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INTERFACE EFFECTS ON DOSE DISTRIBUTIONS IN IRRADIATED MEDIA*

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Abstract. It has long been recognized that nonuniformities in dose distributions may occur in the immediate vicinity of a boundary between two different media. Considerable work has been done to determine interface effects in media irradiated by photons or in media containing β- or α-particle emitters. More recently interface effects have become of interest in additional problems, including pion radiotherapy and radiation effects in electronic microcircuits in space vehicles. These problems arise when pion capture stars or proton-nucleus interactions produce a spectrum of charged nuclear fragments near an interface. The purpose of this paper is to examine interface effects in detail as to their specific origin. We have made Monte Carlo calculations of dose distributions near an interface in a systematic way for a number of idealized cases in order to indicate the separate influences of several factors including different stopping powers of the two media, nonconstancy (e.g., Bragg peak) in the energy loss curve for the particles, different particle spectra in the two media, and curvature of the boundary between the two media.

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1. Introduction

Nonuniformities in dose distributions have long been recognized to occur in the immediate vicinity of a boundary between two different media. Such effects are important in dosimeter response and much work has been done in cavity theory.[1] Also, both theoretical and experimental work has been done[2-3] to estimate interface effects in media irradiated by photons and neutrons. More recently, there has been considerable interest in the use of negative pion beams for radiotherapy. When a negative pion stops in matter, it is absorbed by the nucleus of an atom and its rest energy of approximately 140 MeV is converted into kinetic

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energy of fragments of the capturing nucleus. Such pion capture stars produce neutrons, protons, and other charged heavy nuclear fragments that are high linear energy transfer (LET) radiation and are effective in producing biological effects. It is for this reason that pions appear promising for radiotherapy applications. Pions offer advantages in better dose localization as well as higher relative biological effectiveness (RBE) and lower oxygen enhancement ratio (OER) in the tumor region. It is important, therefore, to understand details of dose distributions near an interface between two media located in the stopping region of a pion beam.

Another area in which interface effects have become of considerable interest is radiation effects in very large-scale integrated circuits. These devices are constructed of multiple layers of different atomic number materials. Dose and charge buildup can result in errors in such devices. Consequently, there has been a great deal of interest in dose buildup near an interface in media irradiated by photons.[4-7] Applications of microelectronics materials in space is increasing and the high energy radiation present there results in nuclear events which produce protons and other nuclear fragments which can also result in dose buildup or nonuniformities near an interface.

Since the charged particle spectra from pion capture stars (or recoil spectra from protonnucleus interactions) are complex, and there are a variety of types of materials between which interface effects are important, we have chosen to make several calculations for idealized cases in order to show quantitatively the way in which various factors affect dose distributions near an interface. We have used Monte Carlo techniques to calculate dose distributions for several configurations described in the remainder of the paper.

2. Description of Calculations

In order to study the effects of the stopping powers of the two media, we have assumed that a "star" consists of the isotropic emission of monoenergetic protons with an energy of 20 MeV. We also assume that there are the same number of stars per gram of material in each media and that they are uniformly distributed. We have assumed that medium

one has the stopping power of soft tissue and that medium two has stopping powers that are multiples of those of medium one (i.e., the proton ranges are multiples of those of medium one). Figure 1 shows the results of three calculations for proton ranges 10%, 30%, and 50% greater in medium two than medium one. At distances from the boundary greater than the range of the protons, the dose in medium one is the same as in medium two since the same amount of energy is released per gram of material in each medium. However, there is a dose discontinuity at the interface that is approximately equal to the ratio of the stopping powers of the two media in each case.

Figure 2 shows calculations in which medium one is tissue and medium two has proton ranges 20% greater than medium one. We assume again that there are the same number of stars per gram in each medium and that the stars produce 10 MeV protons in one case, 20 MeV protons in another case, and 40 MeV protons in the third case. In each case a discontinuity of approximately 20% exists at the interface, the ratio of the stopping powers. The shapes of the dose curves depend on the ranges of the protons as can be seen in the figure.

The next set of calculations is for the case in which a star in medium one produces a 25 MeV proton and a star in medium two produces a 20 MeV proton. Since the same number of stars per gram are assumed in each medium, the dose at distances greater than the range of the protons is 25% higher in medium one than in medium two. The dashed line in Fig. 3 shows the dose distribution when both media have the same proton ranges (that of standard tissue). As the interface is approached through medium one, the dose decreases to a local minimum, then rises through the interface to a local maximum in medium two before decreasing to its constant value at a distance greater than the range of the protons from the interface. The solid curve in Fig. 3 results if the range of the protons in medium two is 20% greater than in medium one. Again, there is a discontinuity of approximately 20% at the interface.

