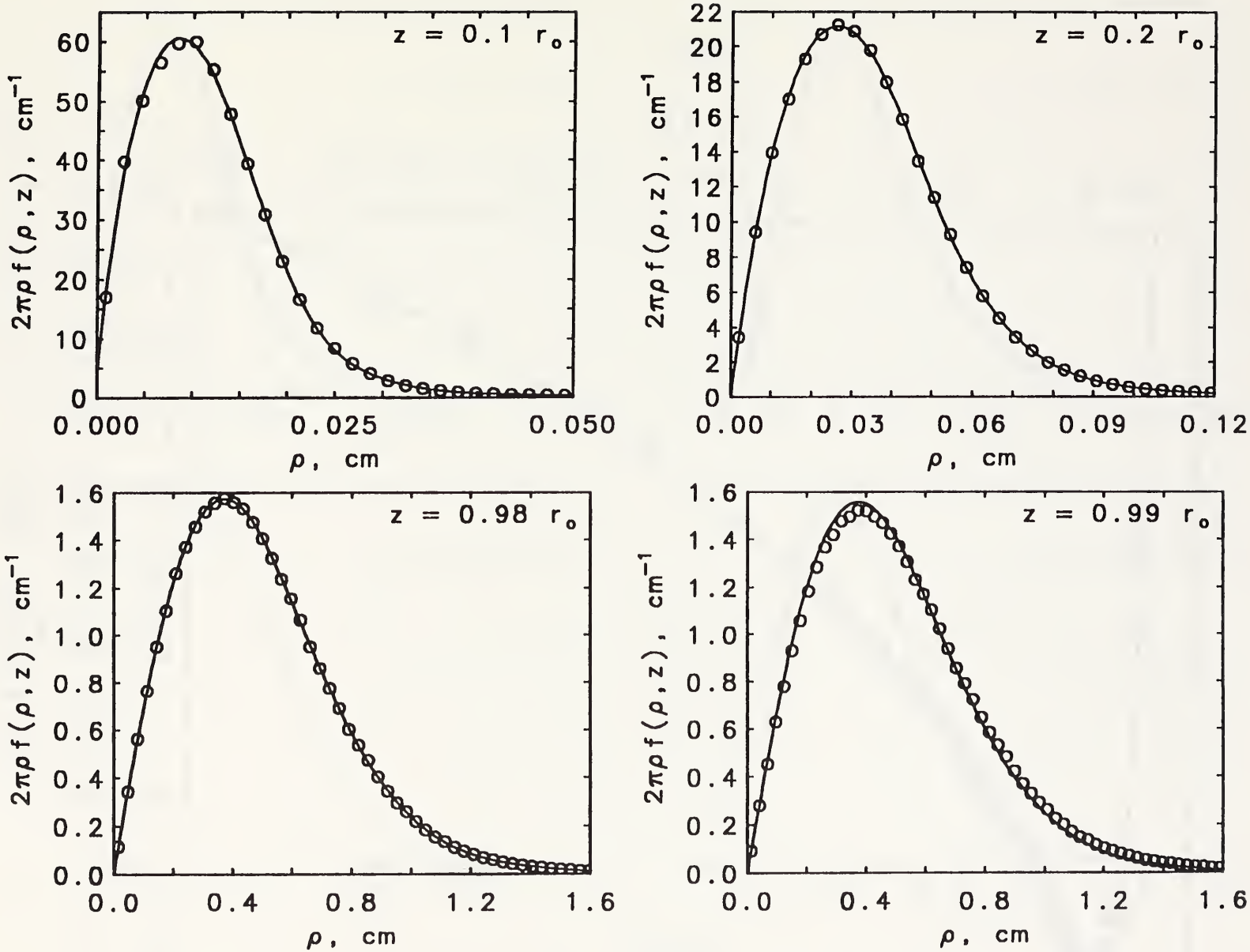

Fig.5

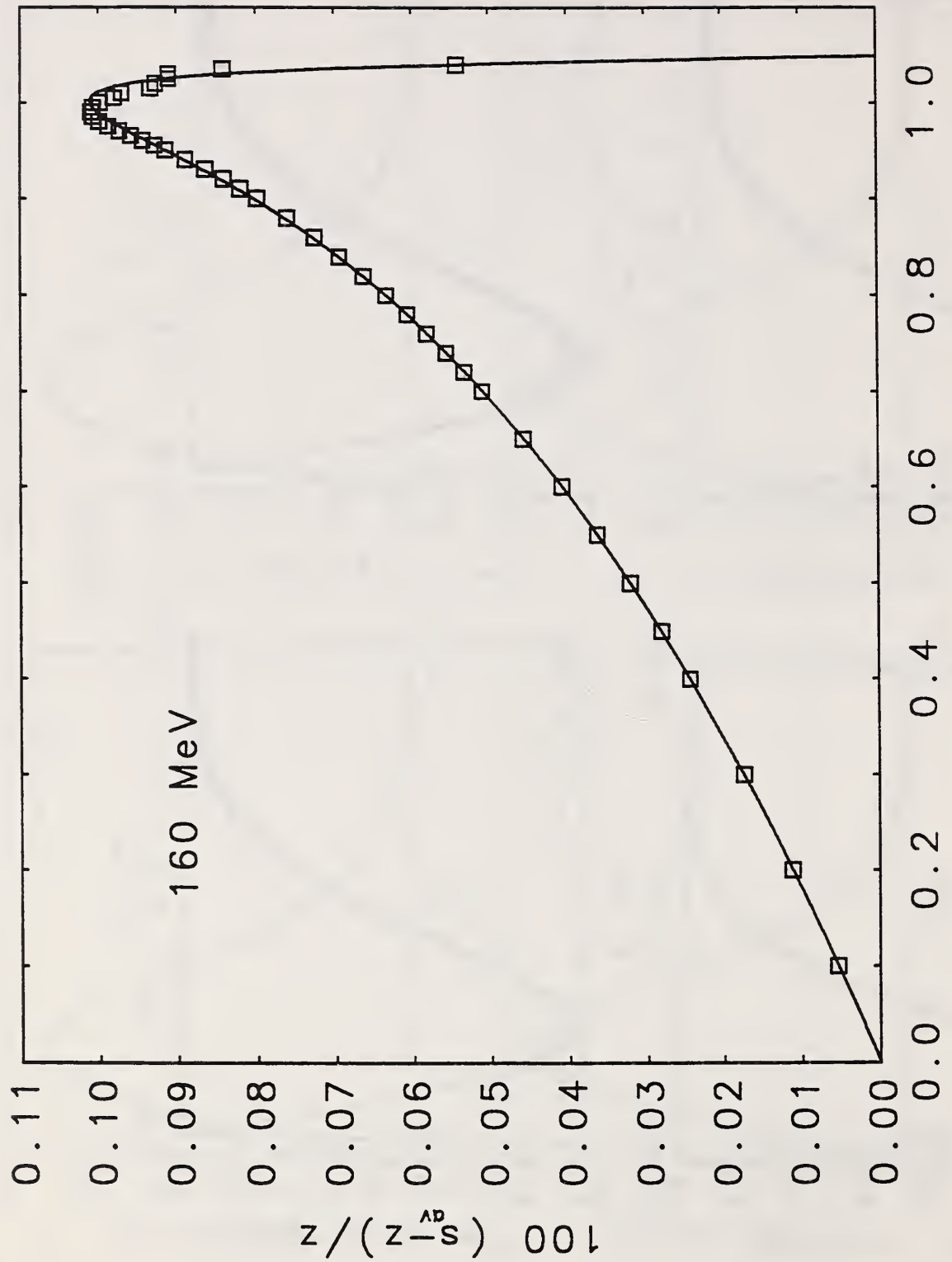
160 MeV
100 (S_AV − Z)/Z
z/r_o
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.0
0.2
0.4
0.6
0.8
1.0

Fig.6

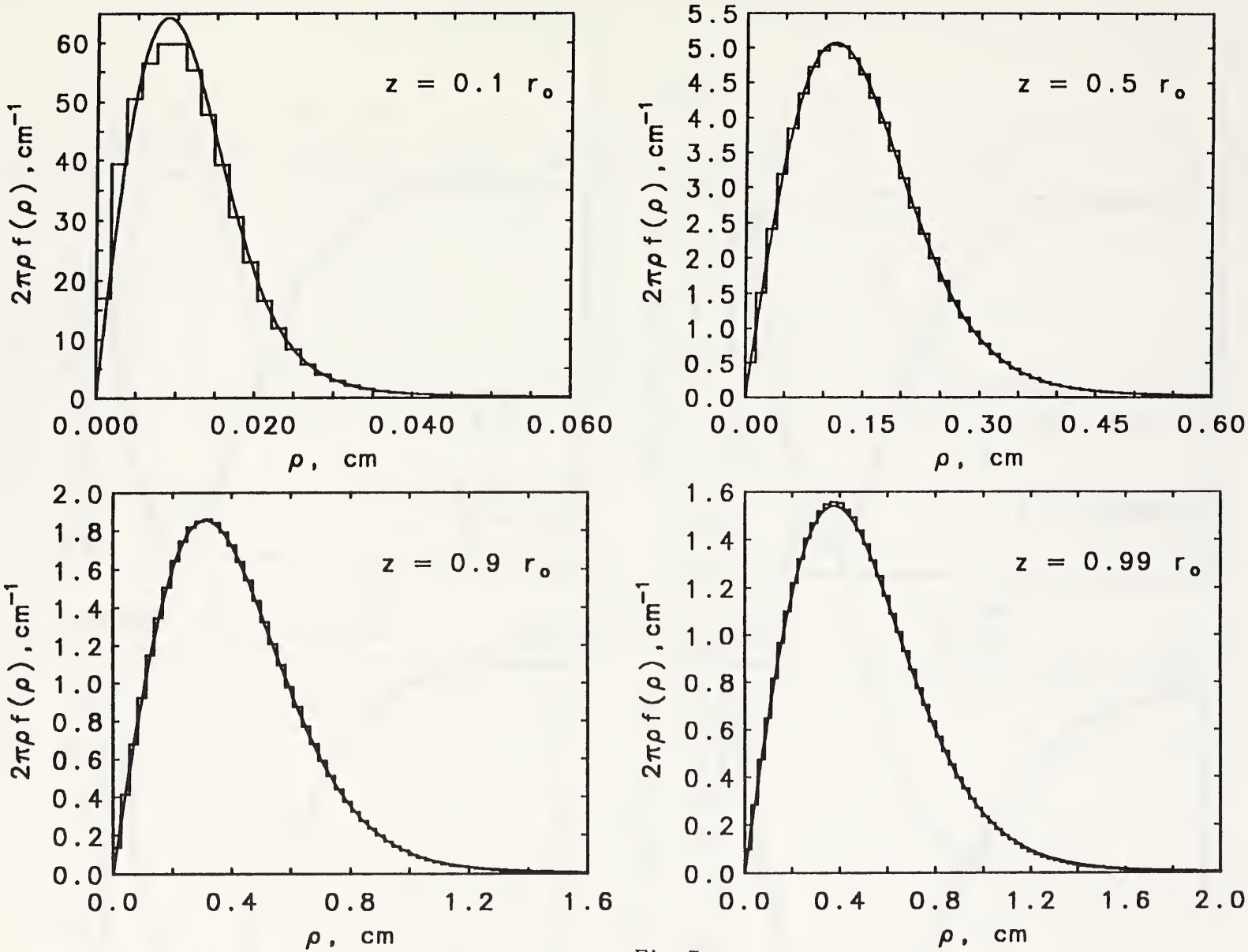
z = 0.1 r₀
z = 0.5 r₀
z = 0.9 r₀
z = 0.99 r₀
2πρ f (ρ), cm⁻¹
ρ, cm
0.000
0.020
0.040
0.060
0.00
0.15
0.30
0.45
0.60
0.0
0.4
0.8
1.2
1.6
2.0

Fig.7a

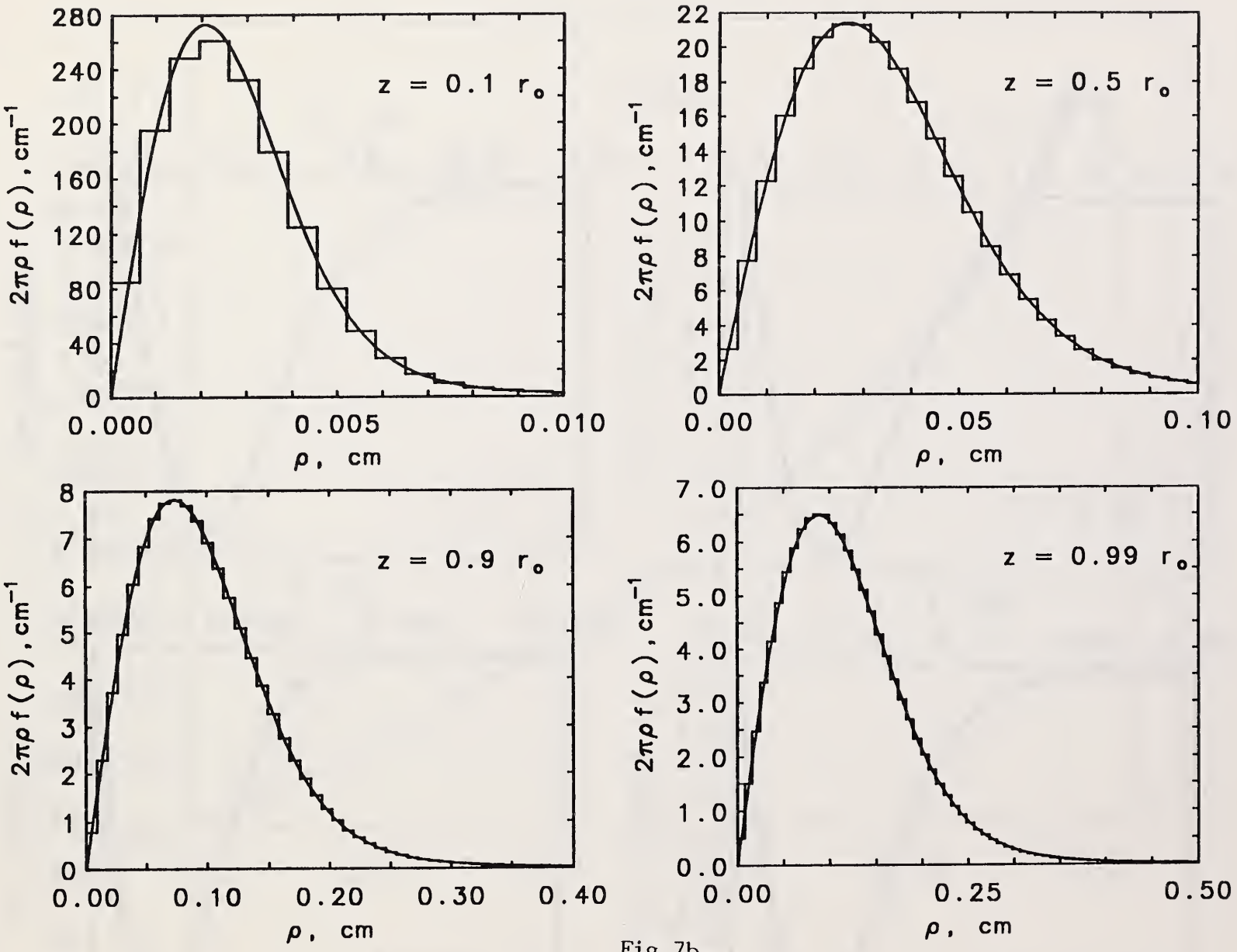
z = 0.1 r₀
z = 0.5 r₀
z = 0.9 r₀
z = 0.99 r₀
2πρ f(ρ), cm⁻¹
ρ, cm
0.000
0.005
0.010
0.00
0.05
0.10
0.25
0.50
0.20
0.30
0.40

Fig.7b

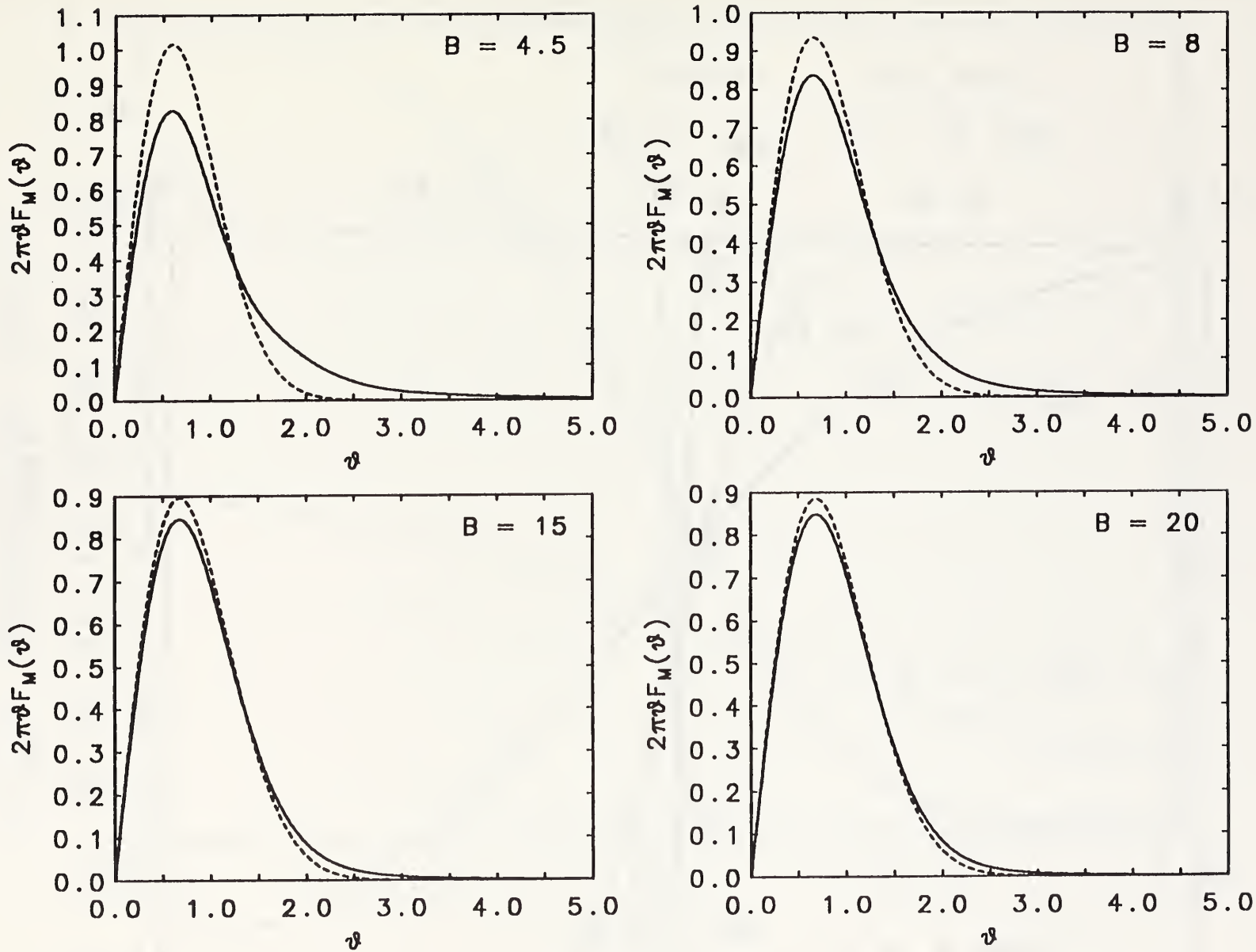
B = 4.5
B = 8
B = 15
B = 20
$2\pi\vartheta F_M(\vartheta)$
ϑ
0.0
1.0
2.0
3.0
4.0
5.0

Fig.8

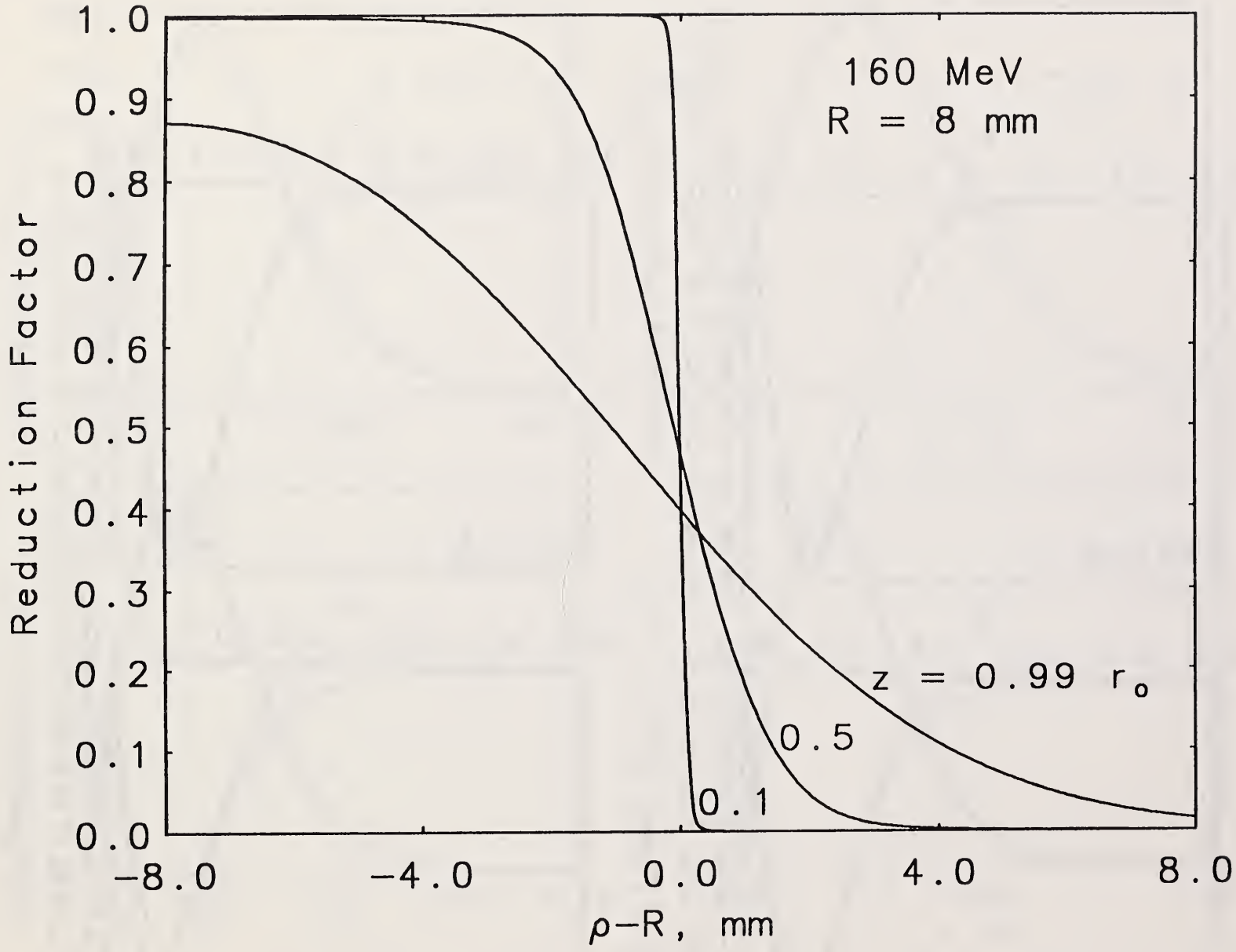
160 MeV
R = 8 mm
Reduction Factor
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
z = 0.99 r_o
0.5
0.1
−8.0
−4.0
0.0
4.0
8.0
ρ−R, mm

Fig.9a

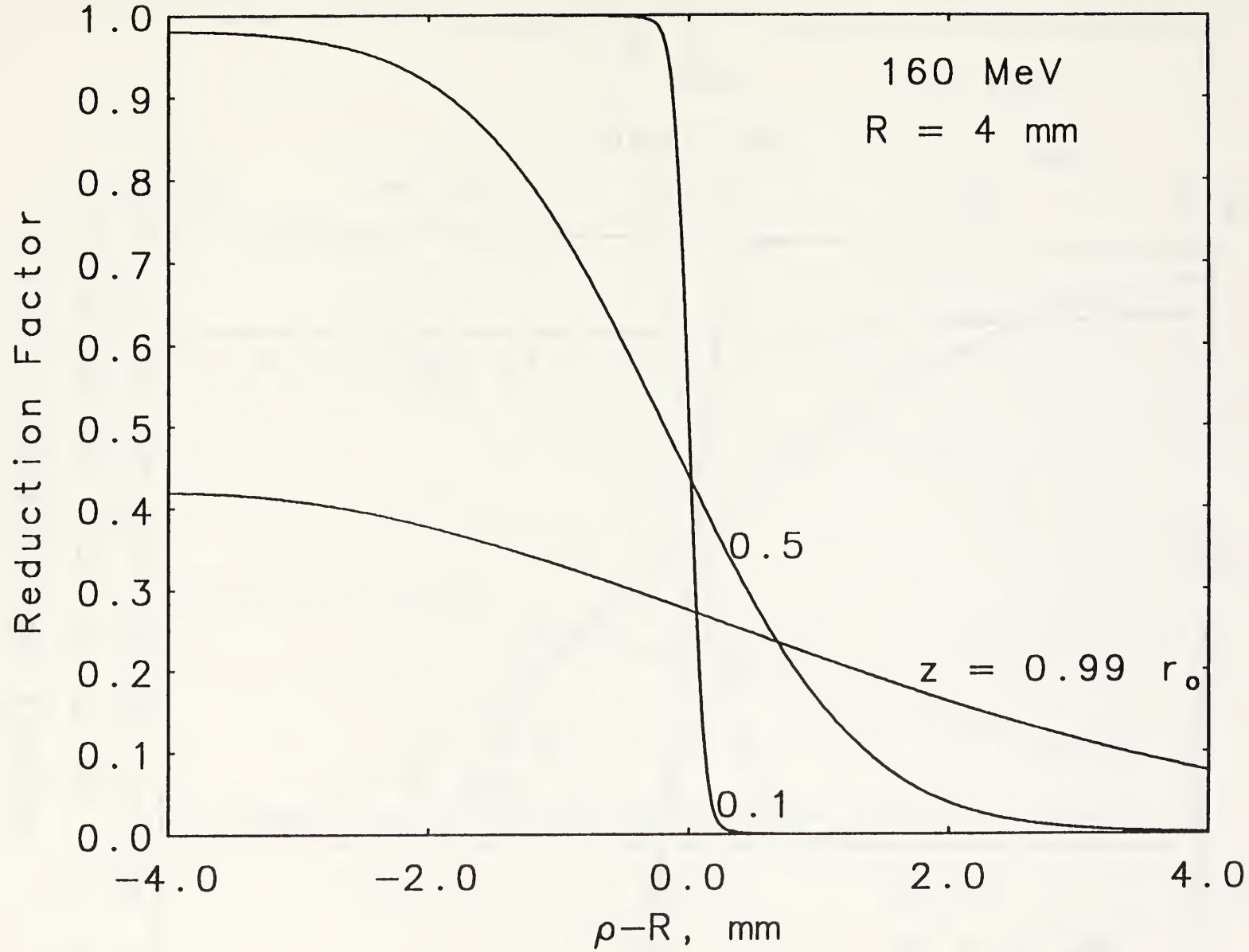
160 MeV
R = 4 mm
Reduction Factor
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.5
z = 0.99 r_o
0.1
−4.0
−2.0
0.0
2.0
4.0
ρ−R, mm

