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CHARACTERIZATION OF A p(66)Be(49) NEUTRON THERAPY BEAM:

I. CENTRAL AXIS DEPTH DOSE AND OFF-AXIS RATIOS

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INTRODUCTION.

The Fermilab Cancer Therapy Facility (CTF)[1,2,3] has been treating cancer patients since September, 1976, with a neutron beam generated by 66 MeV protons incident on a Be target 2.21 cm thick, which removes only 49 MeV from incident protons not undergoing nuclear scattering.* Their residual energy is absorbed in a gold disk 0.5 mm thick. No hardening or flattening filter is employed in the neutron beam, as the penetration and angular distribution of the neutrons at the distances used are satisfactory for clinical use. The characteristics of the early collimation system and the distribution algorithms employed initially have been described elsewhere.[2] After two years of clinical experience, it was decided that modifications to the system would improve daily operations in several ways[3], and a new collimation system was designed and implemented. This note presents some of the features of the new system

* This combination of incident particle type and energy, as well as target material and thickness, is abbreviated p(66)Be(49). (See reference 4)

as well as some characterization of the beams defined by it, e.g., central axis depth dose and off-axis ratios. The algorithms used to represent these characteristics are also discussed.

COLLIMATION SYSTEM.

The new system was designed with a source-axis distance (SAD) of 190 cm, instead of 153.2 cm for the initial system.[1,2] The total length of the interchangeable polyethylene concrete[2] collimators was reduced to 78 cm from 93 cm for the old system, and two removable Benelex[5] liners were used instead of one, making the majority of collimators half as heavy as they had been in the old system. Figure 1 shows the complete new collimator assembly. The target is housed in a water-cooled aluminum holder. Two mirrors are used, one for the field light and another for the coaxial laser beam. The primary collimator is made of steel. The definition of nominal field size was modified from the one employed in the old system[2] to make it more closely compatible with the recently adopted definition of the AAPM Task Group 18.[4] The nominal field size at the SAD of 190 cm is defined by the lines joining the center of the Be-target to the downstream edges of the collimator openings, at 109 cm from the center of the target. The taper of the collimator, on the other hand, is defined by a line joining the edges of the downstream opening of the collimator to the edges of the beam spot at the upstream face of the Be-target. Fig. 2 illustrates these geometrical definitions. As shown below, this design agrees with the definition of the AAPM Task Group 18 within the precision of the measurements.

MEASUREMENTS.

Both the central axis depth doses (CADD) and the off-axis ratios (OAR) were measured in a 37 x 40 x 44 cm^3 phantom filled with T.E. solution[6] of $\rho = 1.07$ g cm^{-3}, having a lucite entrance window 3 mm thick. The temperatures of both the solution and the monitor transmission chambers were continuously monitored by a microcomputer.[2,7] The ratios of probe to monitor collected charges were thus continuously corrected for any temperature changes as well as for electronic drifts and leakage in between machine pulses. The probe was in all cases a 0.1 cm^3 thimble ionization chamber, EG&G model I-18[8], with A-150 T.E. plastic walls and dry air flowing through the cavity at about 5 cc/min. The inside diameter of this chamber is 4.5 mm, and the wall thickness is 1.6 mm. The charge collected was interpreted as being proportional to the total $(n + \gamma)$ dose. The measurements were taken in such a way as to minimize effects due to sensitivity drifts and non-linearity of the integrators.[2] A precision of ± 1% or better was achieved in all measurements. The chamber was placed in the empty tank on the beam axis at a standard position with the help of positioning lasers and at a standard depth using a stainless steel gauge from the front surface of the filled up tank. The chamber was then moved in two dimensions with a remote positioner to the desired points in the tank, the position being monitored and reproduced with a precision of ± 0.5 mm.

CENTRAL AXIS DEPTH DOSES.

The depth dose on the central axis was measured for depths from about 1.4 cm to 30 cm for a range of collimator sizes and different SSDs. Fig. 3 shows the CADD for several field sizes at an SSD of 190 cm, all normalized to 1 at D_{max}. Fig. 4 shows the CADD for a single collimator at various SSDs. The dots represent measured points, while the solid and dashed curves represent the mathematical fit described below. The agreement between the measurements and the fits are very good. The depth at which the dose falls to half the maximum was found to be 16.1 cm for the 10 x 10 cm^2 field at 190 cm SSD, up from 14.3 cm at 153.2 cm SSD with the old system.[2] The dashed parts of the curves correspond to the build-up region measured separately with an extrapolation chamber.[9] The algorithm used for curve fitting to the data derives partly from previous neutron shielding work of one of the authors, and was divided into three components: a build-up factor, a simple exponential attenuation factor, and a geometrical (inverse square law) factor. The total algorithm can be expressed thus:

$$\mathrm{CADD}\ (\mathrm{ESQ},\ \mathrm{SSD},\ z) = \mathrm{U1}\cdot\left[1-\mathrm{U3}\cdot e^{-(z/\mathrm{U4})^{\mathrm{U5}}}\right]\cdot e^{-\frac{z}{\mathrm{U2}}}\cdot\left(\frac{190}{\mathrm{SSD}+z}\right)^{2} \qquad (1)$$

where SSD is the source to skin distance (cm),

z is the depth in T. E. solution + entrance window (cm),

U1 is a normalizing factor, and

ESQ is the equivalent square at the surface.[10]

The dependence of the CADD on ESQ is implicit in the parametrization of U2 through U5.

The dependence of the U2 - U5 parameters on ESQ was derived by fitting all available curves using a multi-parameter least-square fit program developed at CERN,[11] and investigating the behaviour of each parameter. The final formulation, which is used in the curves shown in Fig. 3 and 4, is as follows:

$$\begin{aligned} \mathrm{U2} &= 31.65\cdot\left[1 - 0.596\cdot\exp\ (-\mathrm{ESQ}/19.34)\right] \qquad (2)\\ \mathrm{U3} &= 0.745\\ \mathrm{U4} &= 1.52 + 0.0804\cdot\mathrm{ESQ}\\ \mathrm{U5} &= 0.205 \end{aligned}$$

where $ESQ = \left(2\frac{A \cdot B}{A+B}\right) \cdot \frac{SSD}{190}$ is the equivalent square at the surface for a nominal field size A x B at 190 cm SAD. This algorithm reproduces all the experimental data for depths greater than D_{max} within 2% (within 1% for depths less than 20 cm).

OFF-AXIS RATIOS.

The beam profiles perpendicular to the central axis were measured at several depths from 2 cm to 30 cm for a number of field widths and different SSDs. Fig. 5 shows the off-axis ratios for three widely spaced field sizes at two extreme depths, all normalized to one at the central axis. The smooth curves represent mathematical fits to the data as described below.

From the measured data, the separation of the 50% decrement lines can be obtained and extrapolated to the surface, as required by the AAPM Task Group 18 definition of field size.[4] This has been done in Table I for several field sizes, and the agreement between the derived field sizes and the nominal ones is within 2 mm, which is of the same order as the precision of the measurements.

The off-axis ratios were fitted by an algorithm originated by J. van de Geijn[12,13,14] with some modifications as needed. The van de Geijn approach is to modify a given OAR for a given depth and field size, called the master field, first by dual projection scaling of the off-center distances and then by applying various perturbation functions for different field sizes and depths.[12,14] The OAR for the 20 x 20 at a depth of 2 cm was chosen as the master field.[13] The master field was first reproduced analytically using the type of algorithms used to describe the old system OARs.[2] This is a multi-function, multi-parameter expression developed from the approach of Borger et al.[15] The parameters in the perturbation functions needed to transfer the master field to any other OAR were again optimized by a least-square fit program for all available measurements. Although most of these parameters were found to be constants, as expected by van de Geijn, some had to be made dependent on field size for better fits. Finally, an additional function had to be applied for regions beyond the nominal field width to reproduce the unexpectedly high residual dose in the umbra. The final algorithm reproduces all measured points to within 3% of the central axis value or within 2 mm in the steep penumbra region.

WEDGES.

To improve on the ability to produce satisfactory treatment plans, especially in multi-field treatments, two wedge filters were built and measured. The wedges are made of teflon with simple triangular cross-sections, one with a 36^{o} angle, which turns the isodoses through about 45^{o}, the other with a 45^{o} angle, for about a 60^{o} isodose effect. The attenuation of the central axis dose by the wedges was measured and found to be a function of the nominal equivalent square of the collimators at the isoplane. These dependences, although small, have been fitted to a straight line function by a least-square procedure. They are:

$$WF(45^{o}) = 0.7257 + 0.000985\ ESQ \qquad (3)$$
$$WF(60^{o}) = 0.5538 + 0.001687\ ESQ$$