The local minimum and maximum in the dashed curve in Fig. 3 results because of the nonconstancy of the stopping power, dE/dx, of the protons. If the total ranges of the protons were the same as in standard tissue, but dE/dx were a constant, the dose would be as shown in Fig. 4. For

comparison purposes, the dashed curve in Fig. 3 is redrawn on Fig. 4 and labeled "nonconstant dE/dx."

We have also calculated the dose distribution at an interface between two media in which stars produce protons with the energy spectrum that is produced by negative pion capture in carbon.[8] The protons have energies up to 100 MeV with a mean energy of slightly over 20 MeV. Figure 5 gives the dose if medium one is tissue and medium two has ranges 20% greater than medium one. Since the range in tissue of the highest energy protons in the spectrum is approximately 7 cm, it is several centimeters from the interface before the dose is the same in both media.

The next set of calculations has been performed for cylindrical boundaries between the media of radii 1.0 and 2.0 cm. It is assumed that a star in medium one produces a 25 MeV proton and in medium two a 20 MeV proton. The calculations have been made for medium one on the inside and also on the outside of the curved boundary. The dose along a radius of the cylinder is shown in Fig. 6 as a function of distance from the boundary. The results are plotted so that medium one is always on the left of the interface, shown by negative values on the abscissa. The solid line is the dose at a plane boundary between the two media. It is the same as shown by the dashed line in Fig. 3. If medium one, which produces the higher energy protons, is on the outside of the cylindrical boundary, the dose is increased from that at a plane boundary. If medium one is on the inside of the cylindrical boundary, the dose is decreased.

The results described thus far have involved the assumption that there are the same number of stars per gram of material in both media. However, consider the case of a pion beam incident on a uniform tissue phantom and designed so that there is a uniform stopping distribution over some region. Now suppose there is a plane interface located in the stopping region and perpendicular to the direction of travel of the incident pions. If medium two, behind the plane boundary, has greater ranges than medium one in front of the interface, the density of the stopping pions will be decreased because the incident pions travel farther from the interface before stopping. Figure 7 shows the dose

near the interface in such a case. We assume that a uniform distribution of stars that emit 20 MeV protons exists in medium one which is taken to be tissue. We assume that the ranges of particles in medium two are 20% greater than those in medium one and that the density of stars in medium one is 20% greater than in medium two. If a star in medium two also produces a 20 MeV proton, the dose is shown by the dashed line in Fig. 7. The dose in medium one is 20% higher than in medium two, but there is no enhancement at the interface. However, if stars in medium two produce 25 MeV protons, the results are shown by the solid line in Fig. 7. There is an increase in the dose in medium one near the interface and a decrease in the dose in medium two.

3. Concluding Remarks

We have performed these calculations for idealized geometries in order to show quantitatively the effect of several factors on dose distributions near an interface. A discontinuity at the interface results if the stopping powers of the media on either side of the interface are different. Varying the source particle energies within two media of the same stopping powers produces nonuniformities near the interface and the shape of the dose curves depends upon the shape of the stopping power curves for the particles. However, if the stars are the same in both media and the stopping powers are the same for both media, the density of the media or the density of stars within the media do not produce dose enhancement near the interface. Curvature of the boundary does affect the dose distribution near the boundary.

References

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FIGURE CAPTIONS

Fig. 1. Relative dose profile near an interface between two media having different particle ranges.

Fig. 2. Relative dose profile near an interface between two media having different particle ranges and different star proton energies.

Fig. 3. Relative dose profile near an interface between two media having different particle ranges and different star proton energies.

Fig. 4. Relative dose profile near an interface between two media from protons with constant and nonconstant dE/dx.

Fig. 5. Relative dose profile near an interface between two media, having different particle ranges, from protons with the energy spectrum produced by negative pion capture in carbon.

Fig. 6. Relative dose profile near a cylindrical boundary, of radius 1 cm or 2 cm, between two media from protons with different energies.

Fig. 7. Relative dose profile near an interface between two media with different particle ranges for different star densities and different star proton energies.