Fig.9b

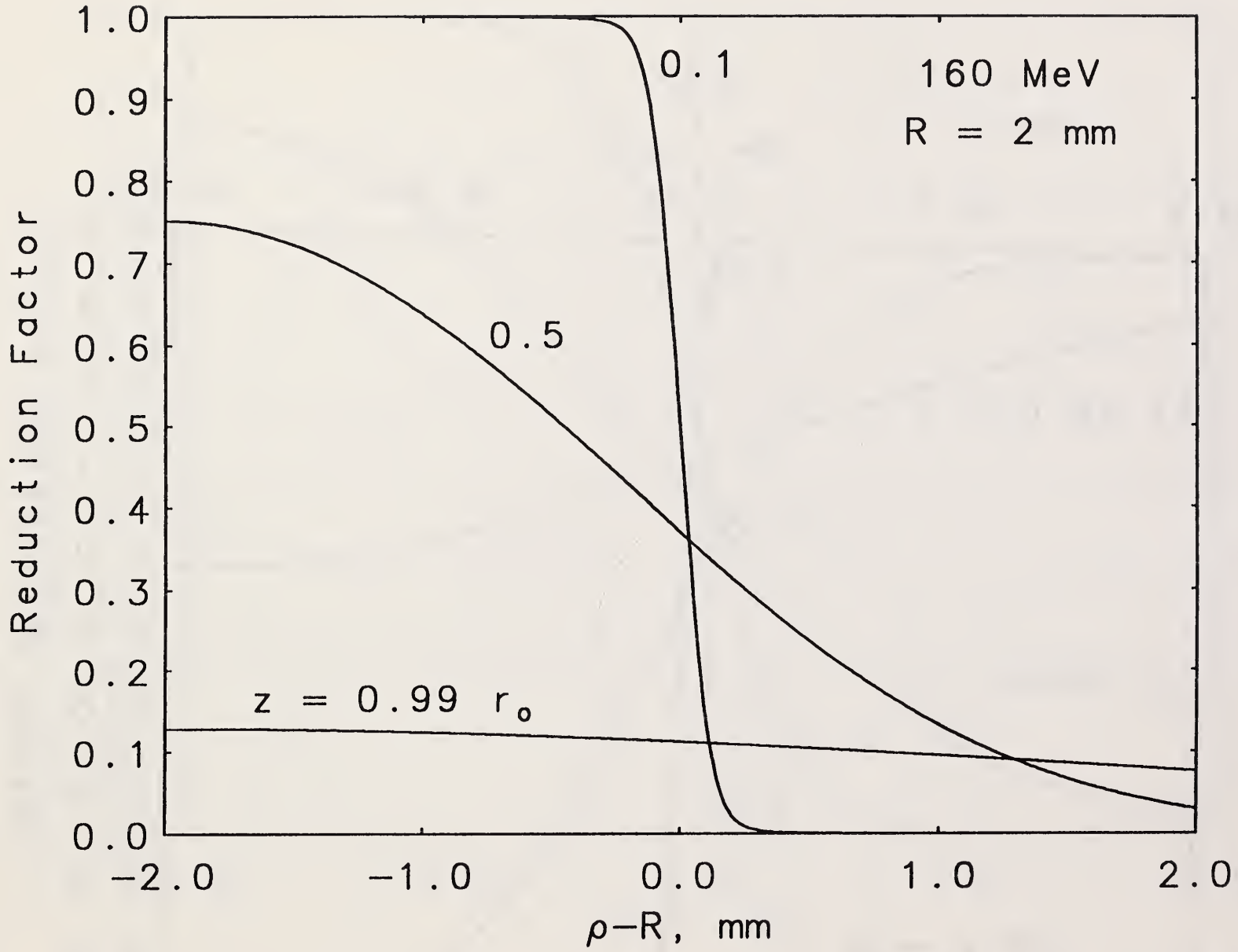
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reduction Factor
0.1
160 MeV
R = 2 mm
0.5
z = 0.99 r_o
−2.0
−1.0
0.0
1.0
2.0
ρ−R, mm

Fig.9c

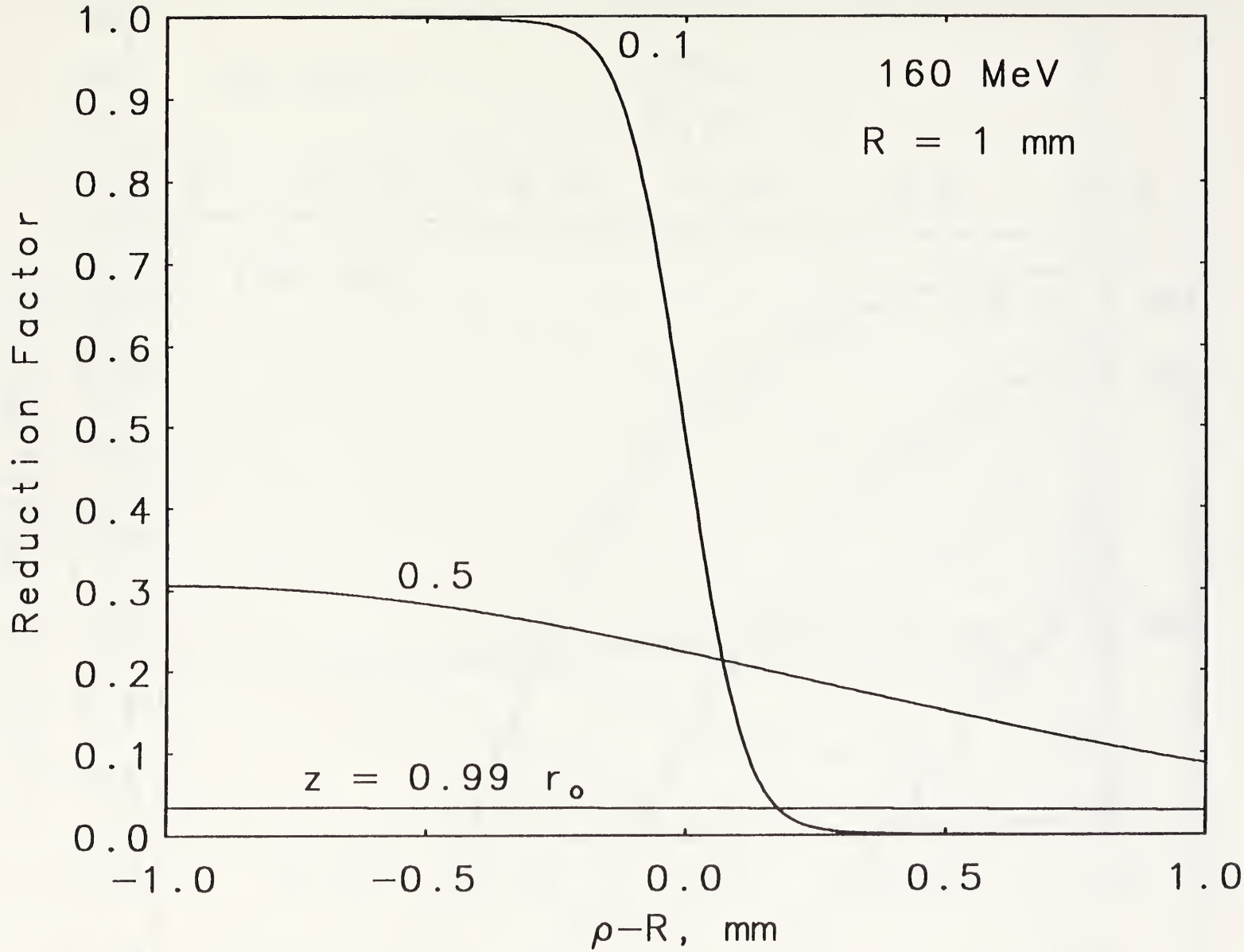
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reduction Factor
0.1
160 MeV
R = 1 mm
0.5
z = 0.99 r$_o$
−1.0
−0.5
0.0
0.5
1.0
ρ−R, mm

Fig.9d

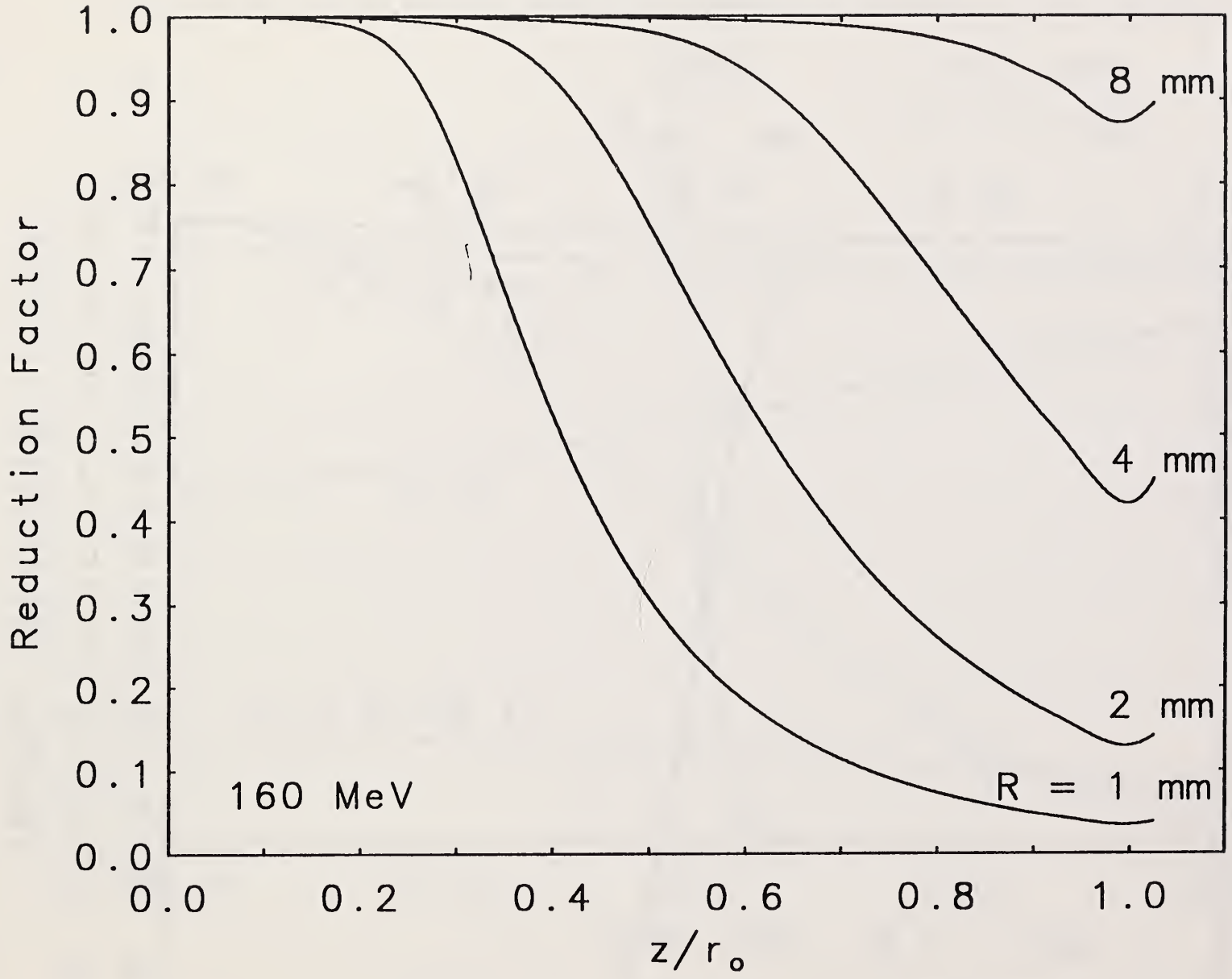
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reduction Factor
0.0
0.2
0.4
0.6
0.8
1.0
z/r₀
8 mm
4 mm
2 mm
R = 1 mm
160 MeV

Fig.10

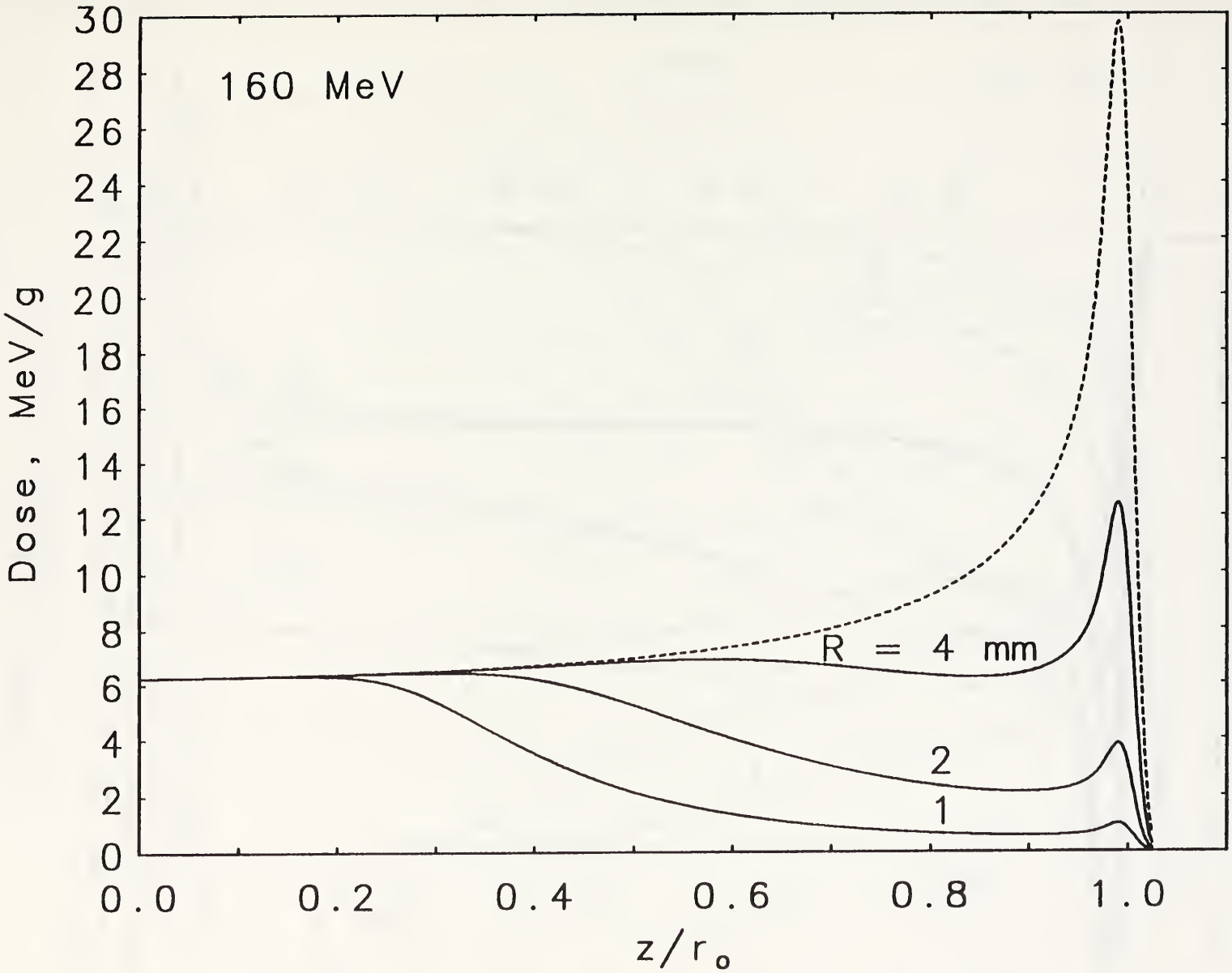
160 MeV
Dose, MeV/g
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
z/r₀
R = 4 mm
2
1

Fig.11

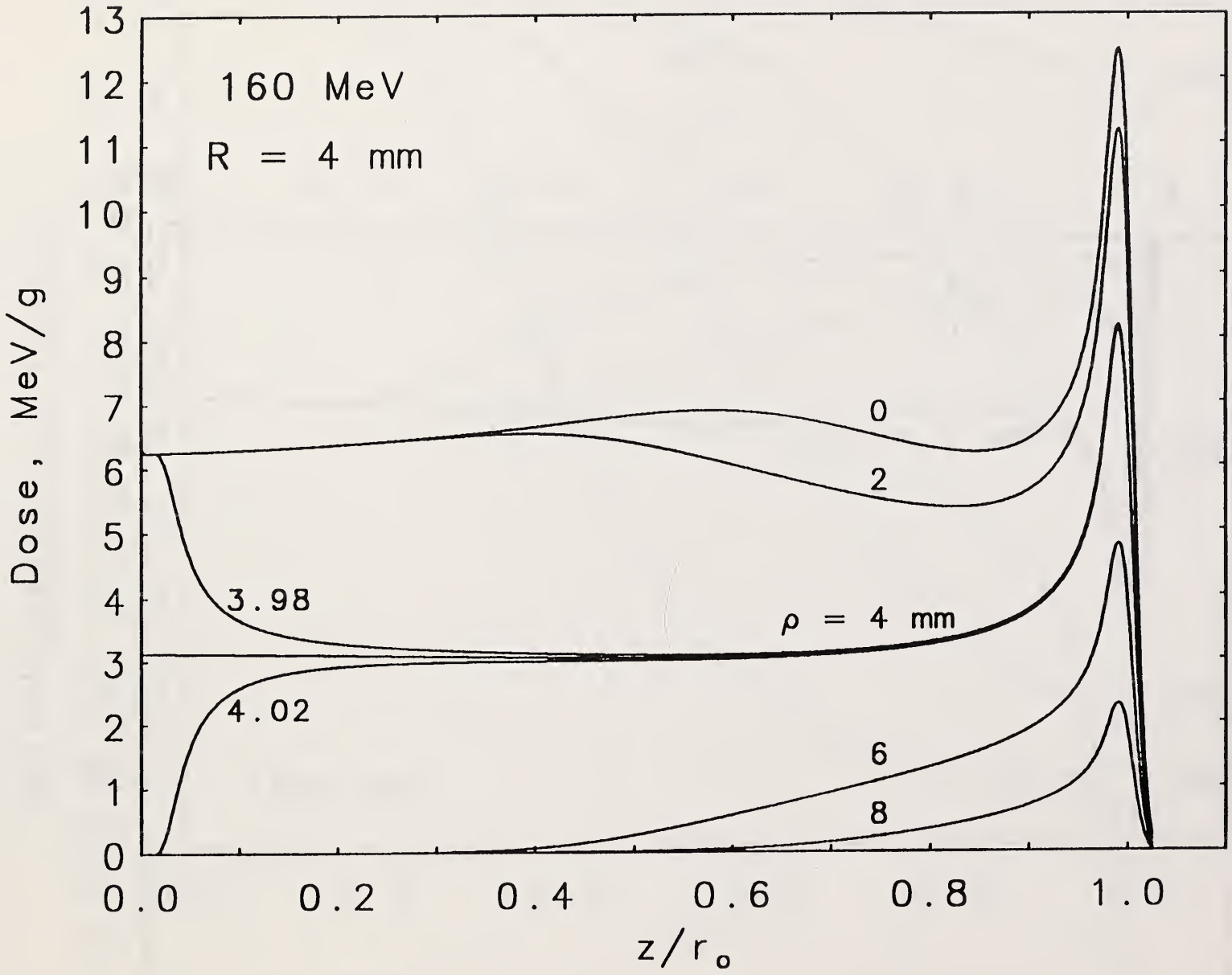
160 MeV
R = 4 mm
Dose, MeV/g
z/r o
0
2
3.98
ρ = 4 mm
4.02
6
8
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13

Fig.12a

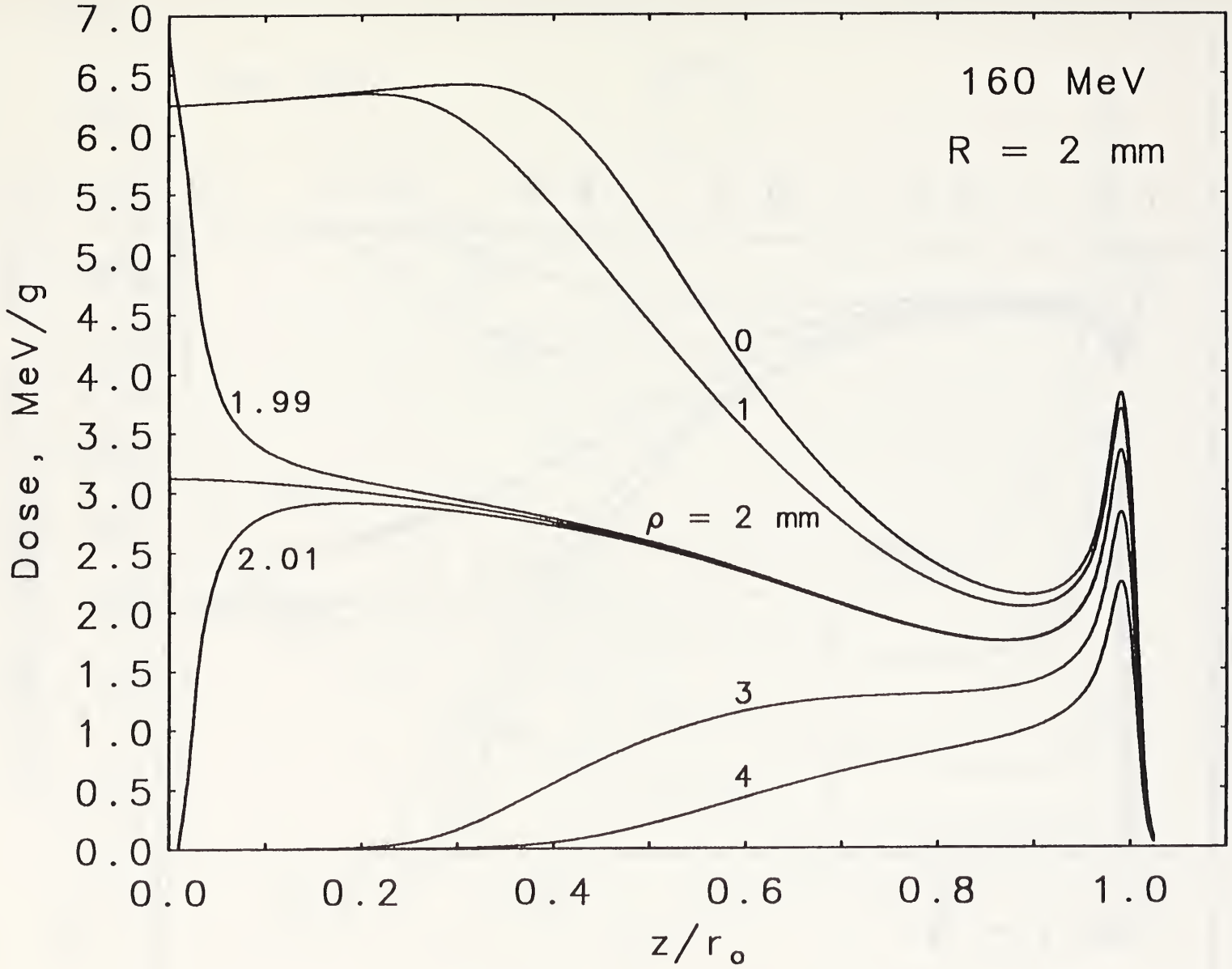
160 MeV
R = 2 mm
Dose, MeV/g
z/r o
0
1
1.99
2.01
ρ = 2 mm
3
4
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0

Fig.12b

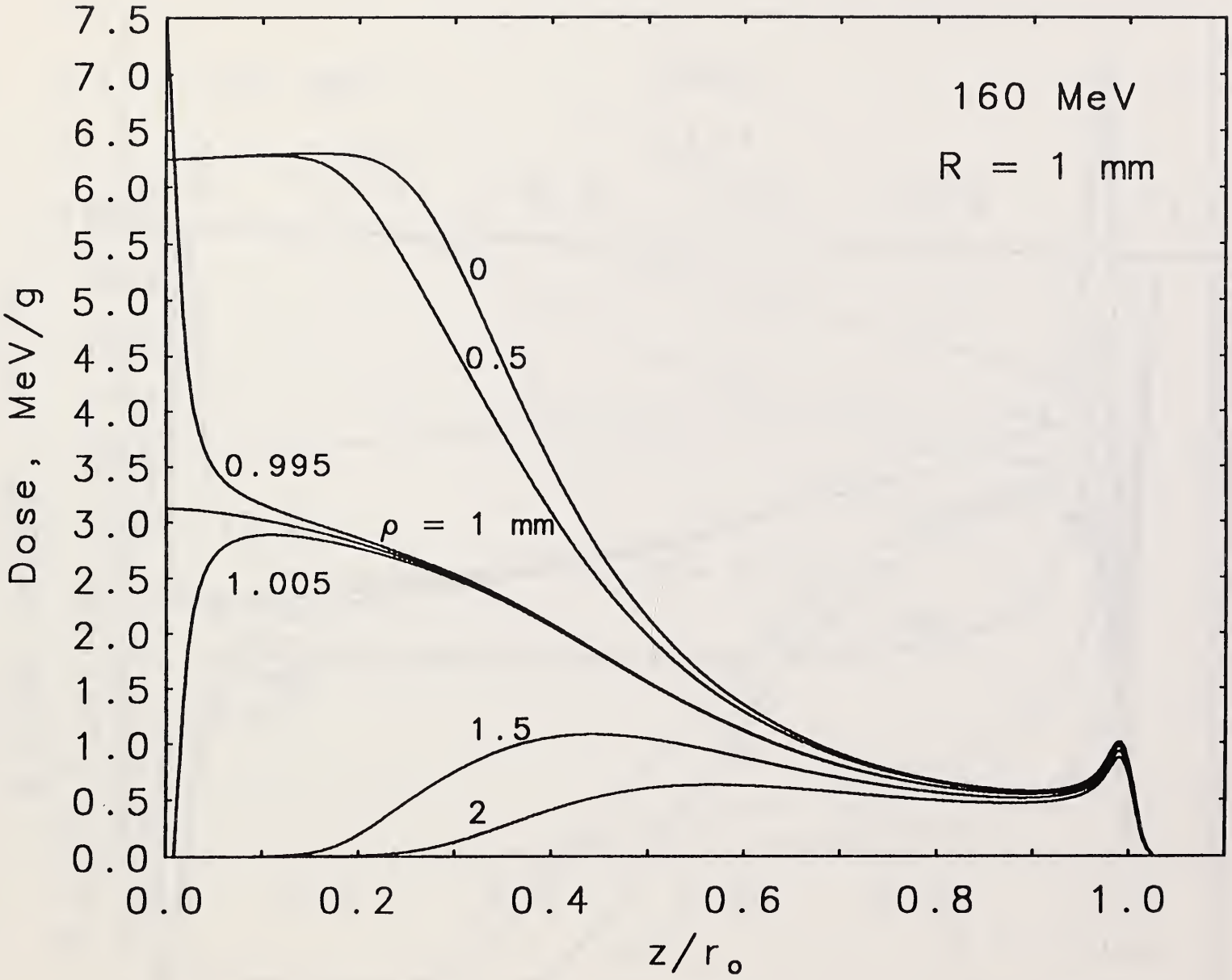
160 MeV
R = 1 mm
0
0.5
0.995
ρ = 1 mm
1.005
1.5
2
Dose, MeV/g
z/r₀
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0