The influence of the wedge filters in the OAR was also measured for various field sizes at various depths. It was found that the modification to the OAR could be described by a single exponential factor:

$$WOAR = OAR \cdot \exp\left[-W \cdot x \cdot \left(\frac{190}{SSD+z}\right)\right] \qquad (4)$$

where x is the off-axis distance in cm, SSD is the source-skin distance, z is the depth and W is a function of both depth and nominal field width L:

$$W = (A + B \cdot L) \cdot [1 - (C + D \cdot L) \cdot z] \qquad (5)$$

where:

$A = 4.66 \cdot 10^{-2}$ for 45^{o} and $7.36 \cdot 10^{-2}$ for 60^{o} wedge
$B = -0.147 \cdot 10^{-2}$ for 45^{o} and $-0.309 \cdot 10^{-2}$ for 60^{o} wedge
$C = 3.80 \cdot 10^{-3}$ for 45^{o} and $8.69 \cdot 10^{-3}$ for 60^{o} wedge
$D = 1.43 \cdot 10^{-3}$ for 45^{o} and $0.057 \cdot 10^{-3}$ for 60^{o} wedge

The fits to the wedged profiles using the above expressions were as good as the fits to the open fields. An example of the effect of the wedges is shown in Fig. 6. Fig. 7 shows an isodose distribution for the 10 x 10 cm^2 field at 190 cm SSD. Figures 8 and 9 show these isodoses shifted by the 45^o and 60^o wedge filters.

CONCLUSIONS.

In summary, the expressions for CADD and OAR, as well as the wedge modifications, have been combined in a treatment planning computer program to produce dose distributions that can be summed over a patient contour to produce reliable isodose distributions. This program is used routinely in planning patient treatments.

ACKNOWLEDGEMENTS.

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TABLE I

Comparison Between Nominal Field Sizes and Decrement Lines

Nominal Field Width at 190 cm SAD (cm)		6	10	14	20
Measured Half-width at Half-maximum at SSD = 180 (cm)	z = 2 cm	2.92	4.92	6.83	9.58
	z = 5 cm	———	4.96	7.00	———
	z = 10 cm	3.29	5.29	7.29	10.04
	z = 15 cm	———	5.50	———	———
	z = 20 cm	3.46	5.67	———	10.75
Extrapolated Full Width at Half-maximum at Surface (cm)		5.64	9.70	13.44	18.90
Nominal Field Width at Surface at SSD = 180 cm (cm)		5.68	9.47	13.26	18.95
Difference in Width (cm)		-0.04	+0.23	+0.18	-0.05

FIGURE CAPTIONS

Fig. 1 Fermilab CTF target and collimator system assembly.

Fig. 2 Field size and taper definitions. Aperture D1 is defined by lines from the center of the target extrapolated to nominal field size DØ at the isoplane:

$$D1 = 0.574\ DØ\ cm$$

Aperture D2 is defined by lines joining D1 and the beam spot size at the upstream face of the target:

$$D2 = 0.165\ DØ + 1.14\ cm$$

Fig. 3 Normalized central axis depth doses for various field sizes at 190 cm SSD. The dots are data. Dashed and solid curves are the parametrized fits.

Fig. 4 Central axis depth doses for the 10 x 10 cm^2 collimator (SAD = 190 cm) for different SSDs. For clarity, the normalization values for D_{max} for SSD = 170 cm and 150 cm have been chosen as 1.25 and 1.5, respectively. The dots are data. Dashed and solid curves are the parametrized fits.

Fig. 5 Normalized off-axis ratios for the 6 x 6, 10 x 10 and 20 x 20 cm^2 collimators, at SSD = 180 cm, at 2 cm and 20 cm deep in T.E. solution. The symbols are data. The curves are the parametrized fits.

Fig. 6 Wedged off-axis ratios, normalized to 1.0 at the central axis. 10 x 10 cm^2 collimator, at an SSD of 180 cm and a depth of 2 cm in T.E. solution. 45^o and 60^o wedges are shown. Symbols are data. The curves are the parametrized fits.

Fig. 7 Isodose distribution in a large T.E. solution phantom for the 10 x 10 cm^2 collimator at SSD = 190 cm.

Fig. 8 Isodose distribution of Figure 7, modified by a 45^o wedge.

Fig. 9 Isodose distribution of Figure 7, modified by a 60^o wedge.