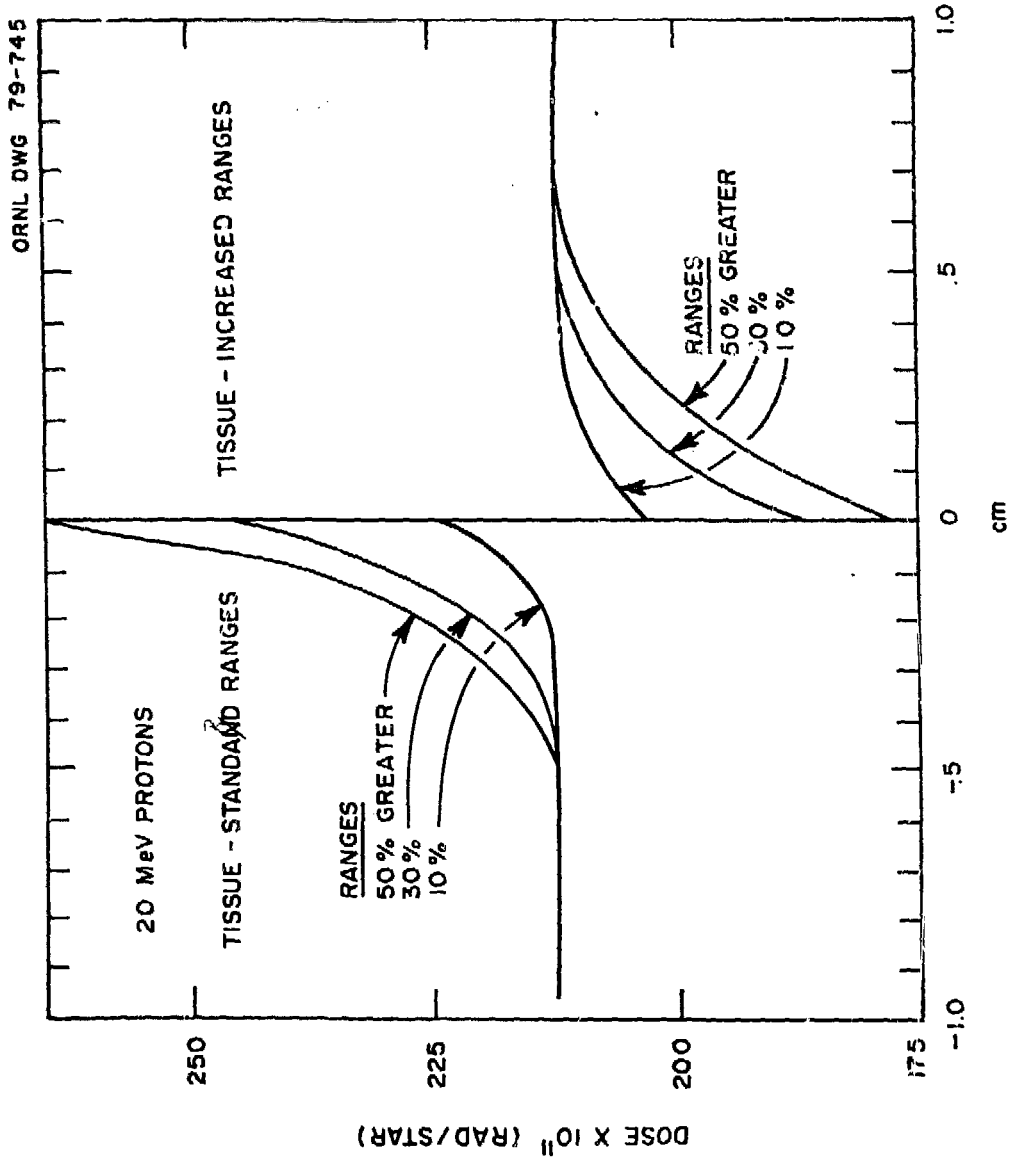
ORNL DWG 79-745
20 MeV PROTONS
TISSUE - STANDARD RANGES
TISSUE - INCREASED RANGES
RANGES
50 % GREATER
30 %
10 %
RANGES
50 % GREATER
30 %
10 %
DOSE X 10¹¹ (RAD/STAR)
250
225
200
175
-1.0
-.5
0
.5
1.0
cm