Fig.12c

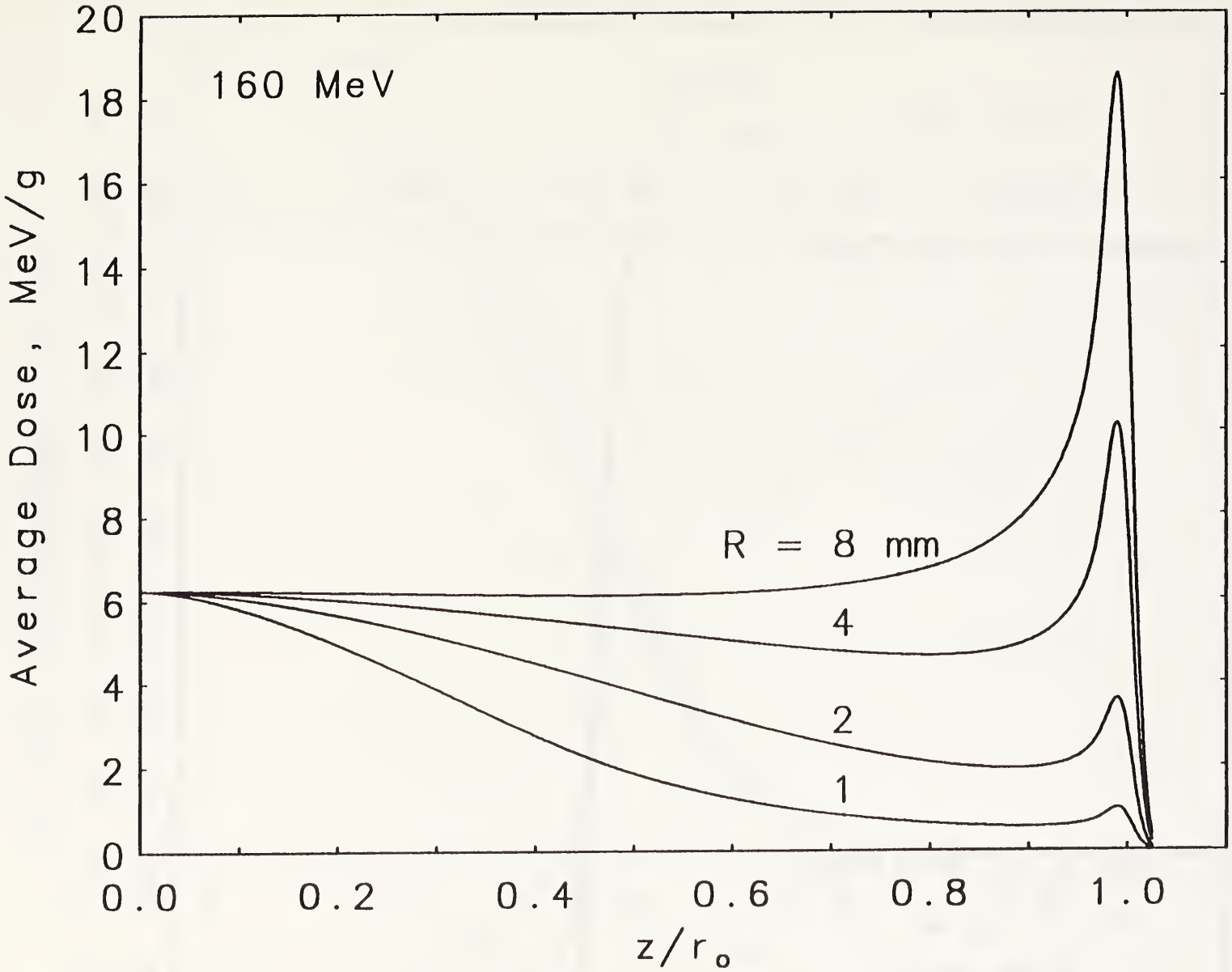
160 MeV
Average Dose, MeV/g
R = 8 mm
4
2
1
z/r₀
0
2
4
6
8
10
12
14
16
18
20
0.0
0.2
0.4
0.6
0.8
1.0

Fig.13

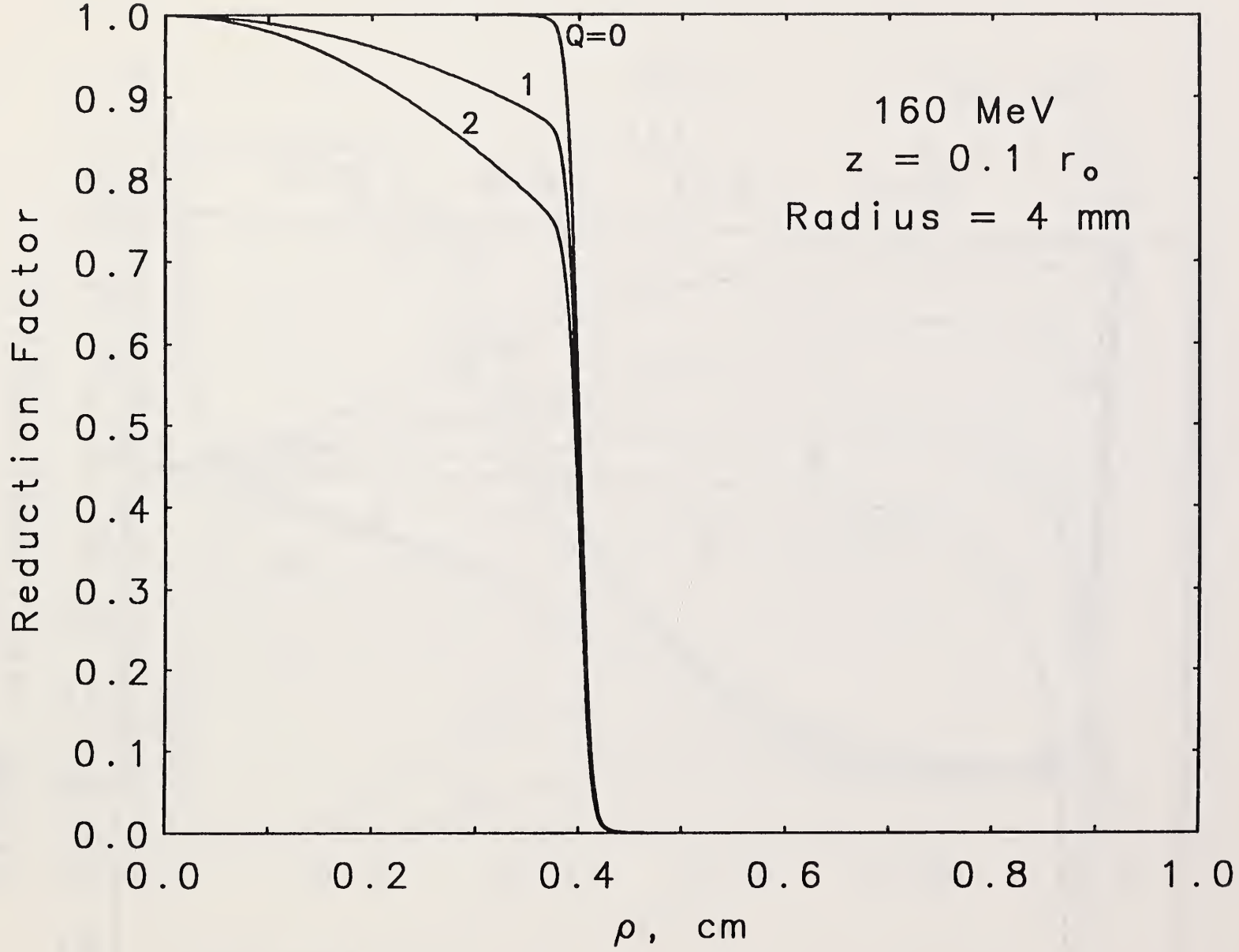
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reduction Factor
Q=0
1
2
160 MeV
z = 0.1 r₀
Radius = 4 mm
0.0
0.2
0.4
0.6
0.8
1.0
ρ, cm

Fig.14a

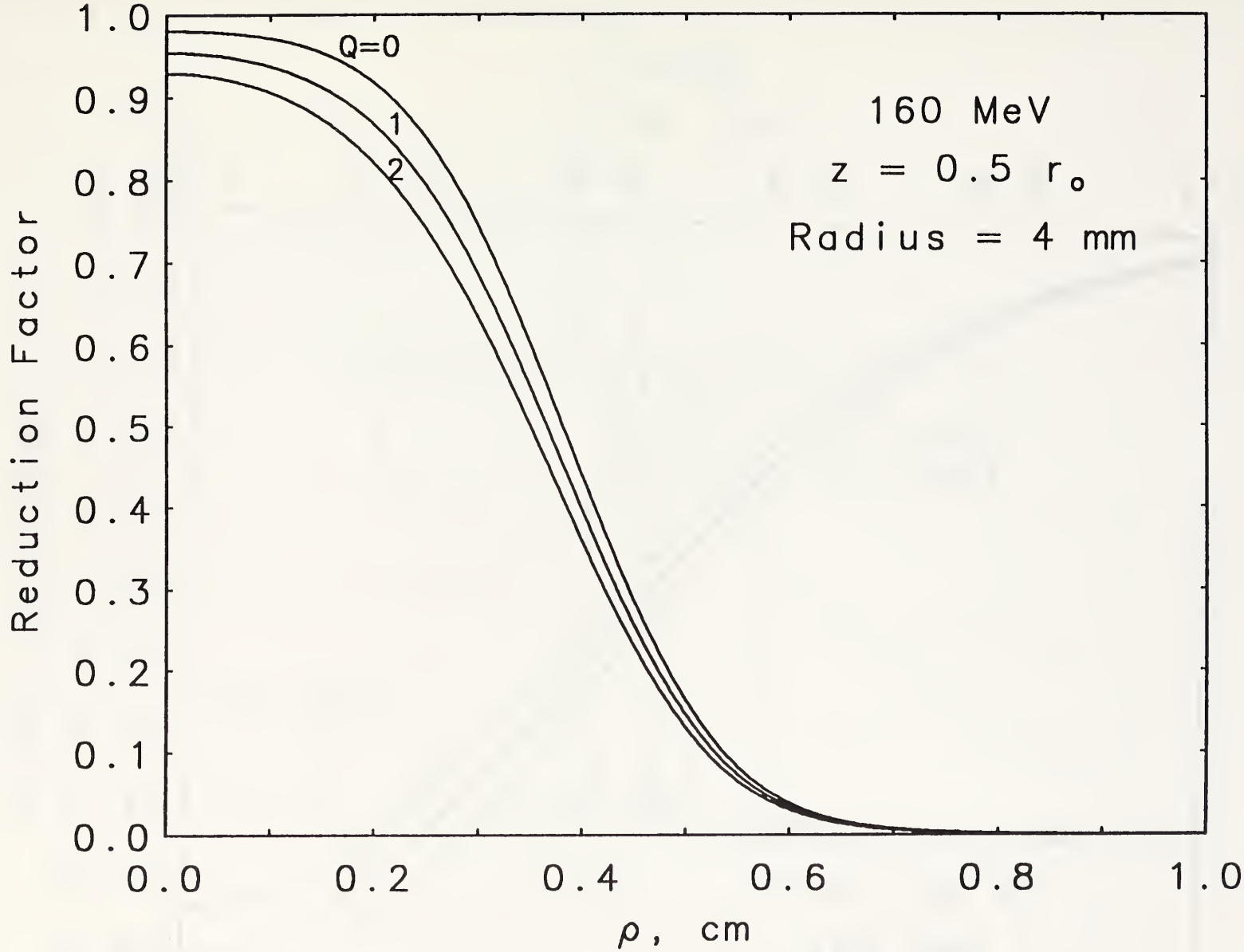
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reduction Factor
Q=0
1
2
160 MeV
z = 0.5 r₀
Radius = 4 mm
0.0
0.2
0.4
0.6
0.8
1.0
ρ, cm

Fig.14b

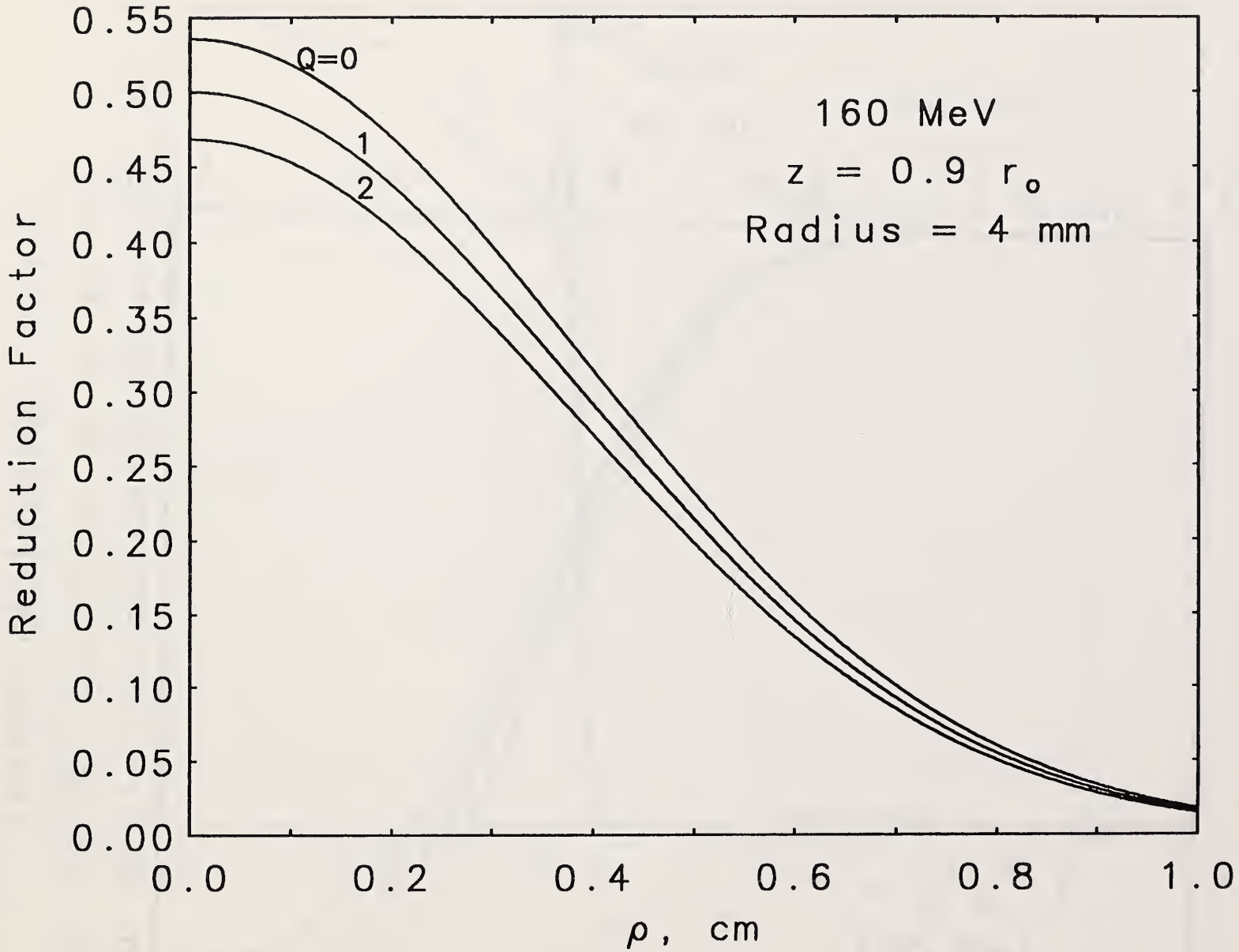
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Reduction Factor
Q=0
1
2
160 MeV
z = 0.9 r₀
Radius = 4 mm
0.0
0.2
0.4
0.6
0.8
1.0
ρ, cm

Fig.14c

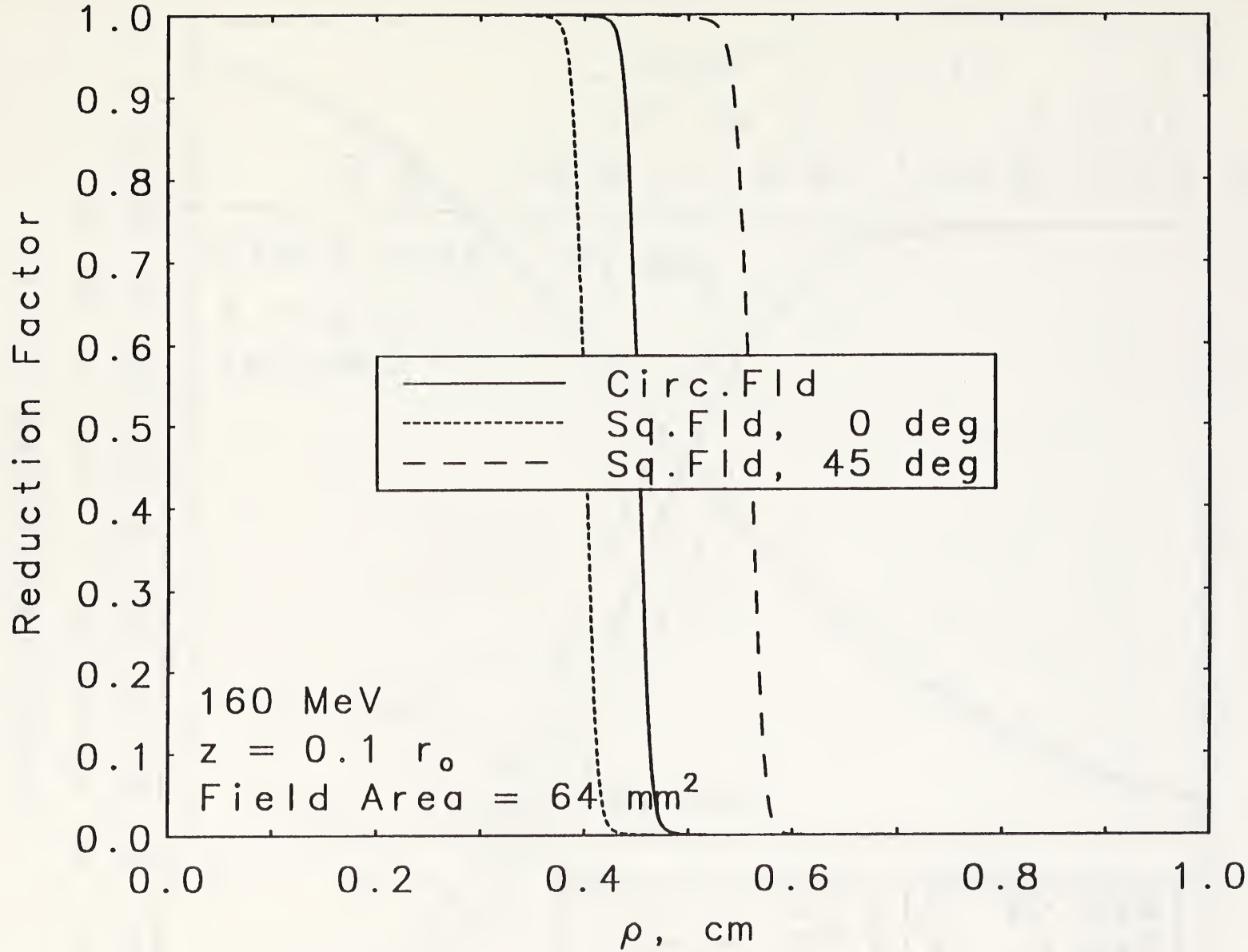
Reduction Factor
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0
ρ, cm
Circ.Fld
Sq.Fld, 0 deg
Sq.Fld, 45 deg
160 MeV
z = 0.1 r₀
Field Area = 64 mm²

Fig.15a

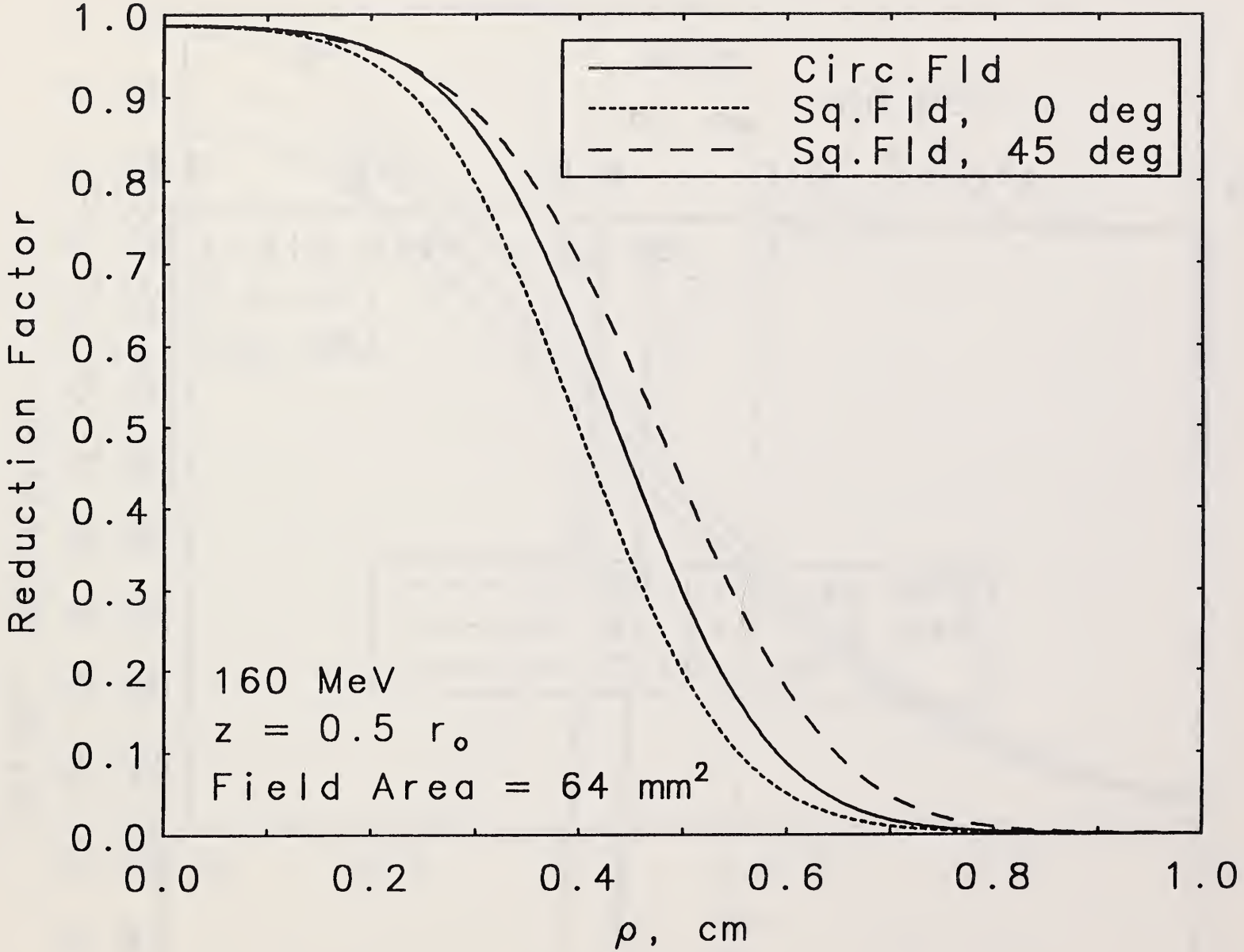
Circ.Fld
Sq.Fld, 0 deg
Sq.Fld, 45 deg
160 MeV
z = 0.5 r₀
Field Area = 64 mm²
Reduction Factor
ρ, cm
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0

Fig.15b

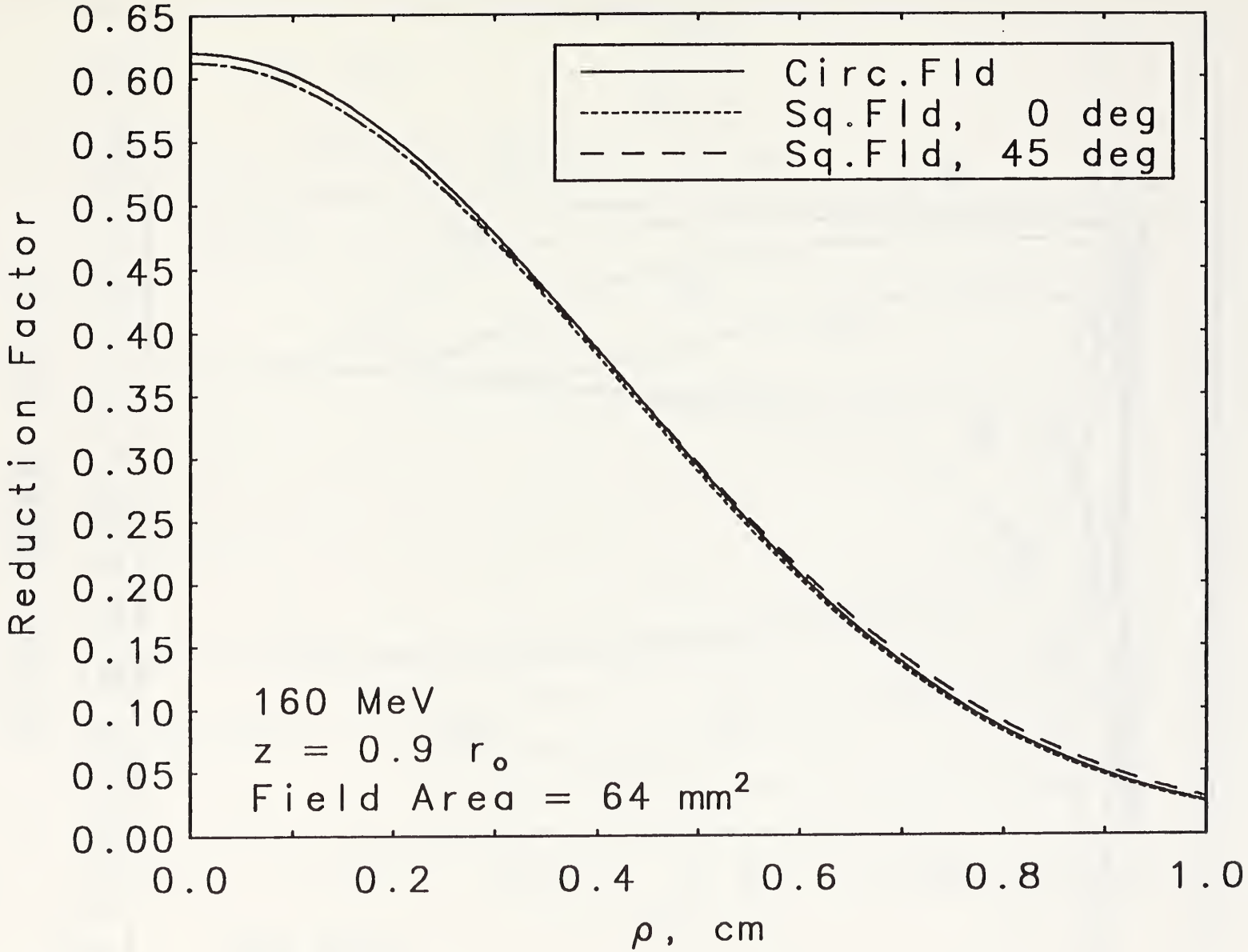
Circ.Fld
Sq.Fld, 0 deg
Sq.Fld, 45 deg
160 MeV
z = 0.9 r₀
Field Area = 64 mm²
Reduction Factor
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
ρ, cm