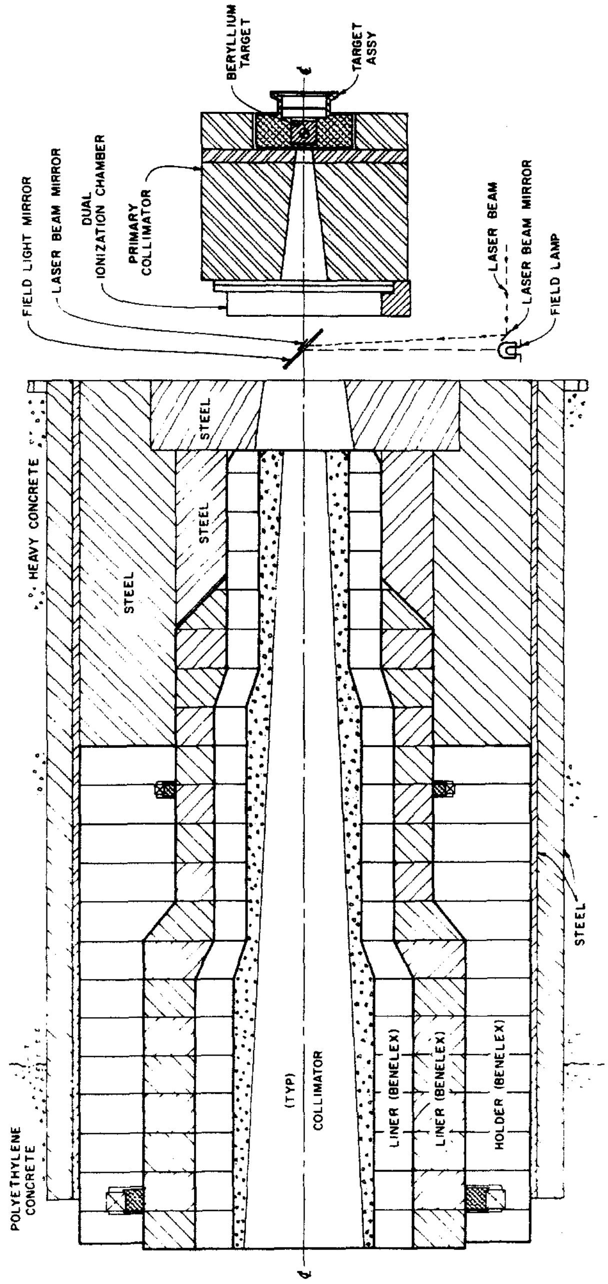
BERYLLIUM TARGET
TARGET ASSY
FIELD LIGHT MIRROR
LASER BEAM MIRROR
DUAL IONIZATION CHAMBER
PRIMARY COLLIMATOR
LASER BEAM
LASER BEAM MIRROR
FIELD LAMP
STEEL
HEAVY CONCRETE
STEEL
STEEL
POLYETHYLENE CONCRETE
(TYP)
COLLIMATOR
LINER (BENELEX)
LINER (BENELEX)
HOLDER (BENELEX)
STEEL

FIGURE 1

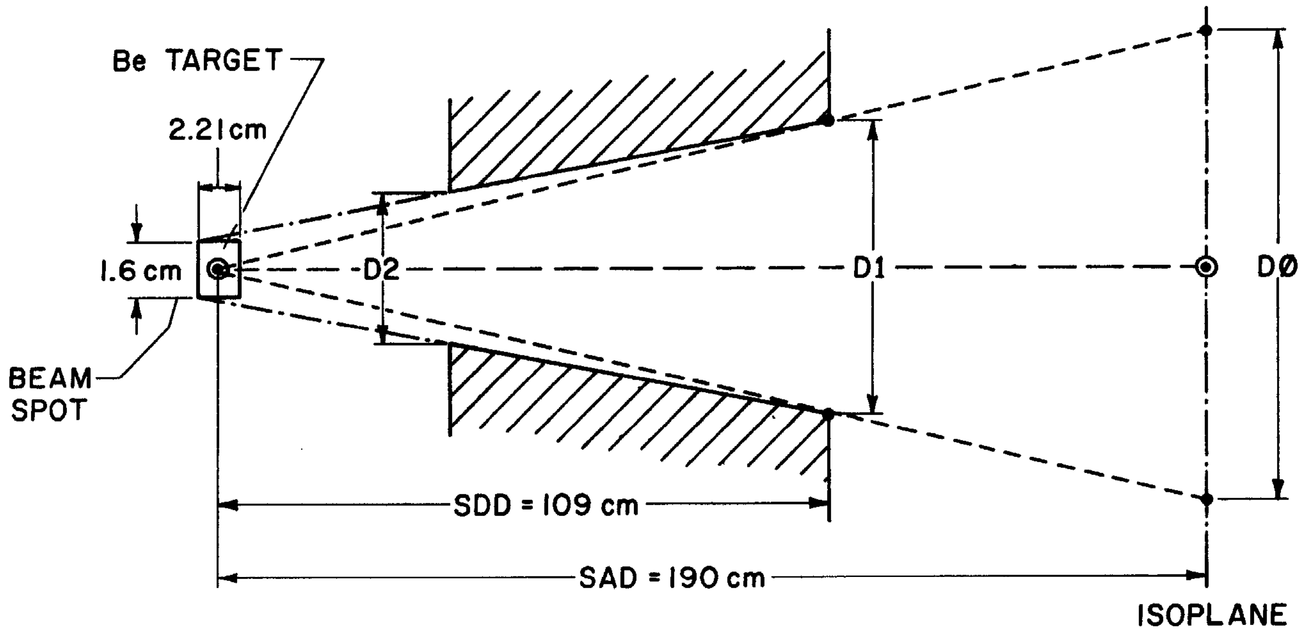
Be TARGET
2.21 cm
1.6 cm
BEAM SPOT
D2
D1
DØ
SDD = 109 cm
SAD = 190 cm
ISOPLANE