Figure 1

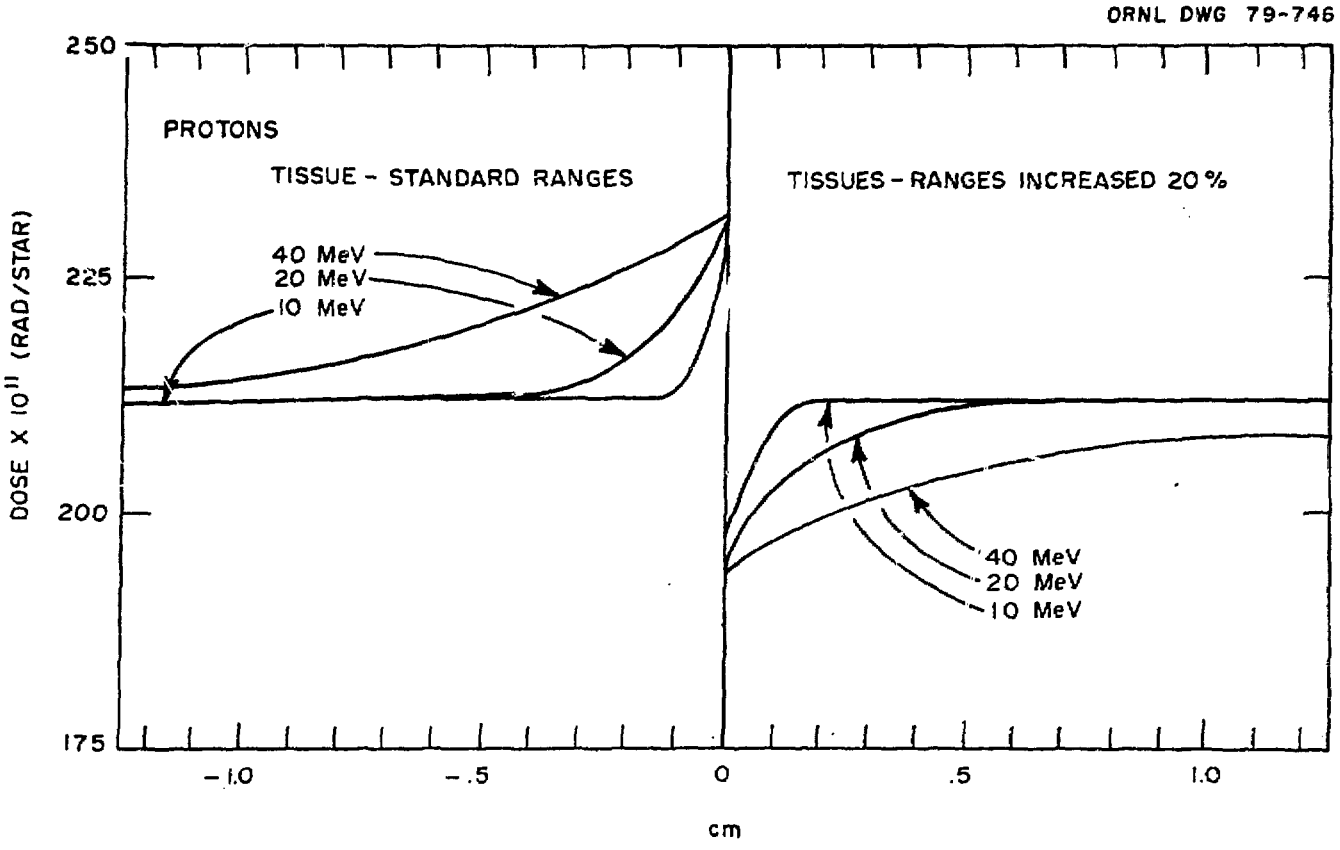
ORNL DWG 79-746
250
225
200
175
PROTONS
TISSUE - STANDARD RANGES
TISSUES - RANGES INCREASED 20 %
40 MeV
20 MeV
10 MeV
40 MeV
20 MeV
10 MeV
DOSE X 10^11 (RAD/STAR)
-1.0
-.5
0
.5
1.0
cm