Fig.15c

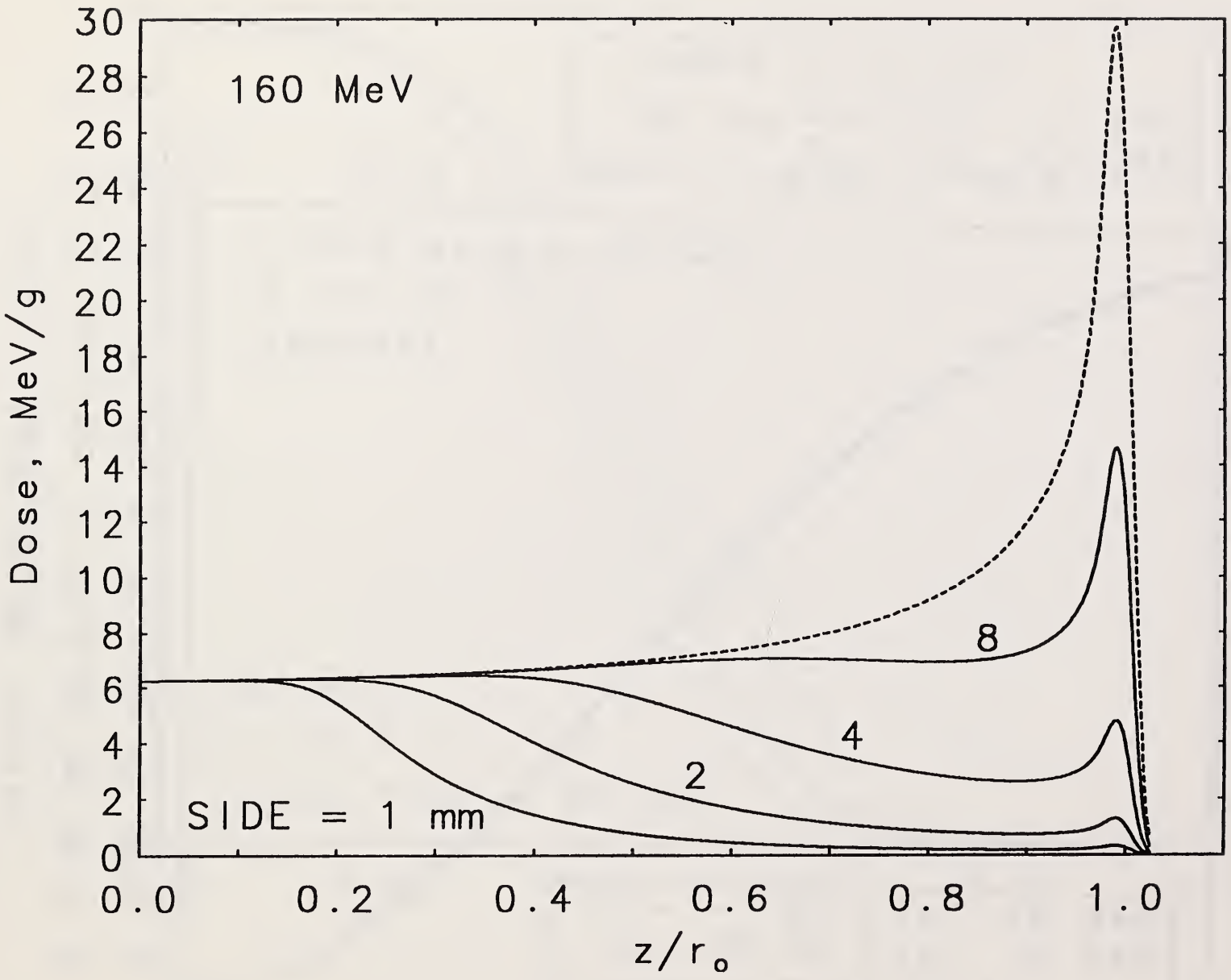
160 MeV
Dose, MeV/g
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
8
4
2
SIDE = 1 mm
0.0
0.2
0.4
0.6
0.8
1.0
z/r o

Fig.16

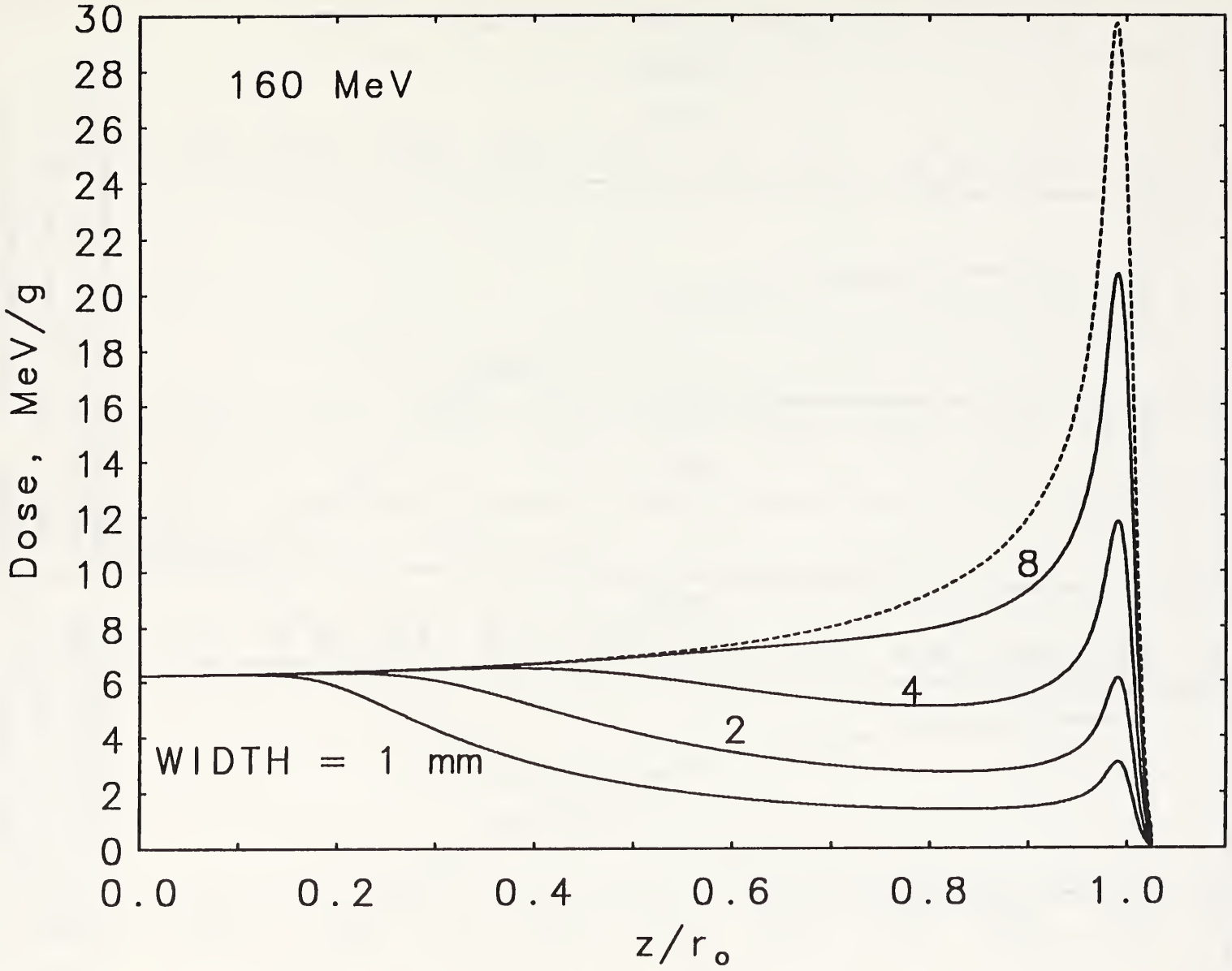
160 MeV
Dose, MeV/g
z/r₀
WIDTH = 1 mm
8
4
2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0.0
0.2
0.4
0.6
0.8
1.0

Fig.17

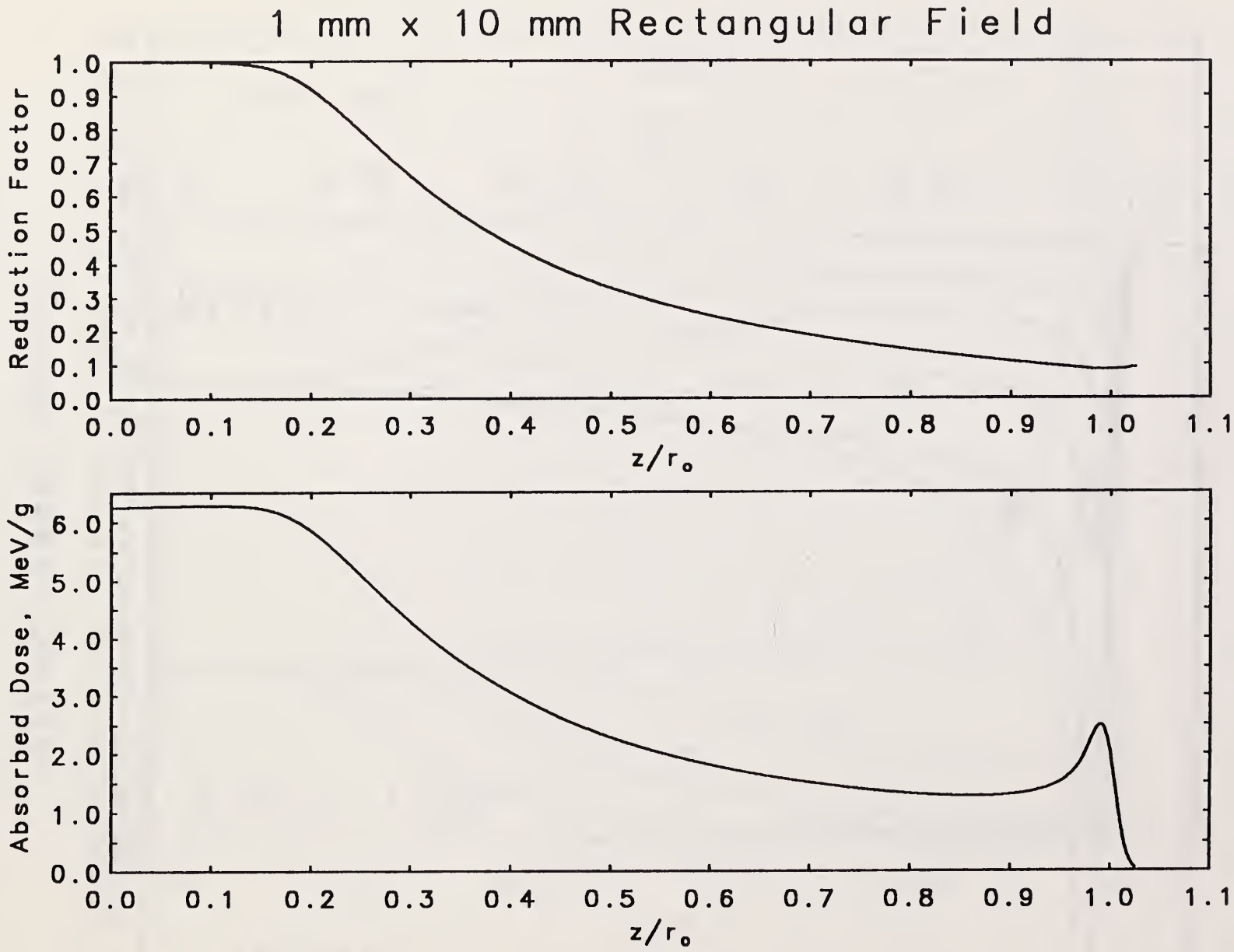
1 mm x 10 mm Rectangular Field
Reduction Factor
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
z/r₀
Absorbed Dose, MeV/g
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
z/r₀

Fig.18a

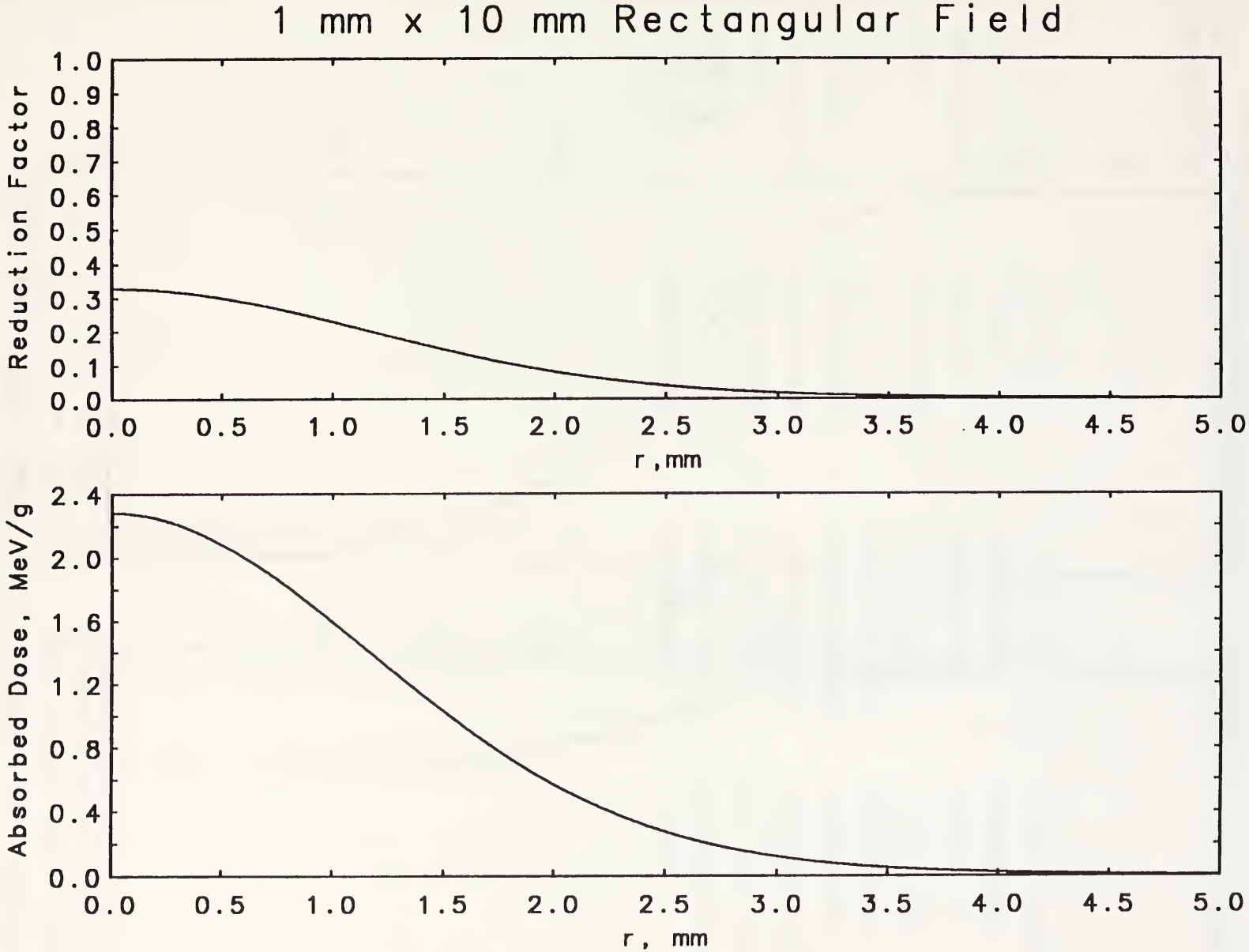
1 mm x 10 mm Rectangular Field
Reduction Factor
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
r, mm
Absorbed Dose, MeV/g
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
r, mm

Fig.18b

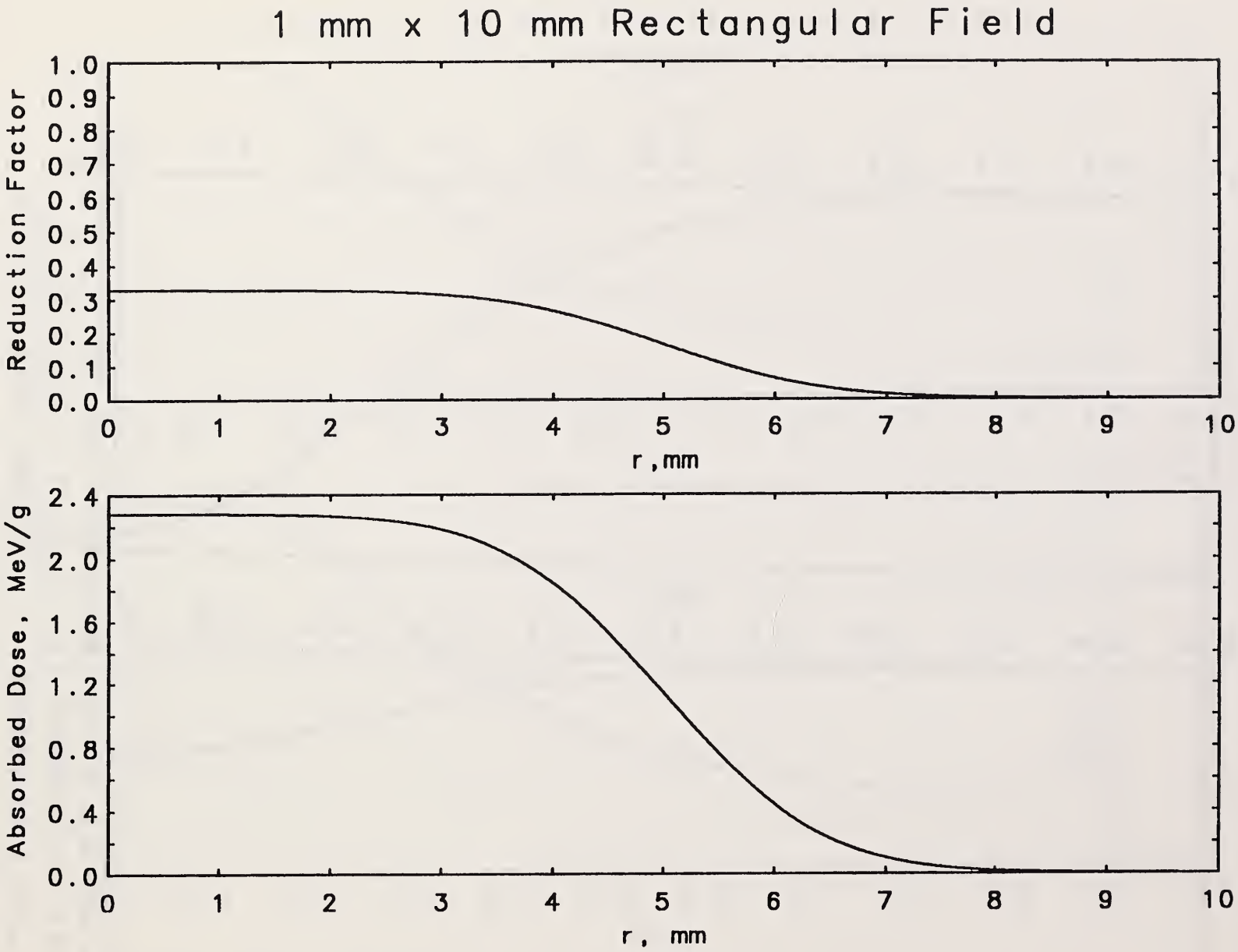
1 mm x 10 mm Rectangular Field
Reduction Factor
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8
9
10
r ,mm
Absorbed Dose, MeV/g
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
1
2
3
4
5
6
7
8
9
10
r , mm

Fig.18c

Appendix 1. Files on Disk

Fortran source codes, executable codes (for use on IBM-compatible personal computers), data files and sample output files are stored on a 3.5 inch 1.44 Mb floppy disk. Included are the following files:

AXPLOT.EXE	FREC.EXE	MOLC2.COF	PTGPOL.FOR
AXPLOT.FOR	FREC.FOR	MORAD.160	PTPOL.EXE
COMPOS.WAT	FREC1.1	MORAD.EXE	PTPOL.FOR
FCIR.1	FREC1.EXE	MORAD.FOR	PTRAD.160
FCIR.2	FREC1.FOR	MORAD10.160	PTRAD.EXE
FCIR.EXE	FREC2.EXE	MORAD160.050	PTRAD.FOR
FCIR.FOR	FREC2.FOR	MORAD50.160	RADPLOT.EXE
FREC.1	MCORR.001	MORAD90.16	RADPLOT.FOR
FREC.2A	MCORR.008	PDEPTH.ARR	STOPRANG.WAT
FREC.2B	MOLC1.COF	PTGPOL.EXE	ZRFILE

Appendix 2. Source Code Listings

The following programs are listed:

PTPOL	Energy deposition distributions from monoenergetic beams
PTGPOL	Energy deposition distributions from beams with a Gaussian spectrum
MORAD	Radial dose distributions from Molière's theory
PTRAD	Radial dose distributions from Monte Carlo program PTRAN
FCIR	Calculation of 3-D dose distributions from circular fields
FREC	Calculation of 3-D dose distribution from rectangular field, along a line starting at the center of the field.
FREC1	Calculation of 3-D dose distribution from rectangular field, for a set of (x,y) positions
FREC2	Same as FREC1, using double numerical quadrature
AXPLOT	Plotting of central-axis absorbed-dose distributions
RADPLOT	Plotting of radial absorbed-dose distributions

```
      PROGRAM PTPOL
C
C     10 May 93. Written by Martin J. Berger, NIST.
C
C               Calculates energy deposition per unit depth, as
C               function of depth, for a monoenergetic beam with
C               with an energy between 50 and 250 MeV. Results are
C               obtained by interpolation in a database of processed
C               results obtained with the Monte Carlo program PTRAN1D
C               at 25 energies between 250 MeV and 50 MeV.
C
C               Required input file:
C               PDEPTH.ARR, processed depth-dose distributions
C
C               The following subroutines are called:
C
C                   SCOFD       Calculates cubic spline coefficients
C                  BSPOLD       Evaluates cubic spline
C                 BSPOLD2       Evaluetes first and second derivative
C                               of cubic spline
C                    SPMAX      Finds maximum of cubic-spline function
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION T(30),TL(30),Z(50),D(30,50),DL(30),
     1 AX1(30),BX1(30),CX1(30),DX1(30),
     5 AR(30),BR(30),CR(30),DR(30),
     6 RG(30),RGL(30),DINT(50),DINT1(50)
      CHARACTER OUTPUT*30,LINE*80
      DATA EPS/1.0D-05/
    1 FORMAT(1H )
    5 FORMAT(A)
      PRINT *,' Enter energy (MeV): '
      READ *, EBEAM
      IF(EBEAM.LE.250.0D0.AND.EBEAM.GE.50.0D0) GO TO 7
      PRINT 6
    6 FORMAT(' Energy is out of range.')
      STOP
    7 PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      OPEN (8,OUTPUT)
      WRITE (8,8) OUTPUT
    8 FORMAT('Program PTPOL, output file ',A)
      WRITE (8,1)
      OPEN (7,'PDEPTH.ARR')
      READ (7,5) LINE
      READ (7,*) NMAX,LMAX
      READ (7,*) (Z(N),N=1,NMAX)
      DO 50 L=1,LMAX
      READ (7,*) T(L),RG(L)
      TL(L)=LOG(T(L))
      RGL(L)=LOG(RG(L))
      READ (7,*) (D(L,N),N=1,NMAX)
      DO 40 N=1,NMAX
      IF(D(L,N).LE.0.0D0) D(L,N)=1.0D-08
   40 CONTINUE
   50 CONTINUE
      CALL SCOFD(TL,RGL,LMAX,AR,BR,CR,DR)
      EBEAML=LOG(EBEAM)
      CALL BSPOLD(EBEAML,TL,AR,BR,CR,DR,LMAX,RES)
      RANGE=EXP(RES)
      DO 80 N=1,NMAX
      DO 70 L=1,LMAX
      DL(L)=LOG(D(L,N))
   70 CONTINUE
      CALL SCOFD(TL,DL,LMAX,AX1,BX1,CX1,DX1)
      CALL BSPOLD(EBEAML,TL,AX1,BX1,CX1,DX1,LMAX,RES)
      DINT(N)=EXP(RES)
   80 CONTINUE
      CALL SPMAX(Z,DINT,NMAX,EPS,ZM,DMAX)
      DO 100 N=1,NMAX
  100 DINT1(N)=DINT(N)/DMAX
  110 WRITE (8,111)
  111 FORMAT('  EBEAM = average beam energy, MeV')
      WRITE (8,112)
  112 FORMAT('  RANGE = CSDA range at energy EBEAM, g/cm2')
      WRITE (8,113)
  113 FORMAT('     ZM = depth (in units of RANGE) at which energy-deposi
     1tion curve peaks')
      WRITE (8,114)
  114 FORMAT('   DMAX = energy deposition per unit depth at peak, MeV cm
     12/g')
      WRITE (8,115)
  115 FORMAT('   NMAX = number of depths')
      WRITE (8,1)
      WRITE (8,116)
  116 FORMAT(4X,'EBEAM',4X,'RANGE',7X,'ZM',5X,'DMAX',3X,'NMAX')
      WRITE (8,117) EBEAM,RANGE,ZM,DMAX,NMAX
  117 FORMAT(F9.2,3F9.4,I7)
      WRITE (8,1)
      WRITE (8,120)
  120 FORMAT('Depths, in units of RANGE')
      WRITE (8,130) (Z(N),N=1,NMAX)
  130 FORMAT(6F12.3)
      WRITE (8,140)
  140 FORMAT('dD/dz, energy-deposition distribution, MeV cm2/g, per inci
     1dent proton')
      WRITE (8,150) (DINT(N),N=1,NMAX)
  150 FORMAT(6F12.6)
      WRITE (8,160)
  160 FORMAT('Relative energy-deposition distribution (peak value unity)
     1')
      WRITE (8,150) (DINT1(N),N=1,NMAX)
      STOP
      END
      SUBROUTINE SPMAX(X,Y,NMAX,EPS,XM,YMAX)
C     3 Mar 93. Finds maximum of spline function.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),Y(1000),A(1000),B(1000),C(1000),D(1000)
      YMAX=0.0
      XM=X(1)
      DO 20 N=1,NMAX
      IF(Y(N)-YMAX)20,20,10
   10 YMAX=Y(N)
      XM=X(N)
   20 CONTINUE
      CALL SCOFD(X,Y,NMAX,A,B,C,D)
   30 CALL BSPOLD2(XM,X,A,B,C,D,NMAX,RES,RES1,RES2)
      XMNEW=XM-RES1/RES2
      RAT=ABS((XMNEW-XM)/XM)
      IF(RAT.LT.EPS) GO TO 40
      XM=XMNEW
      GO TO 30
   40 YMAX=RES
      RETURN
      END
      SUBROUTINE BSPOLD2(S,X,A,B,C,D,N,G,G1,G2)
C     2 Mar 93. Evaluates first and second derivative of cubic-spline
C               function.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),A(1000),B(1000),C(1000),D(1000)
      IF (X(1).GT.X(N)) GO TO 10
      IDIR=0
      MLB=0
      MUB=N
      GO TO 20
   10 IDIR=1
      MLB=N
      MUB=0
   20 IF (S.GE.X(MUB+IDIR)) GO TO 60
      IF (S.LE.X(MLB+1-IDIR)) GO TO 70
      ML=MLB
      MU=MUB
      GO TO 40
   30 IF (IABS(MU-ML).LE.1) GO TO 80
   40 MAV=(ML+MU)/2
      IF (S.LT.X(MAV)) GO TO 50
      ML=MAV
      GO TO 30
   50 MU=MAV
      GO TO 30
   60 MU=MUB+2*IDIR-1
      GO TO 90
   70 MU=MLB-2*IDIR+1
      GO TO 90
   80 MU=MU+IDIR-1
   90 Q=S-X(MU)
      G=((D(MU)*Q+C(MU))*Q+B(MU))*Q+A(MU)
      G1=B(MU)+2.0*C(MU)*Q+3.0*D(MU)*Q*Q
      G2=2.0*C(MU)+6.0*D(MU)*Q
      RETURN
      END
      SUBROUTINE SCOFD(X,F,NMAX,A,B,C,D)
C     1 JAN 87. DOUBLE PRECISION
C  IF S LIES BETWEEN X(M) AND X(M+1), THEN
C  F(S)=((D(M)*S+C(M))*S+B(M))*S+A(M)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),F(1000),A(1000),B(1000),C(1000),D(1000)
      M1=2
      M2=NMAX-1
      S=0.0
      DO 10 M=1,M2
      D(M)=X(M+1)-X(M)
      R=(F(M+1)-F(M))/D(M)
      C(M)=R-S
   10 S=R
      S=0.0
      R=0.0
      C(1)=0.0
      C(NMAX)=0.0
      DO 20 M=M1,M2
      C(M)=C(M)+R*C(M-1)
      B(M)=(X(M-1)-X(M+1))*2.0D0-R*S
      S=D(M)
   20 R=S/B(M)
      MR=M2
      DO 30 M=M1,M2
      C(MR)=(D(MR)*C(MR+1)-C(MR))/B(MR)
   30 MR=MR-1
      DO 40 M=1,M2
      S=D(M)
      R=C(M+1)-C(M)
      D(M)=R/S
```

```
      C(M)=C(M)*3.0D0
      B(M)=(F(M+1)-F(M))/S-(C(M)+R)*S
   40 A(M)=F(M)
      RETURN
      END
      SUBROUTINE BSPOLD(S,X,A,B,C,D,N,G)
C     1 JAN 87. DOUBLE PRECISION
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),A(1000),B(1000),C(1000),D(1000)
      IF (X(1).GT.X(N)) GO TO 10
      IDIR=0
      MLB=0
      MUB=N
      GO TO 20
   10 IDIR=1
      MLB=N
      MUB=0
   20 IF (S.GE.X(MUB+IDIR)) GO TO 60
      IF (S.LE.X(MLB+1-IDIR)) GO TO 70
      ML=MLB
      MU=MUB
      GO TO 40
   30 IF (IABS(MU-ML).LE.1) GO TO 80
   40 MAV=(ML+MU)/2
      IF (S.LT.X(MAV)) GO TO 50
      ML=MAV
      GO TO 30
   50 MU=MAV
      GO TO 30
   60 MU=MUB+2*IDIR-1
      GO TO 90
   70 MU=MLB-2*IDIR+1
      GO TO 90
   80 MU=MU+IDIR-1
   90 Q=S-X(MU)
      G=((D(MU)*Q+C(MU))*Q+B(MU))*Q+A(MU)
      RETURN
      END
```

```
      PROGRAM PTGPOL
C
C     10 May 93. Written by Martin J. Berger, NIST.
C
C
C               Calculates energy deposition per unit depth, as
C               function of depth, for beam with a Gaussian spectrum.
C               The spectrum must be specified in terms of a mean
C               energy, and a relative standard deviation (expressed
C               as a percentage of the mean energy. PTGPOL relies
C               on interpolation in a database of processed results
C               obtained with Monte Carlo program PTRAN1D for proton
C               beams with 25 energies between 250 MeV and 50 MeV.
C
C               Required input file:
C               PDEPTH.ARR, processed depth-dose distributions
C
C               The following subroutines are called:
C
C                   SCOFD       Calculates cubic spline coefficients
C                  BSPOLD       Evaluates cubic spline
C                 BSPOLD2       Evaluetes first and second derivative
C                               of cubic spline
C                    SPMAX      Finds maximum of cubic-spline function
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION T(30),TL(30),Z(50),D(30,50),DL(30),DD(201),DDREL(201),
     1 E(401),WT(401),RGINT(401),AX1(30),BX1(30),CX1(30),DX1(30),
     2 AX3(50),BX3(50),CX3(50),DX3(50),AR(30),BR(30),CR(30),DR(30),
     3 RG(30),RGL(30),DIN(50),DINT(401,50),DS(401,52),ZREF(201)
      CHARACTER INPUT*16,OUTPUT*16,LINE*80
      DATA EPS/1.0D-05/
    1 FORMAT(1H )
    5 FORMAT(A)
      PRINT *,' Enter average beam energy (MeV): '
      READ *, EAV
      PRINT *,' Enter relative standard deviation (percent): '
      READ *, P
      SIGMA=0.01*P*EAV
      PRINT *,' Suggested values: 4.0'
      PRINT *,' Enter cut-off for Gaussian (in units of standard deviati
     lon: '
      READ *, CUT
      ENMAX=EAV+CUT*SIGMA
      IF(ENMAX.LE.250.0D0) GO TO 6
      STOP ' STOP: Some energies in spectrum are above 250 MeV.'
    6 ENMIN=EAV-CUT*SIGMA
      IF(ENMIN.GE.50.0D0) GO TO 7
      STOP ' STOP: Some energies in spectrum are below 50 MeV.'
    7 PRINT *,' Suggested value: 401'
      PRINT *,' Enter number of energies in Gaussian that are sampled: '
      READ *, KMAX
      PRINT *,' Suggested choice: ZRFILE (default)'
      PRINT *,' Enter name of file with list of depths: '
      READ 5, INPUT
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      OPEN (8,OUTPUT)
      WRITE (8,10) OUTPUT
   10 FORMAT('Program PTGPOL, output file ',A)
      WRITE (8,11) INPUT
   11 FORMAT ('List of depths from file ',A)
      WRITE (8,1)
      OPEN (7,INPUT)
      READ (7,*) NRMAX
      READ (7,*) (ZREF(N),N=1,NRMAX)
      CLOSE (7)
      EMIN=EAV-CUT*SIGMA
      EMAX=EAV+CUT*SIGMA
      DE=(EMAX-EMIN)/REAL(KMAX-1)
      DO 15 K=1,KMAX
      E(K)=EMIN+DE*REAL(K-1)
      WT(K)=0.0
      IF(E(K).GT.EMAX) GO TO 15
      IF(E(K).LT.EMIN) GO TO 15
      ARG=0.5*((E(K)-EAV)/SIGMA)**2
      WT(K)=EXP(-ARG)
   15 CONTINUE
      SUM=0.0
      DO 20 K=1,KMAX
   20 SUM=SUM+WT(K)
      DO 30 K=1,KMAX
   30 WT(K)=WT(K)/SUM
      OPEN (7,'PDEPTH.ARR')
      READ (7,5) LINE
      READ (7,*) NMAX,LMAX
      READ (7,*) (Z(N),N=1,NMAX)
      DO 50 L=1,LMAX
      READ (7,*) T(L),RG(L)
      TL(L)=LOG(T(L))
      RGL(L)=LOG(RG(L))
      READ (7,*) (D(L,N),N=1,NMAX)
      DO 40 N=1,NMAX
      IF(D(L,N).LE.0.0D0) D(L,N)=1.0D-08
   40 CONTINUE
   50 CONTINUE
      CALL SCOFD(TL,RGL,LMAX,AR,BR,CR,DR)
      EAVL=LOG(EAV)
      CALL BSPOLD(EAVL,TL,AR,BR,CR,DR,LMAX,RES)
      RGREF=EXP(RES)
      DO 60 K=1,KMAX
      EL=LOG(E(K))
      CALL BSPOLD(EL,TL,AR,BR,CR,DR,LMAX,RES)
   60 RGINT(K)=EXP(RES)
      DO 90 N=1,NMAX
      DO 70 L=1,LMAX
      DL(L)=LOG(D(L,N))
   70 CONTINUE
      CALL SCOFD(TL,DL,LMAX,AX1,BX1,CX1,DX1)
      DO 80 K=1,KMAX
      EL=LOG(E(K))
      CALL BSPOLD(EL,TL,AX1,BX1,CX1,DX1,LMAX,RES)
      DINT(K,N)=RES
   80 CONTINUE
   90 CONTINUE
      DO 140 K=1,KMAX
      DO 100 N=1,NMAX
      DIN(N)=DINT(K,N)
  100 CONTINUE
      CALL SCOFD(Z,DIN,NMAX,AX3,BX3,CX3,DX3)
      DO 130 N=1,NRMAX
      DD(N)=0.0
      ZINT=ZREF(N)*(RGREF/RGINT(K))
      IF(ZINT-1.04)120,110,110
  110 DS(K,N)=0.0
      GO TO 130
  120 CALL BSPOLD(ZINT,Z,AX3,BX3,CX3,DX3,NMAX,RES1)
      DS(K,N)=EXP(RES1)
  130 CONTINUE
  140 CONTINUE
      DO 160 N=1,NRMAX
      DD(N)=0.0
      DO 150 K=1,KMAX
      DD(N)=DD(N)+WT(K)*DS(K,N)
  150 CONTINUE
  160 CONTINUE
      CALL SPMAX(ZREF,DD,NRMAX,EPS,ZM,DMAX)
      DO 180 N=1,NRMAX
  180 DDREL(N)=DD(N)/DMAX
      WRITE (8,191)
  191 FORMAT('     EAV = average beam energy, MeV')
      WRITE (8,192)
  192 FORMAT('  SIGMA = standard deviation of beam spectrum, MeV')
      WRITE (8,193)
  193 FORMAT('      P = 100*SIGMA/EAV, relative standard deviation')
      WRITE (8,194)
  194 FORMAT('    CUT = cut-off for Gaussian beam (in units of SIGMA)')
      WRITE (8,195)
  195 FORMAT('  RGREF = CSDA range at energy EAV')
      WRITE (8,196)
  196 FORMAT('     ZM = depth (in units of RANGE) at which energy-depos
     1ition curve peaks')
      WRITE (8,197)
  197 FORMAT('   DMAX = energy deposition per unit depth at peak, MeV cm
     12/g')
      WRITE (8,198)
  198 FORMAT('  NRMAX = number of depths')
      WRITE (8,1)
      WRITE (8,220)
  220 FORMAT(6X,'EAV',4X,'SIGMA',8X,'P',6X,'CUT',4X,'RGREF',7X,'ZM',
     1 5X,'DMAX',3X,'NRMAX')
      WRITE (8,230) EAV,SIGMA,P,CUT,RGREF,ZM,DMAX,NRMAX
  230 FORMAT(4F9.2,3F9.4,I8)
      WRITE (8,1)
      WRITE (8,240)
  240 FORMAT('Depths, in units of RGREF')
      WRITE (8,250) (ZREF(N),N=1,NRMAX)
  250 FORMAT(6F12.6)
      WRITE (8,260)
  260 FORMAT('dD/dz, energy-deposition distribution, MeV cm2/g, per inci
     1dent proton')
      WRITE (8,250) (DD(N),N=1,NRMAX)
      WRITE (8,270)
  270 FORMAT('Relative energy-deposition distribution (peak value unity'
     1)
      WRITE (8,250) (DOREL(N),N=1,NRMAX)
      STOP
      END
      SUBROUTINE SPMAX(X,Y,NMAX,EPS,XM,YMAX)
C     3 Mar 93. Finds maximum of cubic-spline function.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),Y(1000),A(1000),B(1000),C(1000),D(1000)
      YMAX=0.0
      XM=X(1)
      DO 20 N=1,NMAX
      IF(Y(N)-YMAX)20,20,10
   10 YMAX=Y(N)
      XM=X(N)
   20 CONTINUE
      CALL SCOFD(X,Y,NMAX,A,B,C,D)
   30 CALL BSPOLD2(XM,X,A,B,C,D,NMAX,RES,RES1,RES2)
      XMNEW=XM-RES1/RES2
      RAT=ABS((XMNEW-XM)/XM)
```

```
      IF(RAT.LT.EPS) GO TO 40
      XM=XMNEW
      GO TO 30
   40 YMAX=RES
      RETURN
      END
      SUBROUTINE BSPOLD2(S,X,A,B,C,D,N,G,G1,G2)
C     2 Mar 93. Evaluates first and second derivative.
C               of cubic-spline function
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),A(1000),B(1000),C(1000),D(1000)
      IF (X(1).GT.X(N)) GO TO 10
      IDIR=0
      MLB=0
      MUB=N
      GO TO 20
   10 IDIR=1
      MLB=N
      MUB=0
   20 IF (S.GE.X(MUB+IDIR)) GO TO 60
      IF (S.LE.X(MLB+1-IDIR)) GO TO 70
      ML=MLB
      MU=MUB
      GO TO 40
   30 IF (IABS(MU-ML).LE.1) GO TO 80
   40 MAV=(ML+MU)/2
      IF (S.LT.X(MAV)) GO TO 50
      ML=MAV
      GO TO 30
   50 MU=MAV
      GO TO 30
   60 MU=MUB+2*IDIR-1
      GO TO 90
   70 MU=MLB-2*IDIR+1
      GO TO 90
   80 MU=MU+IDIR-1
   90 Q=S-X(MU)
      G=((D(MU)*Q+C(MU))*Q+B(MU))*Q+A(MU)
      G1=B(MU)+2.0*C(MU)*Q+3.0*D(MU)*Q*Q
      G2=2.0*C(MU)+6.0*D(MU)*Q
      RETURN
      END
      SUBROUTINE SCOFD(X,F,NMAX,A,B,C,D)
C     1 JAN 87. DOUBLE PRECISION
C  IF S LIES BETWEEN X(M) AND X(M+1), THEN
C  F(S)=((D(M)*S+C(M))*S+B(M))*S+A(M)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),F(1000),A(1000),B(1000),C(1000),D(1000)
      M1=2
      M2=NMAX-1
      S=0.0
      DO 10 M=1,M2
      D(M)=X(M+1)-X(M)
      R=(F(M+1)-F(M))/D(M)
      C(M)=R-S
   10 S=R
      S=0.0
      R=0.0
      C(1)=0.0
      C(NMAX)=0.0
      DO 20 M=M1,M2
      C(M)=C(M)+R*C(M-1)
      B(M)=(X(M-1)-X(M+1))*2.0D0-R*S
      S=D(M)
   20 R=S/B(M)
      MR=M2
      DO 30 M=M1,M2
      C(MR)=(D(MR)*C(MR+1)-C(MR))/B(MR)
   30 MR=MR-1
      DO 40 M=1,M2
      S=D(M)
      R=C(M+1)-C(M)
      D(M)=R/S
      C(M)=C(M)*3.0D0
      B(M)=(F(M+1)-F(M))/S-(C(M)+R)*S
   40 A(M)=F(M)
      RETURN
      END
      SUBROUTINE BSPOLD(S,X,A,B,C,D,N,G)
C     1 JAN 87. DOUBLE PRECISION
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),A(1000),B(1000),C(1000),D(1000)
      IF (X(1).GT.X(N)) GO TO 10
      IDIR=0
      MLB=0
      MUB=N
      GO TO 20
   10 IDIR=1
      MLB=N
      MUB=0
   20 IF (S.GE.X(MUB+IDIR)) GO TO 60
      IF (S.LE.X(MLB+1-IDIR)) GO TO 70
      ML=MLB
      MU=MUB
      GO TO 40
   30 IF (IABS(MU-ML).LE.1) GO TO 80
   40 MAV=(ML+MU)/2
      IF (S.LT.X(MAV)) GO TO 50
      ML=MAV
      GO TO 30
   50 MU=MAV
      GO TO 30
   60 MU=MUB+2*IDIR-1
      GO TO 90
   70 MU=MLB-2*IDIR+1
      GO TO 90
   80 MU=MU+IDIR-1
   90 Q=S-X(MU)
      G=((D(MU)*Q+C(MU))*Q+B(MU))*Q+A(MU)
      RETURN
      END
```

```
      PROGRAM MORAD
C
C     8 July 93. Written by Martin J. Berger, NIST.
C
C               Evaluates radial multiple scattering distribution
C               f(rho) of Moliere (Z.Naturf.10a,177-211,1955), as
C               function of the radial distance rho.
C
C               The expansion coefficients in the Moliere formula,
C               are supplied by files MOLC1.COF and MOLC2.COF.
C
C               For application to a water medium, the following
C               data files are required as input:
C
C               STOPRANG.WAT    Proton stopping powers and ranges
C                               in water
C
C               COMPOS.WAT      Composition data for water
C
C               MCORR.001 and   Correction factors for H and O that
C               MCORR.008       convert Thomas-Fermi to Hartree-
C                               Fock screening
C
C               The following subroutines are used:
C
C               SCOFD:  calculates cubic spline coefficients
C               BSPOLD: evaluates cubic spline
C               GRALD:  carries out numerical quadrature
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON X(401),D(401),COF1(401),COF2(401),
     1 DOR(3001),MZ(20),WT(20),CP(20),
     2 APL(20),ALFB(20),FAC1(20),FAC8(20),
     3 AM1(20),BM1(20),CM1(20),DM1(20),
     4 AM8(20),BM8(20),CM8(20),DM8(20)
      COMMON THA1(451),THB1(451),THA2(451),THB2(451),
     1 FA1(451),FB1(451),FA2(451),FB2(451),
     2 AS1(451),BS1(451),CS1(451),DS1(451),
     3 AL1(451),BL1(451),CL1(451),DL1(451),
     4 AS2(451),BS2(451),CS2(451),DS2(451),
     5 AL2(451),BL2(451),CL2(451),DL2(451)
      COMMON ENG(133),ENGL(133),STP(133),RANG(133),RANGL(133),
     1 A1(574),B1(574),C1(574),D1(574),
     2 A2(574),B2(574),C2(574),D2(574),
     3 A3(101),B3(101),C3(101),D3(101),
     3 S(1001),SFAC(1001),TAUFAC(1001),TAU2(1001),BETQ(1001),BET(1001),
     4 GRAND(1001),ZR(120)
      DIMENSION UIN(100)
      CHARACTER*72 HEAD1,HEAD2,TAG
      CHARACTER*16 INPUT,OUTPUT
      DATA UIN/3.6,4.0,4.3,4.6,4.8,5.0,5*5.1,3*5.2,3*5.3,3*5.4,
     1 4*5.5,5*5.6,5*5.7,6*5.8,7*5.9,8*6.0,10*6.1,11*6.2,12*6.3,
     2 12*6.4/
      DATA FCON/1130.0D0/,LMAX/1001/
      DATA AVOG/6.0221367D+23/,EMASS/0.51099906D0/,PMASS/938.27231D0/,
     1 FINE/137.035989D0/,RCLASS/2.81794092D-13/,EUL/0.577215664D0/
      DATA BEPS/1.0E-09/,ZRMAX/0.98/,THMAX/10.0D0/,NMAX/99/,IFAN/1/
    1 FORMAT(1H )
    5 FORMAT(A)
      PI=4.0D0*ATAN(1.0D0)
      RATMQ=(EMASS/PMASS)**2
      CON=4.0D0*PI*AVOG*(RCLASS**2)*RATMQ
      TFCON=((3.0D0*PI)**(2.0D0/3.0D0))/(2.0D0**(7.0D0/3.0D0))
      CON1=RATMQ/(TFCON*FINE)**2
      PRINT *,' Enter initial proton energy (MeV): '
      READ *, TIN
      PRINT *,' Path lengths are to be expressed in units of CSDA range'
      PRINT *,' Options for path length input:'
      PRINT *,'   1) From file'
      PRINT *,'   2) Specify set of path lengths in terms of maximum'
      PRINT *,'      value, ZRMAX, and number of values, NMAX.'
      PRINT *,'   3) Use default values ZRMAX=0.98, NMAX=98.'
      PRINT *,' Enter choice: '
      READ *, INF
      GO TO (6,7,8), INF
    6 PRINT *,' Enter name of path-length input file: '
      READ 5, INPUT
      OPEN (7,INPUT)
      READ (7,*) NMAX
      READ (7,*) (ZR(N),N=1,NMAX)
      CLOSE (7)
      GO TO 12
    7 PRINT *,' Enter maximum path length, ZRMAX: '
      READ *, ZRMAX
      PRINT *,' Enter number of path lengths (no greater than 120): '
      READ *, NMAX
      GO TO 9
    8 ZRMAX=0.98
      NMAX=98
    9 DZR=ZRMAX/DBLE(NMAX)
      DO 10 N=1,NMAX
   10 ZR(N)=DZR*DBLE(N)
   12 PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, KMAX
      PRINT *,' Suggested name: MORAD.nnn'
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      OPEN (8,OUTPUT)
      WRITE (8,13) OUTPUT
   13 FORMAT('Program MORAD, output file ',A)
      WRITE (8,1)
      IF(NMAX.EQ.1) WRITE (8,14) NMAX
   14 FORMAT(I6,' depth')
      IF(NMAX.NE.1) WRITE (8,15) NMAX
   15 FORMAT(I6,' depths')
      IF(KMAX.EQ.1) WRITE (8,16) KMAX
   16 FORMAT(I6,' radial distance')
      IF(KMAX.NE.1) WRITE (8,17) KMAX
   17 FORMAT(I6,' radial distances')
      WRITE (8,1)
      OPEN (UNIT=7,FILE='STOPRANG.WAT')
      READ (7,*) JMAX
      READ (7,*) (ENG(J),J=1,JMAX)
      READ (7,*) (STP(J),J=1,JMAX)
      READ (7,*) (RANG(J),J=1,JMAX)
      CLOSE (7)
      DO 18 J=1,JMAX
      ENGL(J)=LOG(ENG(J))
   18 RANGL(J)=LOG(RANG(J)+1.0D-09)
      CALL SCOFD(ENGL,RANGL,JMAX,A1,B1,C1,D1)
      CALL SCOFD(RANGL,ENGL,JMAX,A2,B2,C2,D2)
      OPEN (7,'COMPOS.WAT')
      READ (7,5) MAT
      READ (7,*) MMAX
      READ (7,20) (MZ(M),WT(M),M=1,MMAX)
   20 FORMAT(6(I3,F9.6))
      CLOSE (7)
      TINL=LOG(TIN)
      CALL BSPOLD(TINL,ENGL,A1,B1,C1,D1,JMAX,RES)
      RGIN=EXP(RES)
      OPEN (UNIT=7,FILE='MOLC1.COF')
      READ (7,5) HEAD1
      READ (7,5) TAG
      READ (7,5) TAG
      READ (7,5) TAG
      READ (7,*) JMA1,JMB1,THCUT1
      READ (7,*) (THA1(J),J=1,JMA1)
      READ (7,*) (FA1(J),J=1,JMA1)
      READ (7,*) (THB1(J),J=1,JMB1)
      READ (7,*) (FB1(J),J=1,JMB1)
      CLOSE (7)
      CALL SCOFD(THA1,FA1,JMA1,AS1,BS1,CS1,DS1)
      CALL SCOFD(THB1,FB1,JMB1,AL1,BL1,CL1,DL1)
      OPEN (UNIT=7,FILE='MOLC2.COF')
      READ (7,5) HEAD2
      READ (7,5) TAG
      READ (7,5) TAG
      READ (7,5) TAG