FIGURE 2

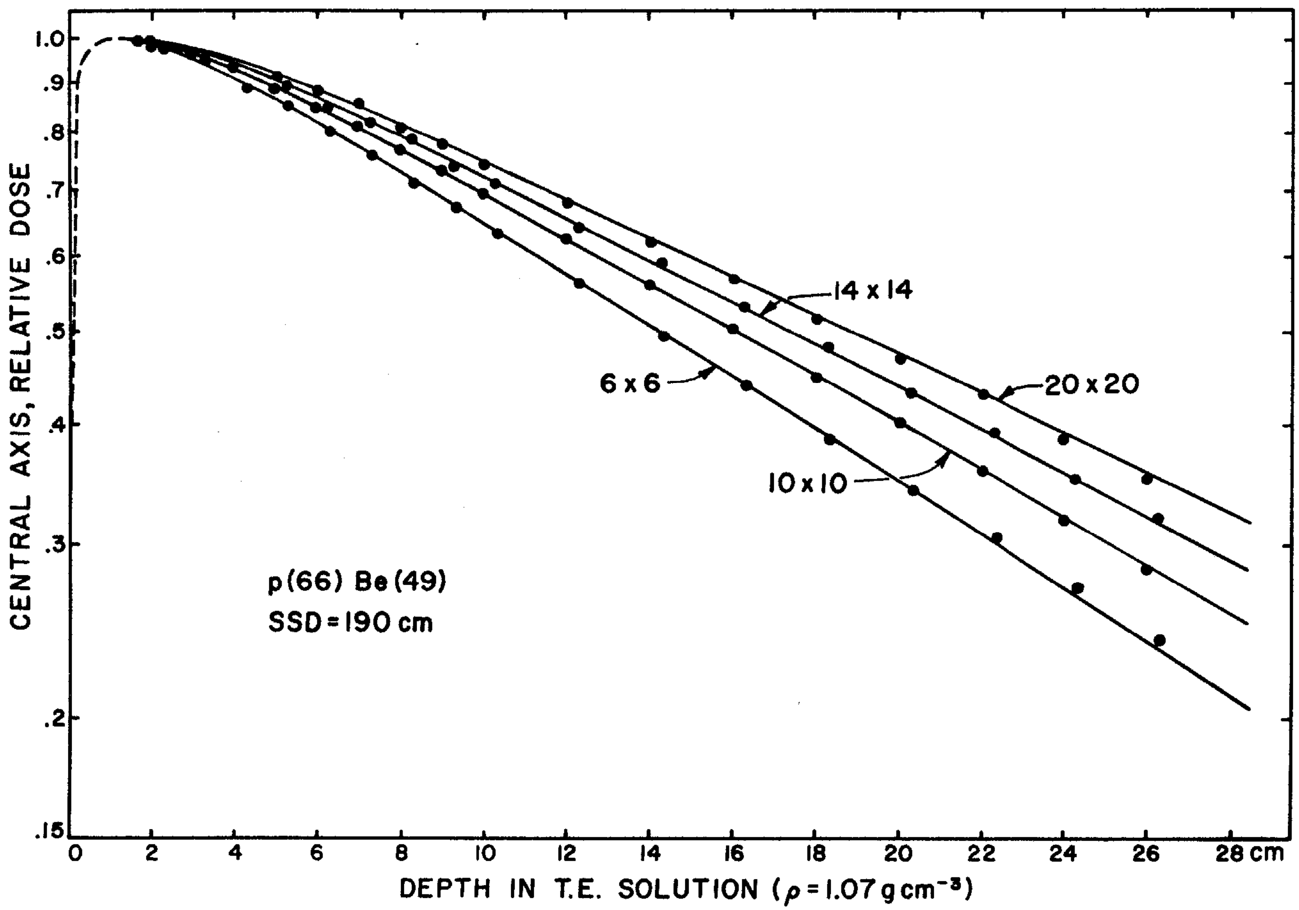
CENTRAL AXIS, RELATIVE DOSE
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.15
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28 cm
DEPTH IN T.E. SOLUTION (ρ = 1.07 g cm⁻³)
14 x 14
20 x 20
6 x 6
10 x 10
p(66) Be(49)
SSD = 190 cm