Figure 2

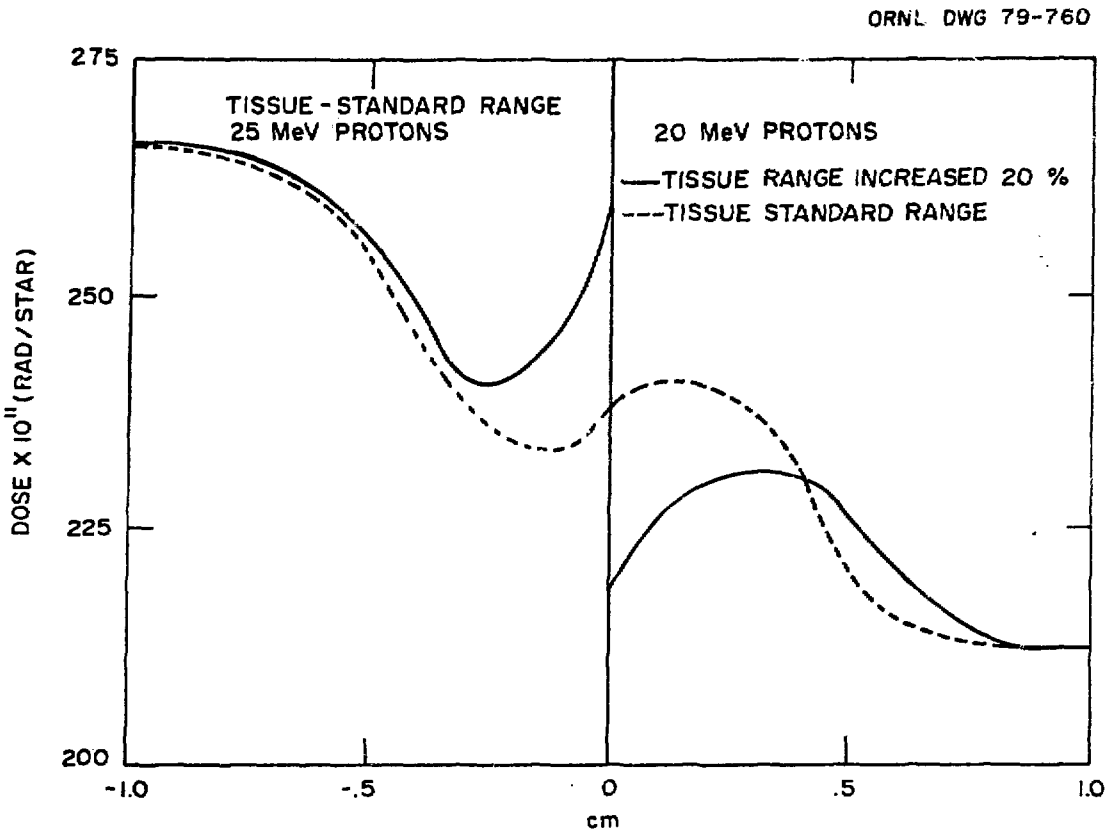
ORNL DWG 79-760
275
250
225
200
DOSE X 10^11 (RAD/STAR)
TISSUE - STANDARD RANGE
25 MeV PROTONS
20 MeV PROTONS
—TISSUE RANGE INCREASED 20 %
---TISSUE STANDARD RANGE
-1.0
-.5
0
.5
1.0
cm

Figure 3

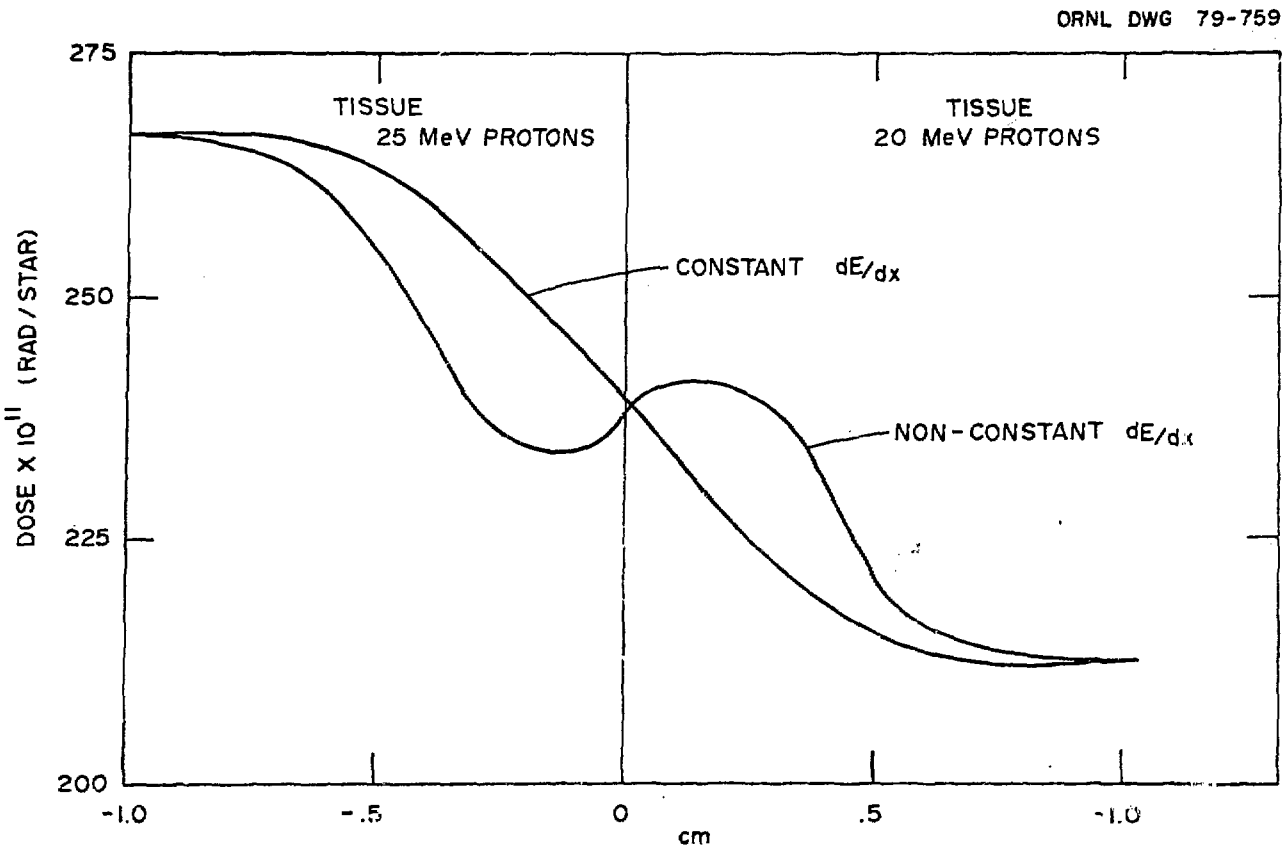
ORNL DWG 79-759
275
250
225
200
DOSE X 10^{11} (RAD/STAR)
TISSUE
25 MeV PROTONS
TISSUE
20 MeV PROTONS
CONSTANT dE/dx
NON-CONSTANT dE/dx
-1.0
-.5
0
.5
1.0
cm