      READ (7,*) JMA2,JMB2,THCUT2
      READ (7,*) (THA2(J),J=1,JMA2)
      READ (7,*) (FA2(J),J=1,JMA2)
      READ (7,*) (THB2(J),J=1,JMB2)
      READ (7,*) (FB2(J),J=1,JMB2)
      CLOSE (7)
      CALL SCOFD(THA2,FA2,JMA2,AS2,BS2,CS2,DS2)
      CALL SCOFD(THB2,FB2,JMB2,AL2,BL2,CL2,DL2)
      OPEN (7,'MCORR.001')
      READ (7,5) TAG
      READ (7,*) MCMAX
      DO 30 MC=1,MCMAX
      READ (7,*) ALFB(MC),FAC1(MC)
   30 CONTINUE
      CLOSE (7)
      CALL SCOFD(ALFB,FAC1,MCMAX,AM1,BM1,CM1,DM1)
      OPEN (7,'MCORR.008')
      READ (7,5) TAG
      READ (7,*) MCMAX
      DO 40 MC=1,MCMAX
      READ (7,*) ALFB(MC),FAC8(MC)
   40 CONTINUE
      CLOSE (7)
      CALL SCOFD(ALFB,FAC8,MCMAX,AM8,BM8,CM8,DM8)
      DO 280 N=1,NMAX
      RFRAC=ZR(N)
      PATH=RGIN*RFRAC
      DS=PATH/REAL(LMAX-1)
      DELTA=DS/3.0D0
      DO 50 L=1,LMAX
      S(L)=DS*REAL(L-1)
      SFAC(L)=(1.0D0-S(L)/PATH)**2
      RGL=LOG(RGIN-S(L))
      CALL BSPOLD(RGL,RANGL,A2,B2,C2,D2,JMAX,RES)
      E=EXP(RES)
      TAU=E/PMASS
      TAUFAC(L)=((TAU+1.0)/TAU/(TAU+2.0))**2
      TAU2(L)=TAU*(TAU+2.0D0)
      BETQ(L)=TAU*(TAU+2.0)/((TAU+1.0)**2)
   50 BET(L)=SQRT(BETQ(L))
      DO 80 M=1,MMAX
      IZ=MZ(M)
      Z=REAL(IZ)
```

```
      IF(IZ.EQ.1) ATWT=1.0079D0
      IF(IZ.EQ.8) ATWT=15.9996D0
      ZTT=Z**(2.0D0/3.0D0)
      ZFT=ZTT**2
      UINF=UIN(IZ)
      CONZ=CON*(Z*Z/ATWT)*WT(M)
      DO 60 L=1,LMAX
   60 GRAND(L)=TAUFAC(L)*SFAC(L)
      CALL GRALD(DELTA,GRAND,LMAX,RES1)
      CP(M)=CONZ*RES1
      DO 70 L=1,LMAX
      ALPH=Z/FINE/BET(L)
      FAC=1.13D0+3.76D0*(ALPH**2)
      IF(M.EQ.1) CALL BSPOLD(ALPH,ALFB,AM1,BM1,CM1,DM1,MCMAX,ANS)
      IF(M.EQ.2) CALL BSPOLD(ALPH,ALFB,AM8,BM8,CM8,DM8,MCMAX,ANS)
      IF(SFAC(L).LE.0.0D0) GO TO 62
      APLOG=LOG(SFAC(L)*CON1*FAC*ANS*ZTT/TAU2(L))
   62 FCORR=0.0D0
      IF(IFAN.EQ.2) GO TO 65
      DFAN=LOG(FCON*BETQ(L)/(ZFT*(1.0D0-BETQ(L))))+UINF-0.5D0*BETQ(L)
      FCORR=DFAN/Z
   65 GRAND(L)=0.0
      IF(SFAC(L).LE.0.0D0) GO TO 70
      GRAND(L)=TAUFAC(L)*SFAC(L)*(APLOG-FCORR)
   70 CONTINUE
      CALL GRALD(DELTA,GRAND,LMAX,RES2)
      APL(M)=CONZ*RES2
   80 CONTINUE
      CHICQ=0.0
      DO 90 M=1,MMAX
   90 CHICQ=CHICQ+CP(M)
      CHIAQL=0.0
      DO 91 M=1,MMAX
   91 CHIAQL=CHIAQL+APL(M)
      CHIAQL=CHIAQL/CHICQ
      CHIAQ=EXP(CHIAQL)
      COL=CHICQ/CHIAQ
      SB=LOG(COL)+1.0D0-2.0D0*EUL
      B=1.15D0+1.122D0*LOG(COL)
  110 BNEW=B-B*(B-LOG(B)-SB)/(B-1.0)
      ARG=ABS((BNEW-B)/B)
      IF(ARG-BEPS)130,120,120
  120 B=BNEW
      GO TO 110
  130 B=BNEW
      BB=B*B
      SCALE=SQRT(CHICQ*B)
      DNORM=(SCALE*PATH)**2
      RMAX=PATH*SCALE*THMAX
      DX=RMAX/DBLE(KMAX-1)
      DELTX=DX/3.0D0
      DO 240 K=1,KMAX
      X(K)=DX*REAL(K-1)
      TH=(X(K)/PATH)/SCALE
      IF(TH-THCUT1)165,165,170
  165 CALL BSPOLD(TH,THA1,AS1,BS1,CS1,DS1,JMA1,COF1(K))
      GO TO 180
  170 CALL BSPOLD(TH,THB1,AL1,BL1,CL1,DL1,JMB1,RES1)
      TERM=0.5D0*(TH**4)
      COF1(K)=RES1/TERM
  180 IF(TH-THCUT2)190,190,200
  190 CALL BSPOLD(TH,THA2,AS2,BS2,CS2,DS2,JMA2,COF2(K))
      GO TO 210
  200 CALL BSPOLD(TH,THB2,AL2,BL2,CL2,DL2,JMB2,RES2)
      TERM=0.5D0*(TH**4)
      COF2(K)=RES2/TERM
  210 ARG=TH*TH
      IF(ARG-86.0)230,230,220
  220 COF0=0.0D0
      GO TO 235
  230 COF0=2.0D0*EXP(-ARG)
  235 DOR(K)=(COF0+COF1(K)/B+COF2(K)/BB)/DNORM
      D(K)=X(K)*DOR(K)
  240 DOR(K)=DOR(K)/(2.0D0*PI)
      CALL GRALD(DELTX,D,KMAX,SUM)
      DO 245 K=1,KMAX
      DOR(K)=DOR(K)/SUM
  245 D(K)=D(K)/SUM
      IF(N.NE.1) GO TO 257
      WRITE (8,250)
  250 FORMAT('  TIN = energy of incident proton beam, MeV')
      WRITE (8,251)
  251 FORMAT(' RGIN = CSDA range at energy TIN, g/cm2')
      WRITE (8,252)
  252 FORMAT('   ZR = depth, in units of RGIN')
      WRITE (8,253)
  253 FORMAT(' RMAX = largest radial distance')
      WRITE (8,254)
  254 FORMAT('  SUM = cumulative integral of Moliere distribution up to
     1RMAX')
      WRITE (8,1)
      WRITE (8,255)
  255 FORMAT(9X,'TIN',8X,'RGIN')
      WRITE (8,256) TIN,RGIN
  256 FORMAT(2F12.6)
      WRITE (8,1)
  257 WRITE (8,258)
  258 FORMAT(10X,'ZR',8X,'RMAX',9X,'SUM')
      WRITE (8,260)  ZR(N),RMAX,SUM
  260 FORMAT(3F12.6)
      WRITE (8,265)
  265 FORMAT('Radial distances, rho, cm')
      WRITE (8,270) (X(K),K=1,KMAX)
      WRITE (8,275)
  275 FORMAT('Radial distribution, f(rho), cm-2')
      WRITE (8,270) (DOR(K),K=1,KMAX)
  270 FORMAT(1P8E12.5)
      print *,n
  280 CONTINUE
      STOP
      END
      SUBROUTINE SCOFD(X,F,NMAX,A,B,C,D)
C     1 JAN 87. DOUBLE PRECISION
C  IF S LIES BETWEEN X(M) AND X(M+1), THEN
C  F(S)=((D(M)*S+C(M))*S+B(M))*S+A(M)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),F(1000),A(1000),B(1000),C(1000),D(1000)
      M1=2
      M2=NMAX-1
      S=0.0
      DO 10 M=1,M2
      D(M)=X(M+1)-X(M)
      R=(F(M+1)-F(M))/D(M)
      C(M)=R-S
   10 S=R
      S=0.0
      R=0.0
      C(1)=0.0
      C(NMAX)=0.0
      DO 20 M=M1,M2
      C(M)=C(M)+R*C(M-1)
      B(M)=(X(M-1)-X(M+1))*2.0D0-R*S
      S=D(M)
   20 R=S/B(M)
      MR=M2
      DO 30 M=M1,M2
      C(MR)=(D(MR)*C(MR+1)-C(MR))/B(MR)
   30 MR=MR-1
      DO 40 M=1,M2
      S=D(M)
      R=C(M+1)-C(M)
      D(M)=R/S
      C(M)=C(M)*3.0D0
      B(M)=(F(M+1)-F(M))/S-(C(M)+R)*S
   40 A(M)=F(M)
      RETURN
      END
      SUBROUTINE BSPOLD(S,X,A,B,C,D,N,G)
C     1 JAN 87. DOUBLE PRECISION
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1000),A(1000),B(1000),C(1000),D(1000)
      IF (X(1).GT.X(N)) GO TO 10
      IDIR=0
      MLB=0
      MUB=N
      GO TO 20
   10 IDIR=1
      MLB=N
      MUB=0
   20 IF (S.GE.X(MUB+IDIR)) GO TO 60
      IF (S.LE.X(MLB+1-IDIR)) GO TO 70
      ML=MLB
      MU=MUB
      GO TO 40
   30 IF (IABS(MU-ML).LE.1) GO TO 80
   40 MAV=(ML+MU)/2
      IF (S.LT.X(MAV)) GO TO 50
      ML=MAV
      GO TO 30
   50 MU=MAV
      GO TO 30
   60 MU=MUB+2*IDIR-1
      GO TO 90
   70 MU=MLB-2*IDIR+1
      GO TO 90
   80 MU=MU+IDIR-1
   90 Q=S-X(MU)
      G=((D(MU)*Q+C(MU))*Q+B(MU))*Q+A(MU)
      RETURN
      END
      SUBROUTINE GRALD(DELTA,G,N,RESULT)
C     1 JAN 87. DOUBLE PRECISION
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION G(2001)
      NL1=N-1
      NL2=N-2
      IF (DBLE(N)-2.0D0*DBLE(N/2)) 100,100,10
C     IF N IS ODD, GO TO 10 - IF N IS EVEN, GO TO 100
   10 IF(N-1)15,15,20
   15 SIGMA=0.0
      GO TO 70
   20 IF(N-3)30,30,40
```

```
 30 SIGMA=G(1)+4.0D0*G(2)+G(3)
    GO TO 70
 40 SUM4=0.0
    DO 50 K=2,NL1,2
 50 SUM4=SUM4+G(K)
    SUM2=0.0
    DO 60 K=3,NL2,2
 60 SUM2=SUM2+G(K)
    SIGMA=G(1)+4.0D0*SUM4+2.0D0*SUM2+G(N)
 70 RESULT=DELTA*SIGMA
    RETURN
100 IF(N-2)110,110,120
110 SIGMA=1.5D0*(G(1)+G(2))
    GO TO 70
120 IF(N-4)130,130,140
130 SIGMA=1.125D0*(G(1)+3.0D0*G(2)+3.0D0*G(3)+G(4))
    GO TO 70
140 IF(N-6)150,150,160
150 SIGMA=G(1)+3.875D0*G(2)+2.625D0*G(3)+2.625D0*G(4)+
   1 3.875D0*G(5)+G(6)
    GO TO 70
160 IF (N-8)170,170,180
170 SIGMA=G(1)+3.875D0*G(2)+2.625D0*G(3)+2.625D0*G(4)+
   1 3.875D0*G(5)+2.0D0*G(6)+4.0D0*G(7)+G(8)
    GO TO 70
180 SIG6=G(1)+3.875D0*G(2)+2.625D0*G(3)+2.625D0*G(4)+
   1 3.875D0*G(5)+G(6)
    SUM4=0.0
    DO 190 K=7,NL1,2
190 SUM4=SUM4+G(K)
    SUM2=0.0
    DO 200 K=8,NL2,2
200 SUM2=SUM2+G(K)
    SIGMA=SIG6+G(6)+4.0D0*SUM4+2.0D0*SUM2+G(N)
    GO TO 70
    END
```

```
      PROGRAM PTRAD
C
C     20 Apr 93. Written by Martin J. Berger, NIST.
C
C                 Calculates radial dose distribution f(rho) for protons in
C                 water at depths equal to the following fractions of the
C                 CSDA range: 0.985, 0.99, 0.995, 1.0, 1.005, 1.01,
C                 0.015, 1.020, 1.025, for beam energies between
C                 50 and 250 MeV. Results are obtained by interpolation
C                 in a database generated with the Monte Carlo program
C                 PTRAN3D.
C
C                 The following input files must be available:
C                 STOPRANG.WAT: Stopping-power and range table for water.
C                 RADF.032,..,RADF.040: database of processed Monte
C                 Carlo results from PTRAN3D.
C
      DIMENSION EBEG(7),EBEGL(7),T(401),RHO(401),FIT(401,7),
     1 F(401),ENG(133),ENGL(133),STP(133),RANG(133),RANGL(133),
     2 A1(133),B1(133),C1(133),D1(133),FT(401),SUM(7),LP(9)
      CHARACTER  EXT*3,INPUT*16,OUTPUT*16
      DATA LP/32,33,34,35,36,37,38,39,40/,MMAX/7/,LMAX/9/
      DATA EBEG/250.0,200.0,160.0,130.0,100.0,70.0,50.0/
    1 FORMAT(1H )
    5 FORMAT(A)
      PI=4.0*ATAN(1.0)
      PRINT *,' Enter energy (MeV): '
      READ *, TIN
      PRINT *,' Suggested name: PTRAD.nnn'
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      OPEN (8,OUTPUT)
      WRITE (8,6) OUTPUT
    6 FORMAT('Program PTRAD, output file ',A)
      WRITE (8,1)
      DO 10 M=1,MMAX
   10 EBEGL(M)=LOG(EBEG(M))
      OPEN (UNIT=7,FILE='STOPRANG.WAT')
      READ (7,*) KMAX
      READ (7,*) (ENG(K),K=1,KMAX)
      READ (7,*) (STP(K),K=1,KMAX)
      READ (7,*) (RANG(K),K=1,KMAX)
      CLOSE (7)
      DO 20 K=1,KMAX
      ENGL(K)=LOG(ENG(K))
   20 RANGL(K)=LOG(RANG(K)+1.0D-09)
      CALL SCOF(ENGL,RANGL,KMAX,A1,B1,C1,D1)
      TINL=LOG(TIN)
      CALL BSPOL(TINL,ENGL,A1,B1,C1,D1,KMAX,RES)
      RGIN=EXP(RES)
      IF(TIN-EBEG(1))30,30,40
   30 IF(TIN-EBEG(MMAX))40,60,60
   40 PRINT 50
   50 FORMAT('Input energy is out of range.')
      STOP
   60 DO 80 M=2,MMAX
      IF(TINL-EBEGL(M))80,70,70
   70 M1=M-1
      M2=M
      GO TO 85
   80 CONTINUE
   85 FAC1=(TINL-EBEGL(M2))/(EBEGL(M1)-EBEGL(M2))
      FAC2=1.0-FAC1
      DO 160 L=1,LMAX
      CALL INDEX(LP(L),EXT)
      INPUT='RADF.'//EXT
      OPEN (7,INPUT)
      READ (7,5) LINE
      READ (7,*) JMAX,TMAX
      READ (7,*) BR
      DO 90 J=1,JMAX
      READ (7,*) IND,T(J),(FIT(J,M),M=1,MMAX)
   90 CONTINUE
      CLOSE (7)
      IF(L.GT.1) GO TO 95
   95 DELTA=T(JMAX)/REAL(JMAX-1)/3.0
      DO 110 M=1,MMAX
      DO 100 J=1,JMAX
  100 FT(J)=FIT(J,M)
      CALL GRAL(DELTA,FT,JMAX,SUM(M))
  110 CONTINUE
      DO 120 M=1,MMAX
      DO 120 J=1,JMAX
  120 FIT(J,M)=FIT(J,M)/SUM(M)
      DO 130 J=1,JMAX
      F(J)=(FAC1*FIT(J,M1)+FAC2*FIT(J,M2))/RGIN
  130 RHO(J)=RGIN*T(J)
      DELTA=DELTA*RGIN
      CALL GRAL(DELTA,F,JMAX,SUMM)
      RTOP=TMAX*RGIN
      IF(L.NE.1) GO TO 136
      WRITE (8,131) LMAX
  131 FORMAT(I6,' depths')
      WRITE (8,132) JMAX
  132 FORMAT(I6,' radial distances')
      WRITE (8,1)
      WRITE (8,133)
  133 FORMAT('  TIN = Energy of incident proton beam, MeV')
      WRITE (8,134)
  134 FORMAT('   BR = depth, in units of CSDA range at energy TIN')
      WRITE (8,135)
  135 FORMAT(' RTOP = maximum radial distance')
      WRITE (8,1)
  136 WRITE (8,138)
  138 FORMAT(9X,'TIN',10X,'BR',8X,'RTOP')
      WRITE (8,140) TIN,BR,RTOP
  140 FORMAT(4F12.6)
      DO 145 J=2,JMAX
  145 F(J)=F(J)/(RHO(J)*2.0*PI)
      F(1)=2.0*F(2)-F(3)
      WRITE (8,148)
  148 FORMAT('Radial distances, rho, cm')
      WRITE (8,150) (RHO(J),J=1,JMAX)
      WRITE (8,149)
  149 FORMAT('Radial distribution, f(rho), cm-2')
      WRITE (8,150) (F(J),J=1,JMAX)
  150 FORMAT(1P8E12.5)
  160 CONTINUE
      STOP
      END
```

```
      PROGRAM FCIR
C
C     15 May 93. Written by Martin J. Berger, NIST.
C
C                Calculates reduction factors and absorbed-dose values
C                for a circular field,  as a function of the radial
C                distance from the center of the field.
C
C     Calls subroutines CIRCLE, SCOFD,BSPOLD and GRALD.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION R(401),F(401),FL(401),ACOF(401),BCOF(401),
     1 CCOF(401),DCOF(401),GRAND(5121),S(401),REDUC(401),DRAD(401),
     2 ZR(120),DDDX(120),RED(120),DAX(120),
     3 ZD(100),DEPOT(100),AP(100),BP(100),CP(100),DP(100)
      CHARACTER*16 INPUT1,INPUT2,INPUT3,OUTPUT,INFIL
      CHARACTER LINE*80
    1 FORMAT(1H )
      DATA NMX/161/,EREDUCL/1.0D-04/
    5 FORMAT(A)
      PI=4.0D0*ATAN(1.0D0)
      PRINT *,' Enter radius of circular field (cm): '
      READ *, RADIUS
      PRINT *,' Options for specifying radial distances'
      PRINT *,'   1) Get set of values from file'
      PRINT *,'   2) Get set of values from keyboard'
      PRINT *,'   3) Specify in terms of maximum distance'
      PRINT *,'      and number of distances: '
      PRINT *,' Enter choice: '
      READ *, INS
      GO TO (6,7,8), INS
    6 PRINT *,' Enter name of file with distance values: '
      READ 5, INFIL
      OPEN (7,INFIL)
      READ (7,*) LMAX
      READ (7,*) (S(L),L=1,LMAX)
      CLOSE (7)
      GO TO 9
    7 PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, LMAX
      PRINT *,' Enter distances (cm): '
      READ *, (S(L),L=1,LMAX)
      GO TO 9
    8 PRINT *,' Enter maximum radial distance (cm): '
      READ *, SMAX
      LMAX=1
      IF(SMAX.LE.0.0D0) GO TO 9
      PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, LMAX
    9 PRINT *,' Enter input file 1 (from MORAD): '
      READ 5, INPUT1
      PRINT *,' Options for depths:'
      PRINT *,'   1) No depths greater than 98% of CSDA range'
      PRINT *,'   2) Some depths greater than 98% of CSDA range'
      PRINT *,' Enter choice: '
      READ *, INDEP
      IF(INDEP.EQ.1) GO TO 10
      PRINT *,' Enter input file 2 (from PTRAD): '
      READ 5, INPUT2
   10 PRINT *,' Enter input file 3 (from PTPOL): '
      READ 5, INPUT3
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      IF(INS.LT.3) GO TO 20
      S(1)=0.0
      IF(LMAX.LE.1) GO TO 20
      DS=SMAX/DBLE(LMAX-1)
      DO 15 L=2,LMAX
   15 S(L)=DS*DBLE(L-1)
   20 OPEN (8,OUTPUT)
      WRITE (8,25) OUTPUT
   25 FORMAT('Program FCIR, output file ',A)
      WRITE (8,26) INPUT1
      IF(INDEP.EQ.2) WRITE (8,26) INPUT2
      WRITE (8,26) INPUT3
   26 FORMAT('Input file ',A)
      IF(INDEP.EQ.1) WRITE (8,1)
      WRITE (8,1)
      WRITE (8,27)
   27 FORMAT('    TIN = energy of incident proton beam, MeV')
      WRITE (8,28)
   28 FORMAT('   RGIN = CSDA range at energy TIN, g/cm2')
      WRITE (8,30)
   30 FORMAT(' RADIUS = radius of circular field, cm')
      WRITE (8,31)
   31 FORMAT('   LMAX = number of radial distances from center of field'
     1)
      WRITE (8,32)
   32 FORMAT('  NCASE = number of depths')
      WRITE (8,1)
      OPEN (6,INPUT1)
      IF(INDEP.EQ.2) OPEN (7,INPUT2)
      READ (6,5) LINE
      READ (6,5) LINE
      READ (6,*) NCASE1
      READ (6,*) JMAX1
      DO 33 LN=1,8
      READ (6,5) LINE
   33 CONTINUE
      READ (6,*) TIN,RGIN
      READ (6,5) LINE
      NCASE2=0
      JMAX2=0
      IF(INDEP.EQ.1) GO TO 35
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) NCASE2
      READ (7,*) JMAX2
      DO 34 LN=1,5
      READ (7,5) LINE
   34 CONTINUE
   35 NCASE=NCASE1+NCASE2
      WRITE (8,36)
   36 FORMAT(9X,'TIN',8X,'RGIN',6X,'RADIUS','  LMAX NCASE')
      WRITE (8,37) TIN,RGIN,RADIUS,LMAX,NCASE
   37 FORMAT(3F12.5,2I6)
      WRITE (8,1)
      IF(LMAX.NE.1) WRITE (8,38)
   38 FORMAT('Radial distances from center of field (cm)')
      IF(LMAX.NE.1) WRITE (8,39) (S(L),L=1,LMAX)
   39 FORMAT(8F12.6)
      OPEN(11,INPUT3)
      DO 40 LN=1,9
      READ (11,5) LINE
   40 CONTINUE
      READ (11,*) G1,G2,G3,G4,KMAX
      READ (11,5) LINE
      READ (11,5) LINE
      READ (11,*) (ZD(K),K=1,KMAX)
      READ (11,*) LINE
      READ (11,*) (DEPOT(K),K=1,KMAX)
      CLOSE (11)
      CALL SCOFD(ZD,DEPOT,KMAX,AP,BP,CP,DP)
      DO 130 NC=1,NCASE
      IF(NC-NCASE1)42,42,43
   42 JMAX=JMAX1
      READ (6,5) LINE
      READ (6,*) ZR(NC),RMAX,SUM
      READ (6,5) LINE
      READ (6,*) (R(J),J=1,JMAX)
      READ (6,5) LINE
      READ (6,*) (F(J),J=1,JMAX)
      GO TO 46
   43 JMAX=JMAX2
      READ (7,5) LINE
      READ (7,*) TIN,ZR(NC),RMAX
      READ (7,5) LINE
      READ (7,*) (R(J),J=1,JMAX)
      READ (7,5) LINE
      READ (7,*) (F(J),J=1,JMAX)
      JTAL=0
      DO 44 J=1,JMAX
      IF(F(J))45,45,44
   44 JTAL=JTAL+1
   45 JMAX=JTAL
   46 DO 47 J=1,JMAX
   47 FL(J)=LOG(2.0D0*PI*F(J))
      CALL SCOFD(R,FL,JMAX,ACOF,BCOF,CCOF,DCOF)
      DO 90 L=1,LMAX
      NMAX=NMX
      OLDVAL=2.0D0
   48 IF(S(L).GE.RADIUS) GO TO 70
      RHMAX=RADIUS-S(L)
      IF(RMAX-RHMAX)49,49,50
   49 REDUC(L)=1.0
      GO TO 90
   50 DRH=RHMAX/DBLE(NMAX-1)
      DO 51 N=1,NMAX
      RHO=DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
   51 GRAND(N)=RHO*EXP(RES)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART1)
      IF(S(L))52,52,53
   52 REDUC(L)=PART1
      GO TO 90
   53 RHMIN=RADIUS-S(L)
      RHMAX=RADIUS+S(L)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 55 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CIRCLE(S(L),RADIUS,RHO,FRAC)
   55 GRAND(N)=FINT*FRAC
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART2)
      REDUC(L)=PART1+PART2
      GO TO 90
```

```
 70 RHMIN=S(L)-RADIUS
    RHMAX=S(L)+RADIUS
    RHMAX=MIN(RHMAX,RMAX)
    DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
    DO 80 N=1,NMAX
    RHO=RHMIN+DRH*DBLE(N-1)
    CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
    FINT=RHO*EXP(RES)
    CALL CIRCLE(S(L),RADIUS,RHO,FRAC)
 80 GRAND(N)=FINT*FRAC
    DELTA=DRH/3.0D0
    CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
    DIFF=ABS(OLDVAL-REDUC(L))
    IF(DIFF-EREDUCL)90,81,81
 81 OLDVAL=REDUC(L)
    IF(NMAX-2561)82,82,90
 82 NMAX=2*NMAX-1
    GO TO 48
 90 CONTINUE
    CALL BSPOLD(ZR(NC),ZD,AP,BP,CP,DP,KMAX,DDDX(NC))
    DO 95 L=1,LMAX
 95 DRAD(L)=DDDX(NC)*REDUC(L)
    IF(LMAX.NE.1) WRITE (8,100) ZR(NC)
100 FORMAT('Depth as fraction of RGIN = ',F5.3)
    IF(LMAX.EQ.1) RED(NC)=REDUC(1)
    IF(LMAX.EQ.1) DAX(NC)=DRAD(1)
    IF(LMAX.NE.1) WRITE (8,105)
105 FORMAT('Reduction factors')
    IF(LMAX.NE.1) WRITE (8,110) (REDUC(L),L=1,LMAX)
110 FORMAT(8F12.6)
    IF(LMAX.NE.1) WRITE (8,115)
115 FORMAT('Absorbed dose, MeV/g, from a beam of 1 proton/cm2')
    IF(LMAX.NE.1) WRITE (8,110) (DRAD(L),L=1,LMAX)
    print 120, ncase,nc
120 format(' ncase = ',i3,'  nc = ',i3)
130 CONTINUE
    IF(LMAX.NE.1) GO TO 170
    WRITE (8,140) S(1)
140 FORMAT('Radial distance (cm) from center of field = ',F5.3)
    WRITE (8,1)
    WRITE (8,150)
150 FORMAT('Depths, in units of RGIN')
    WRITE (8,160) (ZR(NC),NC=1,NCASE)
160 FORMAT(8F12.6)
    WRITE (8,105)
    WRITE (8,160) (RED(NC),NC=1,NCASE)
    WRITE (8,115)
    WRITE (8,160) (DAX(NC),NC=1,NCASE)
170 STOP
    END

    SUBROUTINE CIRCLE(S,RADIUS,RHO,FRAC)
C   4 Feb 93. Calculates arclength fraction in circle.
C
C   Circle has center at origin and has radius R.
C   Reference point is at x>=0 ,y=0.
C
    IMPLICIT DOUBLE PRECISION (A-H,O-Z)
    PI=4.0D0*ATAN(1.0D0)
    IF(S-RADIUS)20,10,20
 10 ARG=RHO/(2.0D0*RADIUS)
    GO TO 30
 20 ARG=(S**2+RHO**2-RADIUS**2)/(2.0D0*S*RHO)
 30 IF(ARG.LT.-1.0D0) ARG=-1.0D0
    IF(ARG.GT.1.0D0) ARG=1.0D0
    FRAC=ACOS(ARG)/PI
    RETURN
    END
```

```
      CALF=COS(ALF)
      SALF=SIN(ALF)
      DO 205 L=1,LMAX
      NMAX=NMX
      OLDVAL=2.0D0
      X=CALF*DS*DBLE(L-1)
      Y=SALF*DS*DBLE(L-1)
  100 IF(X.LE.A.AND.Y.LE.B) GO TO 110
      IF(X.LE.A.AND.Y.GT.B) GO TO 140
      IF(X.GT.A.AND.Y.LE.B) GO TO 160
      IF(X.GT.A.AND.Y.GT.B) GO TO 180
  110 RHMAX=MIN(A-X,B-Y)
      IF(RMAX-RHMAX)115,115,120
  115 REDUC(L)=1.0D0
      GO TO 200
  120 DRH=RHMAX/DBLE(NMAX-1)
      DO 125 N=1,NMAX
      RHO=DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
  125 GRAND(N)=RHO*EXP(RES)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART1)
      RHMIN=MIN(A-X,B-Y)
      RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 130 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,A+X,B+Y,FRAC1)
      CALL CORNER(RHO,A+X,B-Y,FRAC2)
      CALL CORNER(RHO,A-X,B+Y,FRAC3)
      CALL CORNER(RHO,A-X,B-Y,FRAC4)
  130 GRAND(N)=FINT*(FRAC1+FRAC2+FRAC3+FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX.PART2)
      REDUC(L)=PART1+PART2
      GO TO 200
  140 RHMIN=Y-B
      IF(RMAX-RHMIN)142,142,145
  142 REDUC(L)=0.0D0
      GO TO 200
  145 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 150 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,A+X,Y+B,FRAC1)
      CALL CORNER(RHO,A-X,Y+B,FRAC2)
      CALL CORNER(RHO,A+X,Y-B,FRAC3)
      CALL CORNER(RHO,A-X,Y-B,FRAC4)
  150 GRAND(N)=FINT*(FRAC1+FRAC2-FRAC3-FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
      GO TO 200
  160 RHMIN=X-A
      IF(RMAX-RHMIN)162,162,165
  162 REDUC(L)=0.0D0
      GO TO 200
  165 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 170 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,X+A,B+Y,FRAC1)
      CALL CORNER(RHO,X+A,B-Y,FRAC2)
      CALL CORNER(RHO,X-A,B+Y,FRAC3)
      CALL CORNER(RHO,X-A,B-Y,FRAC4)
  170 GRAND(N)=FINT*(FRAC1+FRAC2-FRAC3-FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
      GO TO 200
  180 RHMIN=SQRT((X-A)**2+(Y-B)**2)
      IF(RMAX-RHMIN)182,182,185
  182 REDUC(L)=0.0D0
      GO TO 200
  185 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 190 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,X+A,Y+B,FRAC1)
      CALL CORNER(RHO,X-A,Y+B,FRAC2)
      CALL CORNER(RHO,X+A,Y-B,FRAC3)
      CALL CORNER(RHO,X-A,Y-B,FRAC4)
  190 GRAND(N)=FINT*(FRAC1-FRAC2-FRAC3+FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
  200 DIFF=ABS(OLDVAL-REDUC(L))
      IF(DIFF-EREDUCL)205,201,201
  201 OLDVAL=REDUC(L)
      IF(NMAX-2561)202,202,205
  202 NMAX=2*NMAX-1
      GO TO 100
  205 CONTINUE
      CALL BSPOLD(ZR(NC),ZD,AP,BP,CP,DP,KMAX,DDDX(NC))
      DO 206 L=1,LMAX
  206 DRAD(L)=DDDX(NC)*REDUC(L)
      IF(LMAX.NE.1) WRITE (8,210) ZR(NC)