FIGURE 3

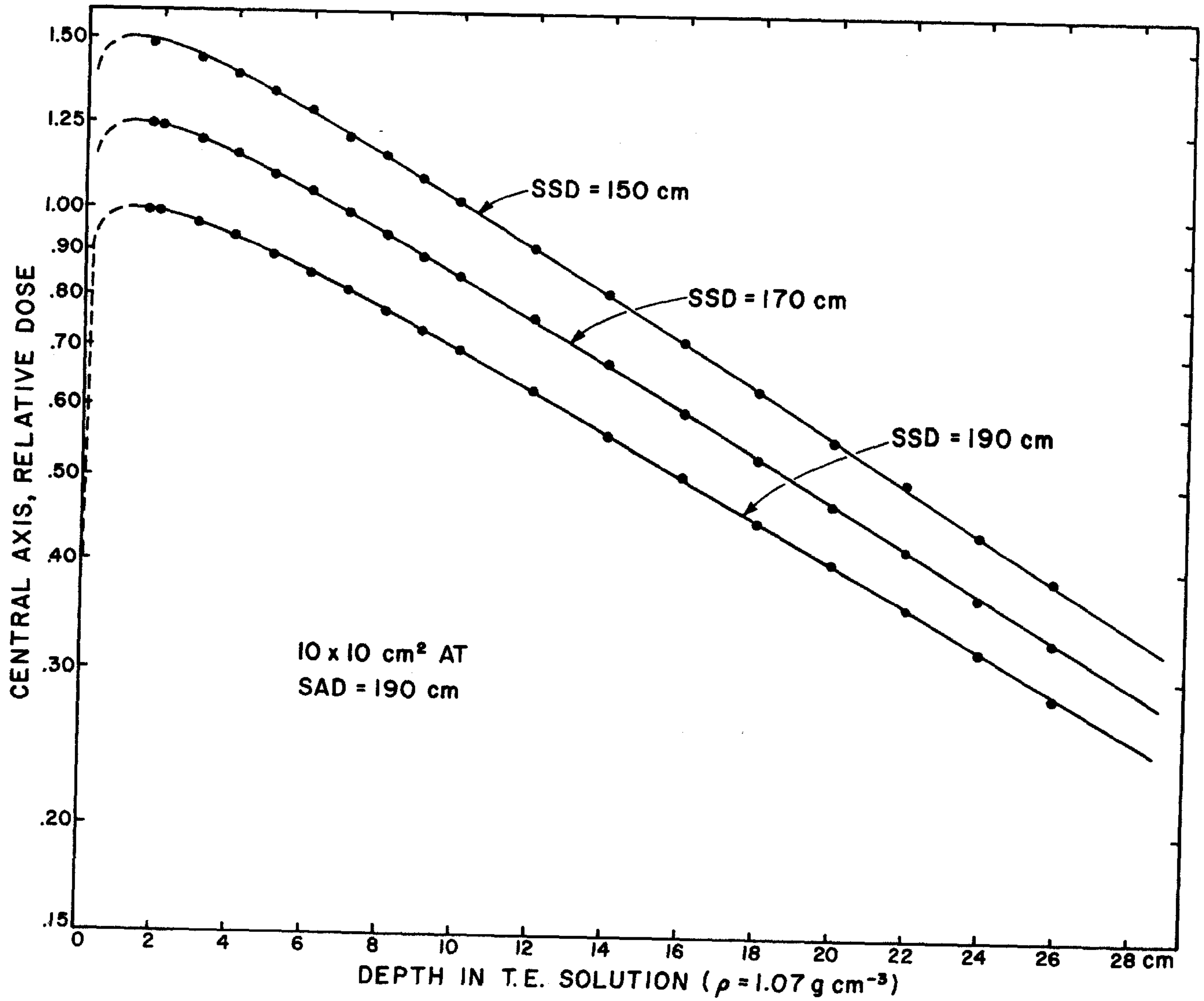
SSD = 150 cm
SSD = 170 cm
SSD = 190 cm
10 x 10 cm² AT
SAD = 190 cm
CENTRAL AXIS, RELATIVE DOSE
1.50
1.25
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.15
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28 cm
DEPTH IN T.E. SOLUTION (ρ = 1.07 g cm⁻³)