Figure 4

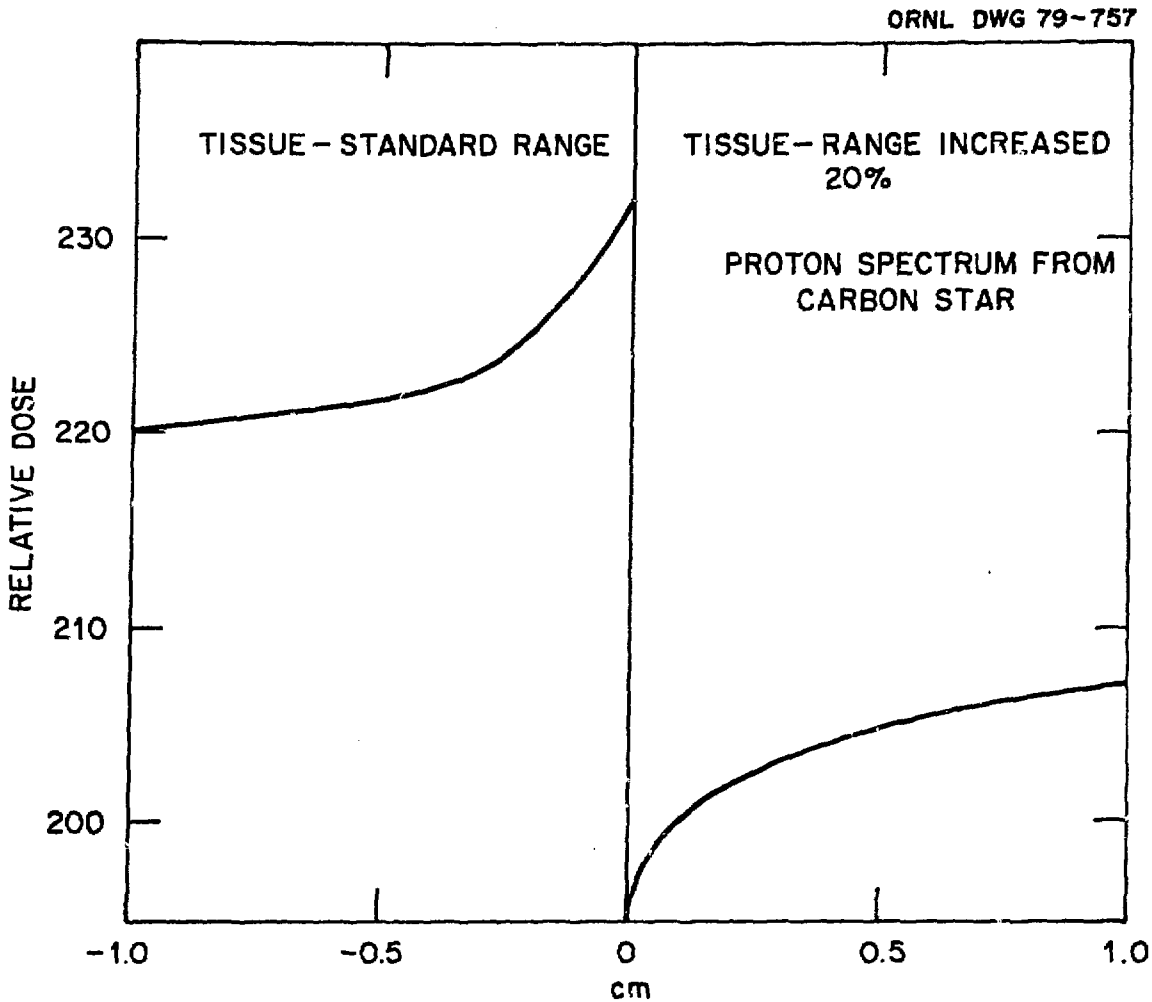
ORNL DWG 79-757
TISSUE – STANDARD RANGE
TISSUE – RANGE INCREASED 20%
PROTON SPECTRUM FROM CARBON STAR
RELATIVE DOSE
230
220
210
200
-1.0
-0.5
0
0.5
1.0
cm