  210 FORMAT('Depth as fraction of RGIN = ',F5.3)
      IF(LMAX.EQ.1) RED(NC)=REDUC(1)
      IF(LMAX.EQ.1) DAX(NC)=DRAD(1)
      IF(LMAX.NE.1) WRITE (8,220)
  220 FORMAT('Reduction factors')
      IF(LMAX.NE.1) WRITE (8,230) (REDUC(L),L=1,LMAX)
  230 FORMAT(8F12.6)
      IF(LMAX.NE.1) WRITE (8,240)
  240 FORMAT('Absorbed dose, MeV/g, from a beam of 1 proton/cm2')
      IF(LMAX.NE.1) WRITE (8,230) (DRAD(L),L=1,LMAX)
      print 245, ncase,nc
  245 format(' ncase = ',i3,'  nc = ',i3)
  250 CONTINUE
      IF(LMAX.NE.1) GO TO 290
      WRITE (8,260) S(1)
  260 FORMAT('Radial distance (cm) from center of field = ',F5.3)
      WRITE (8,1)
      WRITE (8,270)
  270 FORMAT('Depths, in units of RGIN')
      WRITE (8,280) (ZR(NC),NC=1,NCASE)
  280 FORMAT(8F12.6)
      WRITE (8,220)
      WRITE (8,280) (RED(NC),NC=1,NCASE)
      WRITE (8,240)
      WRITE (8,280) (DAX(NC),NC=1,NCASE)
  290 STOP
      END

      SUBROUTINE CORNER(R,SA,SB,FRAC)
C     27 Mar 88. Computes rel.arclength (fracton of 2 pi) for point in
C                corner of rectangle with sides SA and SB.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      TPI=8.0D0*ATAN(1.0D0)
      IF(SA)60,60,5
    5 IF(SB)60,60,6
    6 A=MAX(SA,SB)
      B=MIN(SA,SB)
      IF(R-B)10,10,20
   10 FRAC=0.25D0
      RETURN
   20 IF(R-A)30,30,40
   30 FRAC=0.25D0-ACOS(B/R)/TPI
      RETURN
   40 IF(R*R-A*A-B*B)50,50,60
   50 FRAC=0.25D0-(ACOS(B/R)+ACOS(A/R))/TPI
      RETURN
   60 FRAC=0.0D0
      RETURN
      END
```

```
      PROGRAM FREC
C
C     15 May 93. Written by Martin J. Berger, NIST.
C
C               Calculates reduction factors and absorbed-dose values
C               for a rectangular field.
C
C               Center of coordinate system is at x=0, y=0.
C               Rectangle extends from -A to A in x, -B to B in y.
C
C               Results are calculated as functions of the distance
C               from the center of the field, along a line that makes
C               an angle alpha (between 0 and 90 degrees) with respect
C               to the x-axis.

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION REDUC(401),S(401),R(401),F(401),FL(401),
     1 ACOF(401),BCOF(401),CCOF(401),DCOF(401),GRAND(5121),
     2 ZD(100),DEPOT(100),AP(100),BP(100),CP(100),DP(100),DRAD(401),
     3 ZR(401),DDDX(401),RED(401),DAX(401)
      CHARACTER*16 INPUT1,INPUT2,INPUT3,OUTPUT,INFIL
      CHARACTER LINE*80
      DATA NMX/161/,EREDUCL/1.0D-04/
    1 FORMAT(1H )
    5 FORMAT(A)
      PI=4.0D0*ATAN(1.0D0)
      RADFAC=PI/180.0D0
      PRINT *,' Rectangular field extends from -A to A in x, -B to B in
     1y'
      PRINT *,' Enter values of A and B (cm): '
      READ *, A,B
      PRINT *, ' Line goes through a corner of the rectangle (1=yes, 2=n
     1o): '
      READ *, JVEC
      IF(JVEC.NE.2) GO TO 10
      PRINT *,' Enter angle alpha with respect to x-axis (degrees): '
      READ *, ALPHA
      ALF=ALPHA*RADFAC
      GO TO 11
   10 ALF=ATAN(B/A)
      ALPHA=ALF/RADFAC
   11 PRINT *,' Options for specifying radial distances:'
      PRINT *,'   1) Get set of values from file'
      PRINT *,'   2) Get set of values from keyboard'
      PRINT *,'   3) Specify set of values in terms of maximum distance'
      PRINT *,'      and number of distances, LMAX: '
      PRINT *,' Enter choice: '
      READ *, INS
      GO TO (12,13,14), INS
   12 PRINT *,' Enter name of file with distance values: '
      READ 5, INFIL
      OPEN (7,INFIL)
      READ (7,*) LMAX
      READ (7,*) (S(L),L=1,LMAX)
      CLOSE (7)
      GO TO 15
   13 PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, LMAX
      PRINT *,' Enter distances (cm): '
      READ *, (S(L),L=1,LMAX)
      GO TO 15
   14 PRINT *,' Enter maximum radial distance (cm): '
      READ *, SMAX
      LMAX=1
      IF(SMAX.LE.0.0D0) GO TO 15
      PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, LMAX
   15 PRINT *,' Enter name of input file 1 (from MORAD): '
      READ 5, INPUT1
      PRINT *,' Options for depths:'
      PRINT *,'   1) No depths greater than 98% of CSDA range'
      PRINT *,'   2) Some depths greater than 98% of CSDA range'
      PRINT *,' Enter choice: '
      READ *, INDEP
      IF(INDEP.EQ.1) GO TO 16
      PRINT *,' Enter name of input file 2 (from PTRAD): '
      READ 5, INPUT2
   16 PRINT *,' Enter name of input file 3 (from PTPOL): '
      READ 5, INPUT3
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      IF(INS.LT.3) GO TO 18
      S(1)=0.0
      IF(LMAX.LE.1) GO TO 18
      DS=SMAX/DBLE(LMAX-1)
      DO 17 L=2,LMAX
   17 S(L)=DS*DBLE(L-1)
   18 OPEN (8,OUTPUT)
      WRITE (8,19) OUTPUT
   19 FORMAT('Program FREC, output file ',A)
      WRITE (8,20)INPUT1
      IF(INDEP.EQ.2) WRITE (8,20) INPUT2
      WRITE (8,20) INPUT3
   20 FORMAT('Input file = ',A)
      IF(INDEP.EQ.1) WRITE (8,1)
      WRITE (8,1)
      WRITE (8,25)
   25 FORMAT('    TIN = energy of incident proton beam, MeV')
      WRITE (8,26)
   26 FORMAT('   RGIN = CSDA range at energy TIN, g/cm2')
      WRITE (8,27)
   27 FORMAT('     2A = side of rectangular field, cm')
      WRITE (8,28)
   28 FORMAT('     2B = side of rectanglular field, cm')
      WRITE (8,29)
   29 FORMAT('  ALPHA = angle (deg) defined below')
      WRITE (8,30)
   30 FORMAT('   LMAX = number of radial distances from center of field'
     1)
      WRITE (8,31)
   31 FORMAT('  NCASE = number of depths')
      WRITE (8,1)
      WRITE (8,32)
   32 FORMAT('Rectangular field extends from -A to A in x, and from -B t
     1o B in y.')
      WRITE (8,33)
   33 FORMAT('Line along which reduction factor is calculated starts at
     1the origin')
      WRITE (8,34)
   34 FORMAT('and makes angle ALPHA (deg) with respect to x-axis.')
      WRITE (8,1)
      OPEN (6,INPUT1)
      IF(INDEP.EQ.2) OPEN (7,INPUT2)
      READ (6,5) LINE
      READ (6,5) LINE
      READ (6,*) NCASE1
      READ (6,*) JMAX1
      DO 35 LN=1,8
      READ (6,5) LINE
   35 CONTINUE
      READ (6,*) TIN,RGIN
      READ (6,5) LINE
      NCASE2=0
      JMAX2=0
      IF(INDEP.EQ.1) GO TO 37
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) NCASE2
      READ (7,*) JMAX2
      DO 36 LN=1,5
      READ (7,5) LINE
   36 CONTINUE
   37 NCASE=NCASE1+NCASE2
      WRITE (8,38)
   38 FORMAT(9X,'TIN',8X,'RGIN',11X,'A',11X,'B',7X,'ALPHA','  LMAX NCASE
     1')
      WRITE (8,39) TIN,RGIN,A,B,ALPHA,LMAX,NCASE
   39 FORMAT(5F12.5,2I6)
      IF(LMAX.NE.1) WRITE (8,1)
      IF(LMAX.NE.1) WRITE (8,40)
   40 FORMAT('Radial distances from center of field (cm)')
      IF(LMAX.NE.1) WRITE (8,41) (S(L),L=1,LMAX)
   41 FORMAT(6F12.5)
      OPEN(11,INPUT3)
      DO 42 LN=1,9
      READ (11,5) LINE
   42 CONTINUE
      READ (11,*) G1,G2,G3,G4,KMAX
      READ (11,5) LINE
      READ (11,5) LINE
      READ (11,*) (ZD(K),K=1,KMAX)
      READ (11,*) LINE
      READ (11,*) (DEPOT(K),K=1,KMAX)
      CLOSE (11)
      CALL SCOFD(ZD,DEPOT,KMAX,AP,BP,CP,DP)
      DO 250 NC=1,NCASE
      IF(NC-NCASE1)43,43,44
   43 JMAX=JMAX1
      READ (6,5) LINE
      READ (6,*) ZR(NC),RMAX,SUM
      READ (6,5) LINE
      READ (6,*) (R(J),J=1,JMAX)
      READ (6,5) LINE
      READ (6,*) (F(J),J=1,JMAX)
      GO TO 47
   44 JMAX=JMAX2
      READ (7,5) LINE
      READ (7,*) TIN,ZR(NC),RMAX
      READ (7,5) LINE
      READ (7,*) (R(J),J=1,JMAX)
      READ (7,5) LINE
      READ (7,*) (F(J),J=1,JMAX)
      JTAL=0
      DO 45 J=1,JMAX
      IF(F(J))46,46,45
   45 JTAL=JTAL+1
   46 JMAX=JTAL
   47 DO 48 J=1,JMAX
   48 FL(J)=LOG(2.0D0*PI*F(J))
      CALL SCOFD(R,FL,JMAX,ACOF,BCOF,CCOF,DCOF)
```

```
      PROGRAM FREC1
C
C     15 May 93. Written by Martin J. Berger, NIST.
C
C                Calculates reduction factors and absorbed-dose values
C                for a rectangular field.
C
C                Center of coordinate system is at x=0, y=0.
C                Rectangle extends from -A to A in x, -B to B in y.
C
C                Results are calculated a specified set of (x,y) values.
C                Without loss of generality, it is assumed that x and y
C                are non-negative.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION REDUC(401),XP(401),YP(401),R(401),F(401),FL(401),
     1 ACOF(401),BCOF(401),CCOF(401),DCOF(401),GRAND(5121),
     2 ZD(100),DEPOT(100),AP(100),BP(100),CP(100),DP(100),DRAD(401),
     3 ZR(401),DDDX(401)
      CHARACTER*16 INPUT1,INPUT2,INPUT3,OUTPUT,INFIL
      CHARACTER LINE*80
      DATA NMX/161/,EREDUCL/1.0D-04/
    1 FORMAT(1H )
    5 FORMAT(A)
      PI=4.0D0*ATAN(1.0D0)
      PRINT *,' Rectangular field extends from -A to A in x, -B to B in
     1y'
      PRINT *,' Enter values of A and B (cm): '
      READ *, A,B
      PRINT *,' Options for specifying (x,y)-values:'
      PRINT *,'    1) Enter values from keyboard'
      PRINT *,'    2) Enter values from file:'
      PRINT *,' Enter choice: '
      READ *, INP
      IF(INP.EQ.2) GO TO 7
      PRINT *,' Enter number of (x,y) values: '
      READ *, LMAX
      DO 6 L=1,LMAX
      PRINT *,' Enter x and y (cm, non-negative): '
      READ *, XP(L),YP(L)
    6 CONTINUE
      GO TO 9
    7 PRINT *,' Enter name of input file: '
      READ 5, INFIL
      OPEN (7,INFIL)
      READ (7,*) LMAX
      DO 8 L=1,LMAX
      READ (7,*) XP(L),YP(L)
    8 CONTINUE
      CLOSE(7)
    9 PRINT *,' Enter name of input file 1 (from MORAD): '
      READ 5, INPUT1
      PRINT *,' Options for depths:'
      PRINT *,'   1) No depths greater than 98% of CSDA range'
      PRINT *,'   2) Some depths greater than 98% of CSDA range'
      PRINT *,' Enter choice: '
      READ *, INDEP
      IF(INDEP.EQ.1) GO TO 16
      PRINT *,' Enter name of input file 2 (from PTRAD): '
      READ 5, INPUT2
   16 PRINT *,' Enter name of input file 3 (from PTPOL): '
      READ 5, INPUT3
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      OPEN (8,OUTPUT)
      WRITE (8,19) OUTPUT
   19 FORMAT('Program FREC1, output file ',A)
      WRITE (8,20)INPUT1
      IF(INDEP.EQ.2) WRITE (8,20) INPUT2
      WRITE (8,20) INPUT3
   20 FORMAT('Input file = ',A)
      IF(INDEP.EQ.1) WRITE (8,1)
      WRITE (8,1)
      WRITE (8,21)
   21 FORMAT('Rectangular field extends from -A to A in x, and from -B t
     1o B in y.')
      WRITE (8,1)
      WRITE (8,25)
   25 FORMAT('    TIN = energy of incident proton beam, MeV')
      WRITE (8,26)
   26 FORMAT('   RGIN = CSDA range at energy TIN, g/cm2')
      WRITE (8,27)
   27 FORMAT('     2A = side of rectangular field, cm')
      WRITE (8,28)
   28 FORMAT('     2B = side of rectanglular field, cm')
      WRITE (8,29)
   29 FORMAT('      X = x-distance from center of field, cm')
      WRITE (8,30)
   30 FORMAT('      Y = Y-distance from center of field, cm')
      WRITE (8,31)
   31 FORMAT('   LMAX = number of (X,Y) values')
      WRITE (8,32)
   32 FORMAT('  NCASE = number of depths')
      WRITE (8,33)
   33 FORMAT('  REDUC = reduction factor')
      WRITE (8,34)
   34 FORMAT('   DRAD = absorbed dose, MeV/g')
      WRITE (8,1)
      OPEN (6,INPUT1)
      IF(INDEP.EQ.2) OPEN (7,INPUT2)
      READ (6,5) LINE
      READ (6,5) LINE
      READ (6,*) NCASE1
      READ (6,*) JMAX1
      DO 35 LN=1,8
      READ (6,5) LINE
   35 CONTINUE
      READ (6,*) TIN,RGIN
      READ (6,5) LINE
      NCASE2=0
      JMAX2=0
      IF(INDEP.EQ.1) GO TO 37
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) NCASE2
      READ (7,*) JMAX2
      DO 36 LN=1,5
      READ (7,5) LINE
   36 CONTINUE
   37 NCASE=NCASE1+NCASE2
      WRITE (8,38)
   38 FORMAT(9X,'TIN',8X,'RGIN',11X,'A',11X,'B','  LMAX NCASE')
      WRITE (8,39) TIN,RGIN,A,B,LMAX,NCASE
   39 FORMAT(4F12.5,2I6)
      WRITE (8,1)
      OPEN(11,INPUT3)
      DO 42 LN=1,9
      READ (11,5) LINE
   42 CONTINUE
      READ (11,*) G1,G2,G3,G4,KMAX
      READ (11,5) LINE
      READ (11,5) LINE
      READ (11,*) (ZD(K),K=1,KMAX)
      READ (11,*) LINE
      READ (11,*) (DEPOT(K),K=1,KMAX)
      CLOSE (11)
      CALL SCOFD(ZD,DEPOT,KMAX,AP,BP,CP,DP)
      DO 250 NC=1,NCASE
      IF(NC-NCASE1)43,43,44
   43 JMAX=JMAX1
      READ (6,5) LINE
      READ (6,*) ZR(NC),RMAX,SUM
      READ (6,5) LINE
      READ (6,*) (R(J),J=1,JMAX)
      READ (6,5) LINE
      READ (6,*) (F(J),J=1,JMAX)
      GO TO 47
   44 JMAX=JMAX2
      READ (7,5) LINE
      READ (7,*) TIN,ZR(NC),RMAX
      READ (7,5) LINE
      READ (7,*) (R(J),J=1,JMAX)
      READ (7,5) LINE
      READ (7,*) (F(J),J=1,JMAX)
      JTAL=0
      DO 45 J=1,JMAX
      IF(F(J))46,46,45
   45 JTAL=JTAL+1
   46 JMAX=JTAL
   47 DO 48 J=1,JMAX
   48 FL(J)=LOG(2.0D0*PI*F(J))
      CALL SCOFD(R,FL,JMAX,ACOF,BCOF,CCOF,DCOF)
      DO 205 L=1,LMAX
      NMAX=NMX
      OLDVAL=2.0D0
      X=XP(L)
      Y=YP(L)
  100 IF(X.LE.A.AND.Y.LE.B) GO TO 110
      IF(X.LE.A.AND.Y.GT.B) GO TO 140
      IF(X.GT.A.AND.Y.LE.B) GO TO 160
      IF(X.GT.A.AND.Y.GT.B) GO TO 180
  110 RMMAX=MIN(A-X,B-Y)
      IF(RMAX-RMMAX)115,115,120
  115 REDUC(L)=1.0D0
      GO TO 200
  120 DRH=RMMAX/DBLE(NMAX-1)
      DO 125 N=1,NMAX
      RHO=DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
  125 GRAND(N)=RHO*EXP(RES)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART1)
      RHMIN=MIN(A-X,B-Y)
      RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 130 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,A+X,B+Y,FRAC1)
      CALL CORNER(RHO,A+X,B-Y,FRAC2)
```

```
      CALL CORNER(RHO,A-X,B+Y,FRAC3)
      CALL CORNER(RHO,A-X,B-Y,FRAC4)
  130 GRAND(N)=FINT*(FRAC1+FRAC2+FRAC3+FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART2)
      REDUC(L)=PART1+PART2
      GO TO 200
  140 RHMIN=Y-B
      IF(RMAX-RHMIN)142,142,145
  142 REDUC(L)=0.0D0
      GO TO 200
  145 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 150 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,A+X,Y+B,FRAC1)
      CALL CORNER(RHO,A-X,Y+B,FRAC2)
      CALL CORNER(RHO,A+X,Y-B,FRAC3)
      CALL CORNER(RHO,A-X,Y-B,FRAC4)
  150 GRAND(N)=FINT*(FRAC1+FRAC2-FRAC3-FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
      GO TO 200
  160 RHMIN=X-A
      IF(RMAX-RHMIN)162,162,165
  162 REDUC(L)=0.0D0
      GO TO 200
  165 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 170 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,X+A,B+Y,FRAC1)
      CALL CORNER(RHO,X+A,B-Y,FRAC2)
      CALL CORNER(RHO,X-A,B+Y,FRAC3)
      CALL CORNER(RHO,X-A,B-Y,FRAC4)
  170 GRAND(N)=FINT*(FRAC1+FRAC2-FRAC3-FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
      GO TO 200
  180 RHMIN=SQRT((X-A)**2+(Y-B)**2)
      IF(RMAX-RHMIN)182,182,185
  182 REDUC(L)=0.0D0
      GO TO 200
  185 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 190 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,X+A,Y+B,FRAC1)
      CALL CORNER(RHO,X-A,Y+B,FRAC2)
      CALL CORNER(RHO,X+A,Y-B,FRAC3)
      CALL CORNER(RHO,X-A,Y-B,FRAC4)
  190 GRAND(N)=FINT*(FRAC1-FRAC2-FRAC3+FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
  200 DIFF=ABS(OLDVAL-REDUC(L))
      IF(DIFF-EREDUCL)205,201,201
  201 OLDVAL=REDUC(L)
      IF(NMAX-2561)202,202,205
  202 NMAX=2*NMAX-1
      GO TO 100
  205 CONTINUE
      CALL BSPOLD(ZR(NC),ZD,AP,BP,CP,DP,KMAX,DDDX(NC))
      DO 206 L=1,LMAX
  206 DRAD(L)=DDDX(NC)*REDUC(L)
      WRITE (8,210) ZR(NC)
  210 FORMAT('Depth as fraction of RGIN = ',F5.3)
      WRITE (8,1)
      WRITE (8,221)
  221 FORMAT(11X,'X',11X,'Y',7X,'REDUC',8X,'DRAD')
      DO 223 L=1,LMAX
      WRITE (8,222) XP(L),YP(L),REDUC(L),DRAD(L)
  222 FORMAT(4F12.5)
  223 CONTINUE
      WRITE (8,1)
      print 245, ncase,nc
  245 format(' ncase = ',i3,'  nc = ',i3)
  250 CONTINUE
      STOP
      END

      SUBROUTINE CORNER(R,SA,SB,FRAC)
C     27 Mar 88. Computes rel.arclength (fracton of 2 pi) for point in
C                corner of rectangle with sides SA and SB.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      TPI=8.0D0*ATAN(1.0D0)
      IF(SA)60,60,5
    5 IF(SB)60,60,6
    6 A=MAX(SA,SB)
      B=MIN(SA,SB)
      IF(R-B)10,10,20
   10 FRAC=0.25D0
      RETURN
   20 IF(R-A)30,30,40
   30 FRAC=0.25D0-ACOS(B/R)/TPI
      RETURN
   40 IF(R*R-A*A-B*B)50,50,60
   50 FRAC=0.25D0-(ACOS(B/R)+ACOS(A/R))/TPI
      RETURN
   60 FRAC=0.0D0
      RETURN
      END
```

```
      PROGRAM FREC2
C
C     15 May 93. Written by Martin J. Berger, NIST.
C
C               Calculates reduction factors and absorbed-dose values
C               for a rectangular field. FREC2 is similar to FREC1,
C               but carries out numerical quadrature with respect
C               to x and y.
C
C               Center of coordinate system is at x=0, y=0.
C               Rectangle extends from -A to A in x, -B to B in y.
C
C               Results are calculated a specified set of (x,y) values.
C               Without loss of generality, it is assumed that x and y
C               are non-negative.
C
C     The external functions FUN1 and FUN2 specify the upper and lower
C     limits of y, and the external function FUN3 specifies a constant
C     density of pencil beams, n(x,y)=1. By modifying these external
C     functions, the FREC2 program could be applied to fields with
C     arbitrary shapes and specified pencil-beam density.

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      EXTERNAL FUN1,FUN2,FUN3
      DIMENSION REDUC(401),XP(401),YP(401),R(401),F(401),FL(401),
     1 ACOF(401),BCOF(401),CCOF(401),DCOF(401),GRAND(501),
     2 ZD(100),DEPOT(100),AP(100),BP(100),CP(100),DP(100),DRAD(401),
     3 ZR(401),DDDX(401),TERM(501)
      CHARACTER*16 INPUT1,INPUT2,INPUT3,OUTPUT,INFIL
      CHARACTER LINE*80
    1 FORMAT(1H )
    5 FORMAT(A)
      PI=4.0D0*ATAN(1.0D0)
      PRINT *,' Rectangular field extends from -A to A in x, -B to B in
     1y'
      PRINT *,' Enter values of A and B (cm): '
      READ *, A,B
      PRINT *,' Options for specifying (x,y)-values:'
      PRINT *,'    1) Enter values from keyboard'
      PRINT *,'    2) Enter values from file:'
      PRINT *,' Enter choice: '
      READ *, INP
      IF(INP.EQ.2) GO TO 7
      PRINT *,' Enter number of (x,y) values: '
      READ *, LMAX
      DO 6 L=1,LMAX
      PRINT *,' Enter x and y (cm, non-negative): '
      READ *, XP(L),YP(L)
    6 CONTINUE
      GO TO 9
    7 PRINT *,' Enter name of input file: '
      READ 5, INFIL
      OPEN (7,INFIL)
      READ (7,*) LMAX
      DO 8 L=1,LMAX
      READ (7,*) XP(L),YP(L)
    8 CONTINUE
      CLOSE(7)
    9 PRINT *,' Specification of integration grid:'
      PRINT *,' Enter number of grid points in x: '
      READ *, IGRD
      PRINT *,' Enter number of grid points in y: '
      READ *, JGRD
      PRINT *,' Enter name of input file 1 (from MORAD): '
      READ 5, INPUT1
      PRINT *,' Options for depths:'
      PRINT *,'   1) No depths greater than 98% of CSDA range'
      PRINT *,'   2) Some depths greater than 98% of CSDA range'
      PRINT *,' Enter choice: '
      READ *, INDEP
      IF(INDEP.EQ.1) GO TO 16
      PRINT *,' Enter name of input file 2 (from PTRAD): '
      READ 5, INPUT2
   16 PRINT *,' Enter name of input file 3 (from PTPOL): '
      READ 5, INPUT3
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      OPEN (8,OUTPUT)
      WRITE (8,19) OUTPUT
   19 FORMAT('Program FGEN, output file ',A)
      WRITE (8,20)INPUT1
      IF(INDEP.EQ.2) WRITE (8,20) INPUT2
      WRITE (8,20) INPUT3
   20 FORMAT('Input file = ',A)
      IF(INDEP.EQ.1) WRITE (8,1)
      WRITE (8,1)
      WRITE (8,21)
   21 FORMAT('Rectangular field extends from -A to A in x, and from -B t
     1o B in y.')
      WRITE (8,1)
      WRITE (8,25)
   25 FORMAT('    TIN = energy of incident proton beam, MeV')
      WRITE (8,26)
   26 FORMAT('   RGIN = CSDA range at energy TIN, g/cm2')
      WRITE (8,27)
   27 FORMAT('     2A = side of rectangular field, cm')
      WRITE (8,28)
   28 FORMAT('     2B = side of rectanglular field, cm')
      WRITE (8,29)
   29 FORMAT('  IGRD = number of grid points in x')
      WRITE (8,30)
   30 FORMAT('  JGRD = number of grid points in y')
      WRITE (8,31)
   31 FORMAT('      X = x-distance from center of field, cm')
      WRITE (8,32)
   32 FORMAT('      Y = Y-distance from center of field, cm')
      WRITE (8,33)
   33 FORMAT('   LMAX = number of (X,Y) values')
      WRITE (8,34)
   34 FORMAT('  NCASE = number of depths')
      WRITE (8,35)
   35 FORMAT('   IGRD = number of grid points in x for numerical quadrat
     1ure')
      WRITE (8,36)
   36 FORMAT('   JGRD = number of grid points in y for numerical quadrat
     1ure')
      WRITE (8,37)
   37 FORMAT('  REDUC = reduction factor')
      WRITE (8,38)
   38 FORMAT('   DRAD = absorbed dose, MeV/g')
      WRITE (8,1)
      OPEN (6,INPUT1)
      IF(INDEP.EQ.2) OPEN (7,INPUT2)
      READ (6,5) LINE
      READ (6,5) LINE
      READ (6,*) NCASE1
      READ (6,*) JMAX1
      DO 39 LN=1,8
      READ (6,5) LINE
   39 CONTINUE
      READ (6,*) TIN,RGIN
      READ (6,5) LINE
      NCASE2=0
      JMAX2=0
      IF(INDEP.EQ.1) GO TO 41
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) NCASE2
      READ (7,*) JMAX2
      DO 40 LN=1,5
      READ (7,5) LINE
   40 CONTINUE
   41 NCASE=NCASE1+NCASE2
      WRITE (8,42)
   42 FORMAT(9X,'TIN',8X,'RGIN',11X,'A',11X,'B',2X,'LMAX',1X,'NCASE',
     1 2X,'IGRD',2X,'JGRD')
      WRITE (8,43) TIN,RGIN,A,B,LMAX,NCASE,IGRD,JGRD
   43 FORMAT(4F12.5,4I6)
      WRITE (8,1)
      OPEN(11,INPUT3)
      DO 44 LN=1,9
      READ (11,5) LINE
   44 CONTINUE
      READ (11,*) G1,G2,G3,G4,KMAX
      READ (11,5) LINE