FIGURE 4

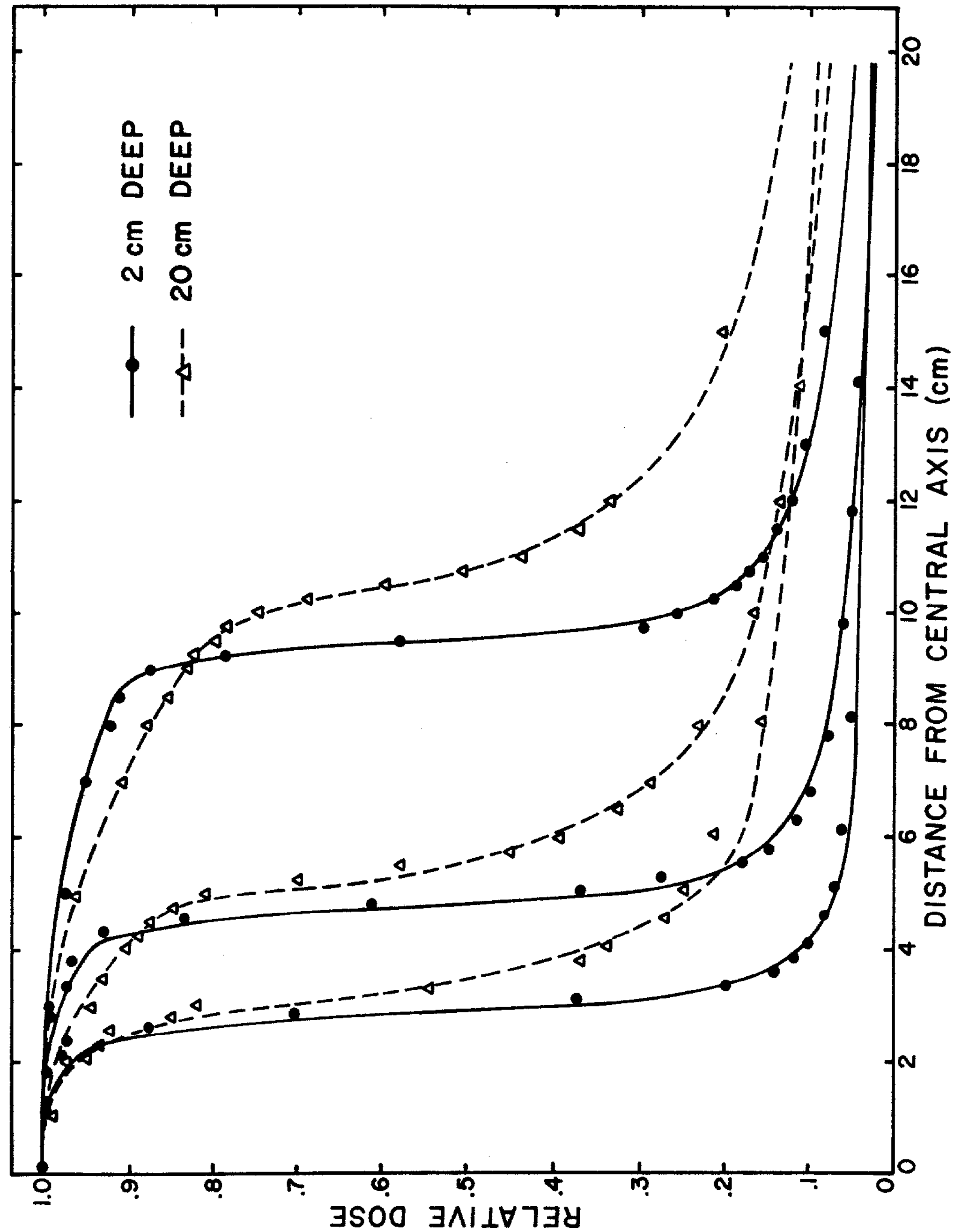
2 cm DEEP
20 cm DEEP
RELATIVE DOSE
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
DISTANCE FROM CENTRAL AXIS (cm)
0
2
4
6
8
10
12
14
16
18
20