Figure 5

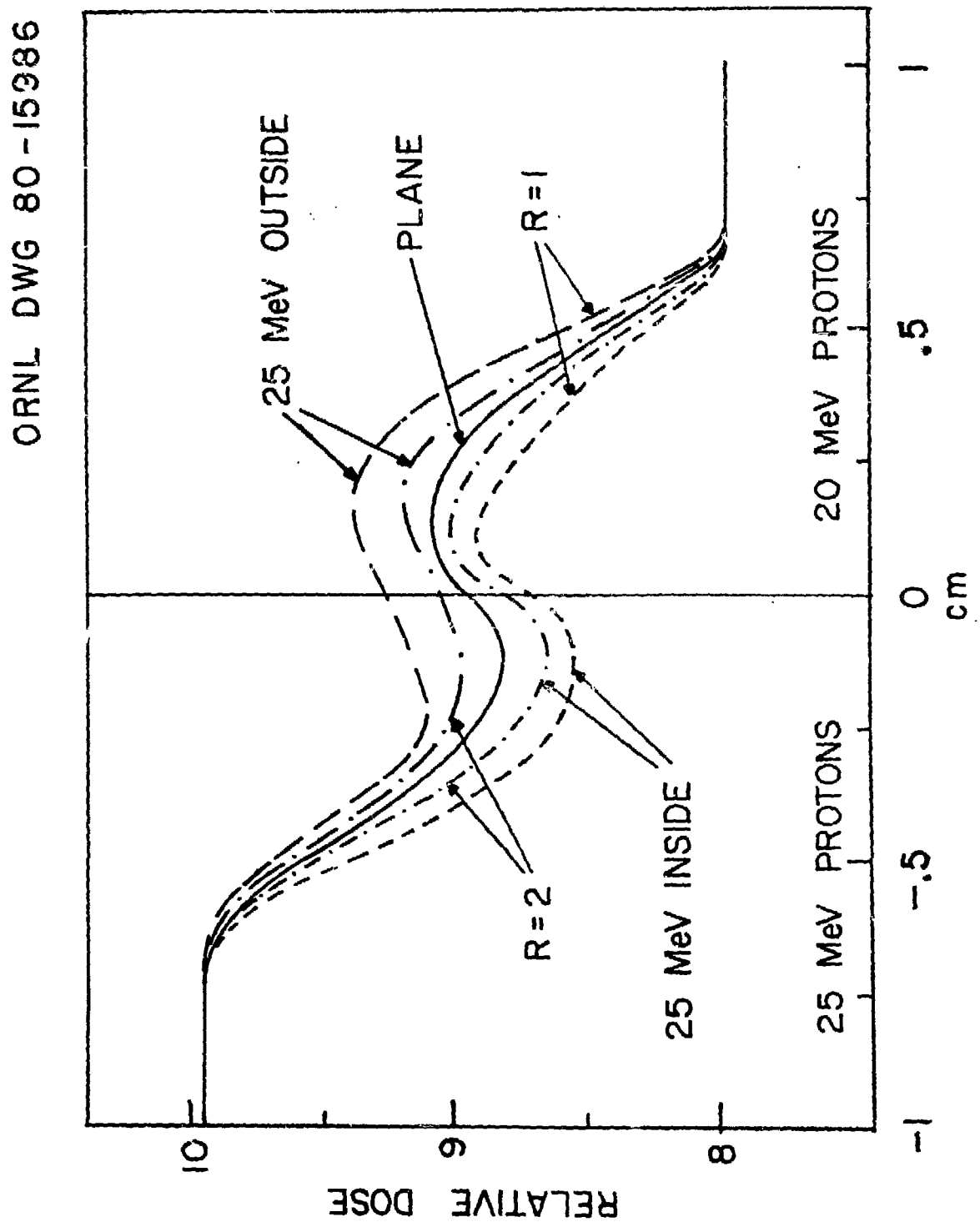
ORNL DWG 80-15986
25 MeV OUTSIDE
PLANE
R=1
R=2
25 MeV INSIDE
25 MeV PROTONS
20 MeV PROTONS
RELATIVE DOSE
10
9
8
-1
-.5
0
.5
1
cm