      READ (11,5) LINE
      READ (11,*) (ZD(K),K=1,KMAX)
      READ (11,*) LINE
      READ (11,*) (DEPOT(K),K=1,KMAX)
      CLOSE (11)
      CALL SCOFD(ZD,DEPOT,KMAX,AP,BP,CP,DP)
      DO 250 NC=1,NCASE
      IF(NC-NCASE1)45,45,46
   45 JMAX=JMAX1
      READ (6,5) LINE
      READ (6,*) ZR(NC),RMAX,SUM
      READ (6,5) LINE
      READ (6,*) (R(J),J=1,JMAX)
      READ (6,5) LINE
      READ (6,*) (F(J),J=1,JMAX)
      GO TO 49
   46 JMAX=JMAX2
      READ (7,5) LINE
      READ (7,*) TIN,ZR(NC),RMAX
      READ (7,5) LINE
      READ (7,*) (R(J),J=1,JMAX)
      READ (7,5) LINE
      READ (7,*) (F(J),J=1,JMAX)
      JTAL=0
      DO 47 J=1,JMAX
      IF(F(J))48,48,47
   47 JTAL=JTAL+1
   48 JMAX=JTAL
   49 DO 50 J=1,JMAX
   50 FL(J)=LOG(2.0D0*PI*F(J))
      CALL SCOFD(R,FL,JMAX,ACOF,BCOF,CCOF,DCOF)
      DO 205 L=1,LMAX
      REDUC(L)=0.0D0
      XMIN=-A
      XMAX=A
      DGX=(XMAX-XMIN)/DBLE(IGRD-1)
      DELTAX=DGX/3.0D0
```

```
      DO 80 I=1,IGRD
      X=XMIN+DGX*DBLE(I-1)
      DGY=(FUN2(X,B)-FUN1(X,B))/DBLE(JGRD-1)
      DELTAY=DGY/3.0D0
      DO 70 J=1,JGRD
      Y=FUN1(X,B)+DGY*DBLE(J-1)
      ARG=SQRT((XP(L)-X)**2+(YP(L)-Y)**2)
      IF(ARG-RMAX)60,60,55
   55 GRAND(J)=0.0D0
      GO TO 70
   60 CALL BSPOLD(ARG,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      GRAND(J)=FUN3(X,Y)*EXP(RES)
   70 CONTINUE
      CALL GRALD(DELTAY,GRAND,JGRD,TERM(I))
   80 CONTINUE
      CALL GRALD(DELTAX,TERM,IGRD,SUMM)
      REDUC(L)=SUMM/(2.0D0*PI)
  205 CONTINUE
      CALL BSPOLD(ZR(NC),ZD,AP,BP,CP,DP,KMAX,DDDX(NC))
      DO 206 L=1,LMAX
  206 DRAD(L)=DDDX(NC)*REDUC(L)
      WRITE (8,210) ZR(NC)
  210 FORMAT('Depth as fraction of RGIN = ',F5.3)
      WRITE (8,1)
      WRITE (8,221)
  221 FORMAT(11X,'X',11X,'Y',7X,'REDUC',8X,'DRAD')
      DO 223 L=1,LMAX
      WRITE (8,222) XP(L),YP(L),REDUC(L),DRAD(L)
  222 FORMAT(4F12.5)
  223 CONTINUE
      WRITE (8,1)
      print 245, ncase,nc
  245 format(' ncase = ',13,'  nc = ',13)
  250 CONTINUE
      STOP
      END
      DOUBLE PRECISION FUNCTION FUN1(X,B)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      FUN1=-B
      RETURN
      END
      DOUBLE PRECISION FUNCTION FUN2(X,B)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      FUN2=B
      RETURN
      END
      DOUBLE PRECISION FUNCTION FUN3(X,Y)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      FUN3=1.0D0
      RETURN
      END
```

```
      PROGRAM AXPLOT
C
C     24 July 93. Written by Martin J. Berger, NIST.
C
C     Plots reduction factor and absorbed dose along central axis
C     of circular or rectangular field.
C
      DIMENSION Z(107),D(107),RED(107),A1(107),B1(107),C1(107),D1(107),
     1 A2(107),B2(107),C2(107),D2(107),X(801),Y1(801),Y2(801)
      CHARACTER INPUT*16,LINE*80,TITLE*80
      DATA JMAX/801/
    5 FORMAT(A)
      PRINT *,' Options for input:'
      PRINT *,'   1) Circular field'
      PRINT *,'   2) Rectangular field'
      PRINT *,' Enter choice: '
      READ *, IN
      PRINT *,' Enter name of input file: '
      READ 5, INPUT
      PRINT *,' Enter title of plot: '
      READ 5, TITLE
      OPEN (7,INPUT)
      GO TO (10,40), IN
   10 DO 20 LN=1,12
      READ (7,5) LINE
   20 CONTINUE
      READ (7,*) G1,G2,G3,IG,NMAX
      DO 30 LN=1,4
      READ (7,5) LINE
   30 CONTINUE
      READ (7,*) (Z(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (RED(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (D(N),N=1,NMAX)
      CLOSE (7)
      GO TO 70
   40 DO 50 LN=1,18
      READ (7,5) LINE
   50 CONTINUE
      READ (7,*) G1,G2,G3,G4,G5,IG,NMAX
      DO 60 LN=1,4
      READ (7,5) LINE
   60 CONTINUE
      READ (7,*) (Z(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (RED(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (D(N),N=1,NMAX)
      CLOSE (7)
   70 CALL SCOF(Z,RED,NMAX,A1,B1,C1,D1)
      CALL SCOF(Z,D,NMAX,A2,B2,C2,D2)
      DX=Z(NMAX)/REAL(JMAX-1)
      DO 80 J=1,JMAX
      X(J)=DX*REAL(J-1)
      CALL BSPOL(X(J),Z,A1,B1,C1,D1,NMAX,Y1(J))
      CALL BSPOL(X(J),Z,A2,B2,C2,D2,NMAX,Y2(J))
   80 CONTINUE
      CALL SETDV('HPG')
  100 CALL LINLOG(0,0,1)
      CALL SIDTEX(TITLE,1,'z/r_o',1,'Reduction Factor',1,' ',1)
      CALL PLAC(1.0,0.5,0.0,1.0)
      CALL SETLIM(2,3,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y1)
      CALL VG
      CALL SIDTEX('  ',1,'z/r_o',1,'Absorbed Dose, MeV/g',1,' ',1)

      CALL PLAC(0.5,0.0,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y2)
      CALL VG
      IF(LOOPIN().EQ.1) GO TO 100
      STOP
      END
```

```
      PROGRAM RADPLOT
C
C     24 July 93. Written by Martin J. Berger, NIST.
C
C     Plots reduction factor and absorbed dose at a fixed depth,
C     as functions of the radial distance from the center of the field.

      DIMENSION RHO(201),RED(201),D(201),A1(201),B1(201),C1(201),
     1 D1(201),A2(201),B2(201),C2(201),D2(201),X(801),Y1(801),
     2 Y2(801)
      CHARACTER INPUT*16,LINE*80,TITLE*80
      DATA JMAX/801/
    5 FORMAT(A)
      PRINT *,' Options for input:'
      PRINT *,'   1) Circular field'
      PRINT *,'   2) Rectangular field'
      PRINT *,' Enter choice: '
      READ *, IN
      PRINT *,' Enter name of input file: '
      READ 5, INPUT
      PRINT *,' Enter title of plot: '
      READ 5, TITLE
      OPEN (7,INPUT)
      GO TO (10,40), IN
   10 DO 20 LN=1,12
      READ (7,5) LINE
   20 CONTINUE
      READ (7,*) G1,G2,G3,LMAX
      READ (7,5)
      READ (7,5)
      READ (7,*) (RHO(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) (RED(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,*) (D(L),L=1,LMAX)
      GO TO 60
   40 DO 50 LN=1,18
      READ (7,5) LINE
   50 CONTINUE
      READ (7,*) G1,G2,G3,G4,G5,LMAX
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) (RHO(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) (RED(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,*) (D(L),L=1,LMAX)
   60 CLOSE (7)
      CALL SCOF(RHO,RED,LMAX,A1,B1,C1,D1)
      CALL SCOF(RHO,D,LMAX,A2,B2,C2,D2)
      DX=RHO(LMAX)/REAL(JMAX-1)
      DO 70 J=1,JMAX
      X(J)=DX*REAL(J-1)
      CALL BSPOL(X(J),RHO,A1,B1,C1,D1,LMAX,Y1(J))
      CALL BSPOL(X(J),RHO,A2,B2,C2,D2,LMAX,Y2(J))
      X(J)=10.0*X(J)
   70 CONTINUE
      CALL SETDV('HPG')
  100 CALL LINLOG(0,0,1)
      CALL SIDTEX(TITLE,1,'r,mm',1,'Reduction Factor',1,' ',1)
      CALL PLAC(1.0,0.5,0.0,1.0)
      CALL SETLIM(2,3,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y1)
      CALL VG
      CALL SIDTEX('  ',1,'r, mm',1,'Absorbed Dose, MeV/g',1,' ',1)

      CALL PLAC(0.5,0.0,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y2)
      CALL VG
      IF(LOOPIN().EQ.1) GO TO 100
      STOP
      END
```

```
      CALF=COS(ALF)
      SALF=SIN(ALF)
      DO 205 L=1,LMAX
      NMAX=NMX
      OLDVAL=2.0D0
      X=CALF*DS*DBLE(L-1)
      Y=SALF*DS*DBLE(L-1)
  100 IF(X.LE.A.AND.Y.LE.B) GO TO 110
      IF(X.LE.A.AND.Y.GT.B) GO TO 140
      IF(X.GT.A.AND.Y.LE.B) GO TO 160
      IF(X.GT.A.AND.Y.GT.B) GO TO 180
  110 RHMAX=MIN(A-X,B-Y)
      IF(RMAX-RHMAX)115,115,120
  115 REDUC(L)=1.0D0
      GO TO 200
  120 DRH=RHMAX/DBLE(NMAX-1)
      DO 125 N=1,NMAX
      RHO=DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
  125 GRAND(N)=RHO*EXP(RES)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART1)
      RHMIN=MIN(A-X,B-Y)
      RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 130 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,A+X,B+Y,FRAC1)
      CALL CORNER(RHO,A+X,B-Y,FRAC2)
      CALL CORNER(RHO,A-X,B+Y,FRAC3)
      CALL CORNER(RHO,A-X,B-Y,FRAC4)
  130 GRAND(N)=FINT*(FRAC1+FRAC2+FRAC3+FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,PART2)
      REDUC(L)=PART1+PART2
      GO TO 200
  140 RHMIN=Y-B
      IF(RMAX-RHMIN)142,142,145
  142 REDUC(L)=0.0D0
      GO TO 200
  145 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 150 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,A+X,Y+B,FRAC1)
      CALL CORNER(RHO,A-X,Y+B,FRAC2)
      CALL CORNER(RHO,A+X,Y-B,FRAC3)
      CALL CORNER(RHO,A-X,Y-B,FRAC4)
  150 GRAND(N)=FINT*(FRAC1+FRAC2-FRAC3-FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
      GO TO 200
  160 RHMIN=X-A
      IF(RMAX-RHMIN)162,162,165
  162 REDUC(L)=0.0D0
      GO TO 200
  165 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 170 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,X+A,B+Y,FRAC1)
      CALL CORNER(RHO,X+A,B-Y,FRAC2)
      CALL CORNER(RHO,X-A,B+Y,FRAC3)
      CALL CORNER(RHO,X-A,B-Y,FRAC4)
  170 GRAND(N)=FINT*(FRAC1+FRAC2-FRAC3-FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
      GO TO 200
  180 RHMIN=SQRT((X-A)**2+(Y-B)**2)
      IF(RMAX-RHMIN)182,182,185
  182 REDUC(L)=0.0D0
      GO TO 200
  185 RHMAX=SQRT((X+A)**2+(Y+B)**2)
      RHMAX=MIN(RHMAX,RMAX)
      DRH=(RHMAX-RHMIN)/DBLE(NMAX-1)
      DO 190 N=1,NMAX
      RHO=RHMIN+DRH*DBLE(N-1)
      CALL BSPOLD(RHO,R,ACOF,BCOF,CCOF,DCOF,JMAX,RES)
      FINT=RHO*EXP(RES)
      CALL CORNER(RHO,X+A,Y+B,FRAC1)
      CALL CORNER(RHO,X-A,Y+B,FRAC2)
      CALL CORNER(RHO,X+A,Y-B,FRAC3)
      CALL CORNER(RHO,X-A,Y-B,FRAC4)
  190 GRAND(N)=FINT*(FRAC1-FRAC2-FRAC3+FRAC4)
      DELTA=DRH/3.0D0
      CALL GRALD(DELTA,GRAND,NMAX,REDUC(L))
  200 DIFF=ABS(OLDVAL-REDUC(L))
      IF(DIFF-EREDUCL)205,201,201
  201 OLDVAL=REDUC(L)
      IF(NMAX-2561)202,202,205
  202 NMAX=2*NMAX-1
      GO TO 100
  205 CONTINUE
      CALL BSPOLD(ZR(NC),ZD,AP,BP,CP,DP,KMAX,DDDX(NC))
      DO 206 L=1,LMAX
  206 DRAD(L)=DDDX(NC)*REDUC(L)
      IF(LMAX.NE.1) WRITE (8,210) ZR(NC)
  210 FORMAT('Depth as fraction of RGIN = ',F5.3)
      IF(LMAX.EQ.1) RED(NC)=REDUC(1)
      IF(LMAX.EQ.1) DAX(NC)=DRAD(1)
      IF(LMAX.NE.1) WRITE (8,220)
  220 FORMAT('Reduction factors')
      IF(LMAX.NE.1) WRITE (8,230) (REDUC(L),L=1,LMAX)
  230 FORMAT(8F12.6)
      IF(LMAX.NE.1) WRITE (8,240)
  240 FORMAT('Absorbed dose, MeV/g, from a beam of 1 proton/cm2')
      IF(LMAX.NE.1) WRITE (8,230) (DRAD(L),L=1,LMAX)
      print 245, ncase,nc
  245 format(' ncase = ',i3,'  nc = ',i3)
  250 CONTINUE
      IF(LMAX.NE.1) GO TO 290
      WRITE (8,260) S(1)
  260 FORMAT('Radial distance (cm) from center of field = ',F5.3)
      WRITE (8,1)
      WRITE (8,270)
  270 FORMAT('Depths, in units of RGIN')
      WRITE (8,280) (ZR(NC),NC=1,NCASE)
  280 FORMAT(8F12.6)
      WRITE (8,220)
      WRITE (8,280) (RED(NC),NC=1,NCASE)
      WRITE (8,240)
      WRITE (8,280) (DAX(NC),NC=1,NCASE)
  290 STOP
      END

      SUBROUTINE CORNER(R,SA,SB,FRAC)
C     27 Mar 88. Computes rel.arclength (fracton of 2 pi) for point in
C                corner of rectangle with sides SA and SB.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      TPI=8.0D0*ATAN(1.0D0)
      IF(SA)60,60,5
    5 IF(SB)60,60,6
    6 A=MAX(SA,SB)
      B=MIN(SA,SB)
      IF(R-B)10,10,20
   10 FRAC=0.25D0
      RETURN
   20 IF(R-A)30,30,40
   30 FRAC=0.25D0-ACOS(B/R)/TPI
      RETURN
   40 IF(R*R-A*A-B*B)50,50,60
   50 FRAC=0.25D0-(ACOS(B/R)+ACOS(A/R))/TPI
      RETURN
   60 FRAC=0.0D0
      RETURN
      END
```

```
      PROGRAM FREC
C
C     15 May 93. Written by Martin J. Berger, NIST.
C
C               Calculates reduction factors and absorbed-dose values
C               for a rectangular field.
C
C               Center of coordinate system is at x=0, y=0.
C               Rectangle extends from -A to A in x, -B to B in y.
C
C               Results are calculated as functions of the distance
C               from the center of the field, along a line that makes
C               an angle alpha (between 0 and 90 degrees) with respect
C               to the x-axis.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION REDUC(401),S(401),R(401),F(401),FL(401),
     1 ACOF(401),BCOF(401),CCOF(401),DCOF(401),GRAND(5121),
     2 ZD(100),DEPOT(100),AP(100),BP(100),CP(100),DP(100),DRAD(401),
     3 ZR(401),DDDX(401),RED(401),DAX(401)
      CHARACTER*16 INPUT1,INPUT2,INPUT3,OUTPUT,INFIL
      CHARACTER LINE*80
      DATA NMX/161/,EREDUCL/1.0D-04/
    1 FORMAT(1H )
    5 FORMAT(A)
      PI=4.0D0*ATAN(1.0D0)
      RADFAC=PI/180.0D0
      PRINT *,' Rectangular field extends from -A to A in x, -B to B in
     1y'
      PRINT *,' Enter values of A and B (cm): '
      READ *, A,B
      PRINT *, ' Line goes through a corner of the rectangle (1=yes, 2=n
     1o): '
      READ *, JVEC
      IF(JVEC.NE.2) GO TO 10
      PRINT *,' Enter angle alpha with respect to x-axis (degrees): '
      READ *, ALPHA
      ALF=ALPHA*RADFAC
      GO TO 11
   10 ALF=ATAN(B/A)
      ALPHA=ALF/RADFAC
   11 PRINT *,' Options for specifying radial distances:'
      PRINT *,'   1) Get set of values from file'
      PRINT *,'   2) Get set of values from keyboard'
      PRINT *,'   3) Specify set of values in terms of maximum distance'
      PRINT *,'      and number of distances, LMAX: '
      PRINT *,' Enter choice: '
      READ *, INS
      GO TO (12,13,14), INS
   12 PRINT *,' Enter name of file with distance values: '
      READ 5, INFIL
      OPEN (7,INFIL)
      READ (7,*) LMAX
      READ (7,*) (S(L),L=1,LMAX)
      CLOSE (7)
      GO TO 15
   13 PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, LMAX
      PRINT *,' Enter distances (cm): '
      READ *, (S(L),L=1,LMAX)
      GO TO 15
   14 PRINT *,' Enter maximum radial distance (cm): '
      READ *, SMAX
      LMAX=1
      IF(SMAX.LE.0.0D0) GO TO 15
      PRINT *,' Enter number of radial distances (no greater than 401):
     1'
      READ *, LMAX
   15 PRINT *,' Enter name of input file 1 (from MORAD): '
      READ 5, INPUT1
      PRINT *,' Options for depths:'
      PRINT *,'   1) No depths greater than 98% of CSDA range'
      PRINT *,'   2) Some depths greater than 98% of CSDA range'
      PRINT *,' Enter choice: '
      READ *, INDEP
      IF(INDEP.EQ.1) GO TO 16
      PRINT *,' Enter name of input file 2 (from PTRAD): '
      READ 5, INPUT2
   16 PRINT *,' Enter name of input file 3 (from PTPOL): '
      READ 5, INPUT3
      PRINT *,' Enter name of output file: '
      READ 5, OUTPUT
      IF(INS.LT.3) GO TO 18
      S(1)=0.0
      IF(LMAX.LE.1) GO TO 18
      DS=SMAX/DBLE(LMAX-1)
      DO 17 L=2,LMAX
   17 S(L)=DS*DBLE(L-1)
   18 OPEN (8,OUTPUT)
      WRITE (8,19) OUTPUT
   19 FORMAT('Program FREC, output file ',A)
      WRITE (8,20)INPUT1
      IF(INDEP.EQ.2) WRITE (8,20) INPUT2
      WRITE (8,20) INPUT3
   20 FORMAT('Input file = ',A)
      IF(INDEP.EQ.1) WRITE (8,1)
      WRITE (8,1)
      WRITE (8,25)
   25 FORMAT('     TIN = energy of incident proton beam, MeV')
      WRITE (8,26)
   26 FORMAT('    RGIN = CSDA range at energy TIN, g/cm2')
      WRITE (8,27)
   27 FORMAT('      2A = side of rectangular field, cm')
      WRITE (8,28)
   28 FORMAT('      2B = side of rectanglular field, cm')
      WRITE (8,29)
   29 FORMAT('   ALPHA = angle (deg) defined below')
      WRITE (8,30)
   30 FORMAT('    LMAX = number of radial distances from center of field'
     1)
      WRITE (8,31)
   31 FORMAT('   NCASE = number of depths')
      WRITE (8,1)
      WRITE (8,32)
   32 FORMAT('Rectangular field extends from -A to A in x, and from -B t
     1o B in y.')
      WRITE (8,33)
   33 FORMAT('Line along which reduction factor is calculated starts at
     1the origin')
      WRITE (8,34)
   34 FORMAT('and makes angle ALPHA (deg) with respect to x-axis.')
      WRITE (8,1)
      OPEN (6,INPUT1)
      IF(INDEP.EQ.2) OPEN (7,INPUT2)
      READ (6,5) LINE
      READ (6,5) LINE
      READ (6,*) NCASE1
      READ (6,*) JMAX1
      DO 35 LN=1,8
      READ (6,5) LINE
   35 CONTINUE
      READ (6,*) TIN,RGIN
      READ (6,5) LINE
      NCASE2=0
      JMAX2=0
      IF(INDEP.EQ.1) GO TO 37
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) NCASE2
      READ (7,*) JMAX2
      DO 36 LN=1,5
      READ (7,5) LINE
   36 CONTINUE
   37 NCASE=NCASE1+NCASE2
      WRITE (8,38)
   38 FORMAT(9X,'TIN',8X,'RGIN',11X,'A',11X,'B',7X,'ALPHA',' LMAX NCASE
     1')
      WRITE (8,39) TIN,RGIN,A,B,ALPHA,LMAX,NCASE
   39 FORMAT(5F12.5,2I6)
      IF(LMAX.NE.1) WRITE (8,1)
      IF(LMAX.NE.1) WRITE (8,40)
   40 FORMAT('Radial distances from center of field (cm)')
      IF(LMAX.NE.1) WRITE (8,41) (S(L),L=1,LMAX)
   41 FORMAT(6F12.5)
      OPEN(11,INPUT3)
      DO 42 LN=1,9
      READ (11,5) LINE
   42 CONTINUE
      READ (11,*) G1,G2,G3,G4,KMAX
      READ (11,5) LINE
      READ (11,5) LINE
      READ (11,*) (ZD(K),K=1,KMAX)
      READ (11,*) LINE
      READ (11,*) (DEPOT(K),K=1,KMAX)
      CLOSE (11)
      CALL SCOFD(ZD,DEPOT,KMAX,AP,BP,CP,DP)
      DO 250 NC=1,NCASE
      IF(NC-NCASE1)43,43,44
   43 JMAX=JMAX1
      READ (6,5) LINE
      READ (6,*) ZR(NC),RMAX,SUM
      READ (6,5) LINE
      READ (6,*) (R(J),J=1,JMAX)
      READ (6,5) LINE
      READ (6,*) (F(J),J=1,JMAX)
      GO TO 47
   44 JMAX=JMAX2
      READ (7,5) LINE
      READ (7,*) TIN,ZR(NC),RMAX
      READ (7,5) LINE
      READ (7,*) (R(J),J=1,JMAX)
      READ (7,5) LINE
      READ (7,*) (F(J),J=1,JMAX)
      JTAL=0
      DO 45 J=1,JMAX
      IF(F(J))46,46,45
   45 JTAL=JTAL+1
   46 JMAX=JTAL
   47 DO 48 J=1,JMAX
   48 FL(J)=LOG(2.0D0*PI*F(J))
      CALL SCOFD(R,FL,JMAX,ACOF,BCOF,CCOF,DCOF)
```

```
      PROGRAM AXPLOT
C
C     24 July 93. Written by Martin J. Berger, NIST.
C
C     Plots reduction factor and absorbed dose along central axis
C     of circular or rectangular field.
C
      DIMENSION Z(107),D(107),RED(107),A1(107),B1(107),C1(107),D1(107),
     1 A2(107),B2(107),C2(107),D2(107),X(801),Y1(801),Y2(801)
      CHARACTER INPUT*16,LINE*80,TITLE*80
      DATA JMAX/801/
    5 FORMAT(A)
      PRINT *,' Options for input:'
      PRINT *,'   1) Circular field'
      PRINT *,'   2) Rectangular field'
      PRINT *,' Enter choice: '
      READ *, IN
      PRINT *,' Enter name of input file: '
      READ 5, INPUT
      PRINT *,' Enter title of plot: '
      READ 5, TITLE
      OPEN (7,INPUT)
      GO TO (10,40), IN
   10 DO 20 LN=1,12
      READ (7,5) LINE
   20 CONTINUE
      READ (7,*) G1,G2,G3,IG,NMAX
      DO 30 LN=1,4
      READ (7,5) LINE
   30 CONTINUE
      READ (7,*) (Z(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (RED(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (D(N),N=1,NMAX)
      CLOSE (7)
      GO TO 70
   40 DO 50 LN=1,18
      READ (7,5) LINE
   50 CONTINUE
      READ (7,*) G1,G2,G3,G4,G5,IG,NMAX
      DO 60 LN=1,4
      READ (7,5) LINE
   60 CONTINUE
      READ (7,*) (Z(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (RED(N),N=1,NMAX)
      READ (7,5) LINE
      READ (7,*) (D(N),N=1,NMAX)
      CLOSE (7)
   70 CALL SCOF(Z,RED,NMAX,A1,B1,C1,D1)
      CALL SCOF(Z,D,NMAX,A2,B2,C2,D2)
      DX=Z(NMAX)/REAL(JMAX-1)
      DO 80 J=1,JMAX
      X(J)=DX*REAL(J-1)
      CALL BSPOL(X(J),Z,A1,B1,C1,D1,NMAX,Y1(J))
      CALL BSPOL(X(J),Z,A2,B2,C2,D2,NMAX,Y2(J))
   80 CONTINUE
      CALL SETDV('HPG')
  100 CALL LINLOG(0,0,1)
      CALL SIDTEX(TITLE,1,'z/r_o',1,'Reduction Factor',1,' ',1)
      CALL PLAC(1.0,0.5,0.0,1.0)
      CALL SETLIN(2,3,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y1)
      CALL VG
      CALL SIDTEX('  ',1,'z/r_o',1,'Absorbed Dose, MeV/g',1,' ',1)

      CALL PLAC(0.5,0.0,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y2)
      CALL VG
      IF(LOOPIN().EQ.1) GO TO 100
      STOP
      END
```

```
      PROGRAM RADPLOT
C
C     24 July 93. Written by Martin J. Berger, NIST.
C
C     Plots reduction factor and absorbed dose at a fixed depth,
C     as functions of the radial distance from the center of the field.

      DIMENSION RHO(201),RED(201),D(201),A1(201),B1(201),C1(201),
     1 D1(201),A2(201),B2(201),C2(201),D2(201),X(801),Y1(801),
     2 Y2(801)
      CHARACTER INPUT*16,LINE*80,TITLE*80
      DATA JMAX/801/
    5 FORMAT(A)
      PRINT *,' Options for input:'
      PRINT *,'   1) Circular field'
      PRINT *,'   2) Rectangular field'
      PRINT *,' Enter choice: '
      READ *, IN
      PRINT *,' Enter name of input file: '
      READ 5, INPUT
      PRINT *,' Enter title of plot: '
      READ 5, TITLE
      OPEN (7,INPUT)
      GO TO (10,40), IN
   10 DO 20 LN=1,12
      READ (7,5) LINE
   20 CONTINUE
      READ (7,*) G1,G2,G3,LMAX
      READ (7,5)
      READ (7,5)
      READ (7,*) (RHO(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) (RED(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,*) (D(L),L=1,LMAX)
      GO TO 60
   40 DO 50 LN=1,18
      READ (7,5) LINE
   50 CONTINUE
      READ (7,*) G1,G2,G3,G4,G5,LMAX
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) (RHO(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,5) LINE
      READ (7,*) (RED(L),L=1,LMAX)
      READ (7,5) LINE
      READ (7,*) (D(L),L=1,LMAX)
   60 CLOSE (7)
      CALL SCOF(RHO,RED,LMAX,A1,B1,C1,D1)
      CALL SCOF(RHO,D,LMAX,A2,B2,C2,D2)
      DX=RHO(LMAX)/REAL(JMAX-1)
      DO 70 J=1,JMAX
      X(J)=DX*REAL(J-1)
      CALL BSPOL(X(J),RHO,A1,B1,C1,D1,LMAX,Y1(J))
      CALL BSPOL(X(J),RHO,A2,B2,C2,D2,LMAX,Y2(J))
      X(J)=10.0*X(J)
   70 CONTINUE
      CALL SETDV('HPG')
  100 CALL LINLOG(0,0,1)
      CALL SIDTEX(TITLE,1,'r,mm',1,'Reduction Factor',1,' ',1)
      CALL PLAC(1.0,0.5,0.0,1.0)
      CALL SETLIM(2,3,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y1)
      CALL VG
      CALL SIDTEX('  ',1,'r, mm',1,'Absorbed Dose, MeV/g',1,' ',1)

      CALL PLAC(0.5,0.0,0.0,1.0)
      CALL HOWPLT(0,1,1)
      CALL CURV(JMAX,X,Y2)
      CALL VG
      IF(LOOPIN().EQ.1) GO TO 100
      STOP
      END
```