Figure 6

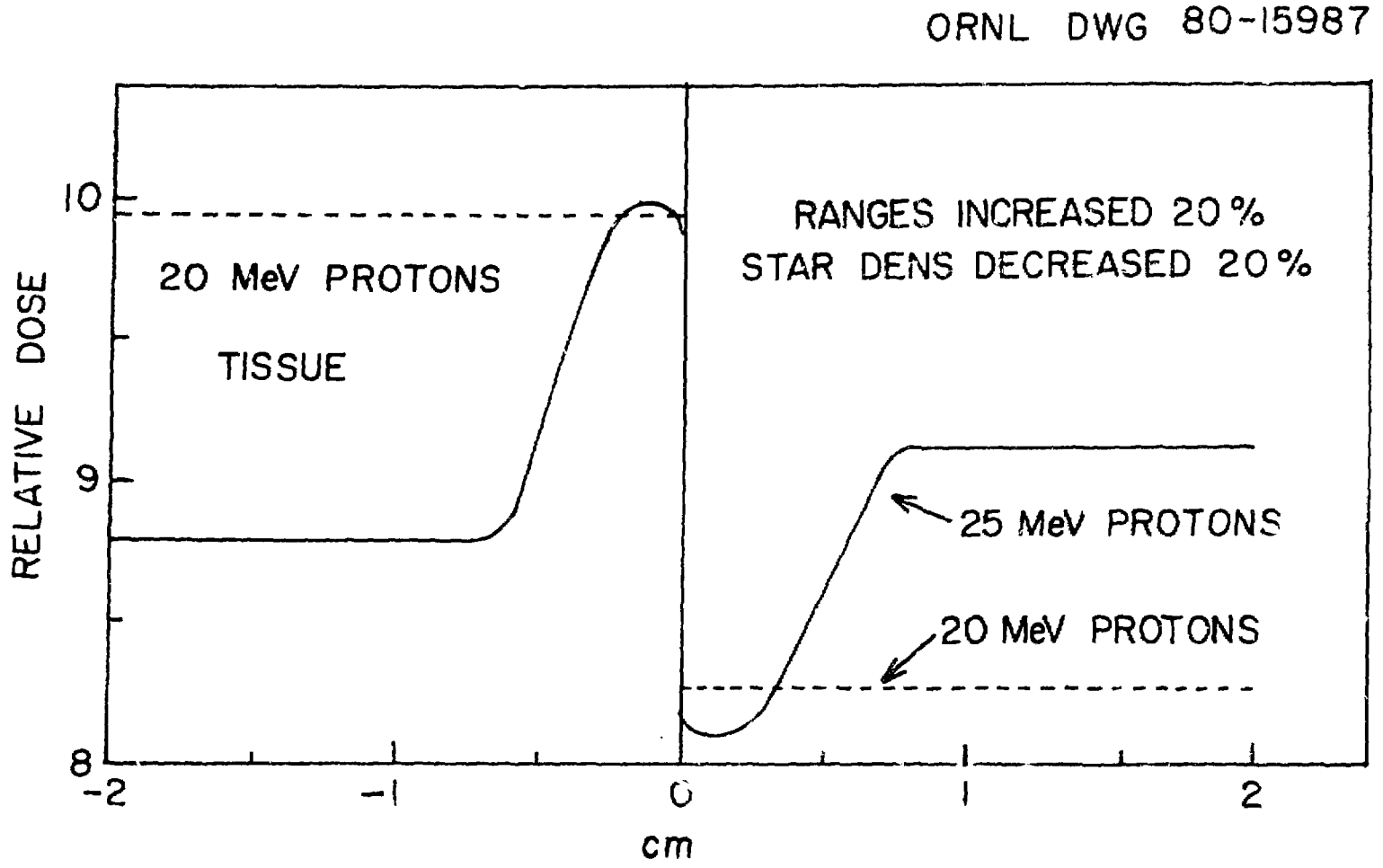
ORNL DWG 80-15987
RELATIVE DOSE
10
9
8
20 MeV PROTONS
TISSUE
RANGES INCREASED 20%
STAR DENS DECREASED 20%
25 MeV PROTONS
20 MeV PROTONS
-2
-1
0
1
2
cm

Figure 7