FIGURE 5

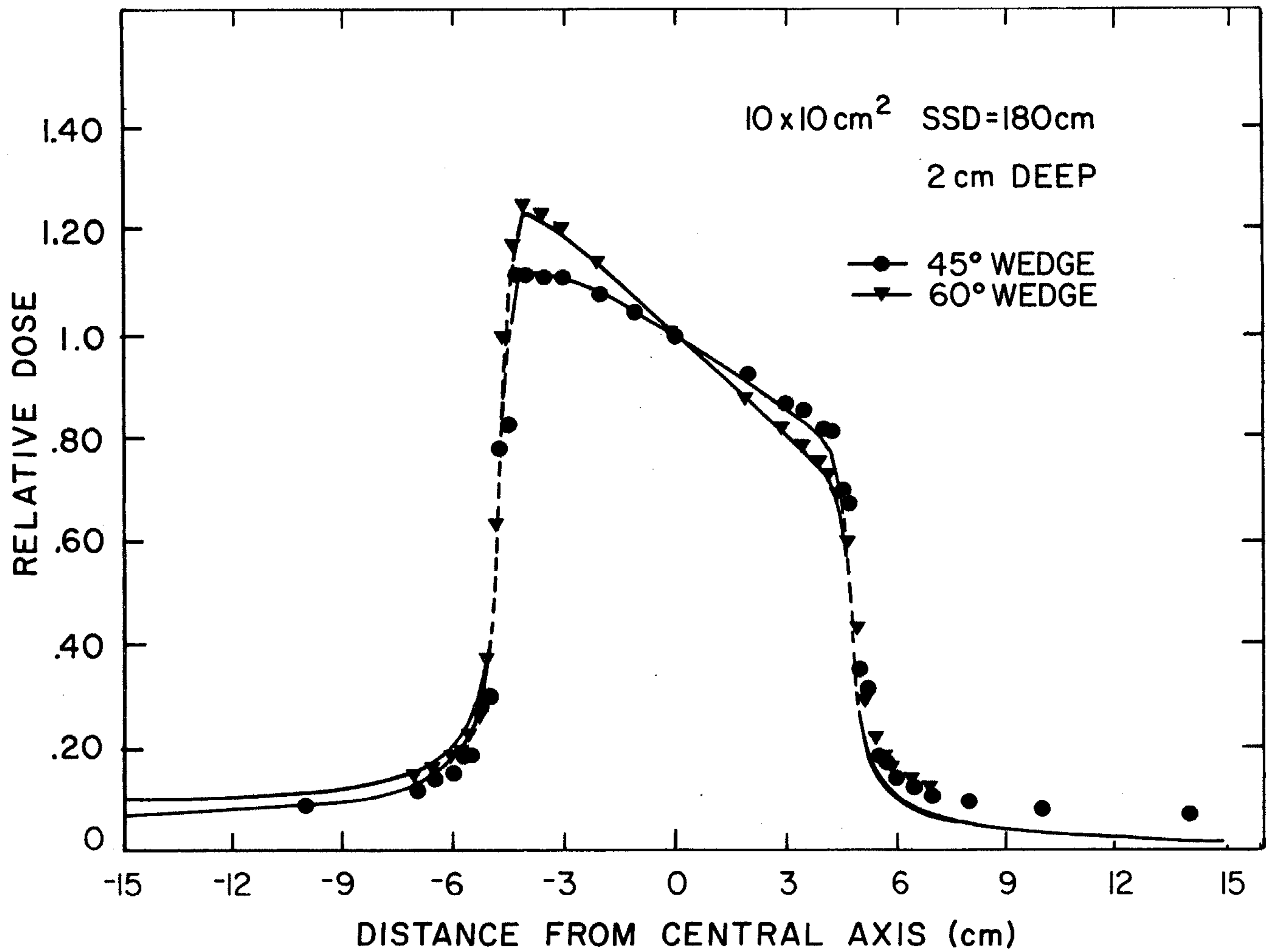
10 x 10 cm^2 SSD=180cm
2 cm DEEP
45° WEDGE
60° WEDGE
RELATIVE DOSE
1.40
1.20
1.0
.80
.60
.40
.20
0
-15
-12
-9
-6
-3
0
3
6
9
12
15
DISTANCE FROM CENTRAL AXIS (cm)

FIGURE 6

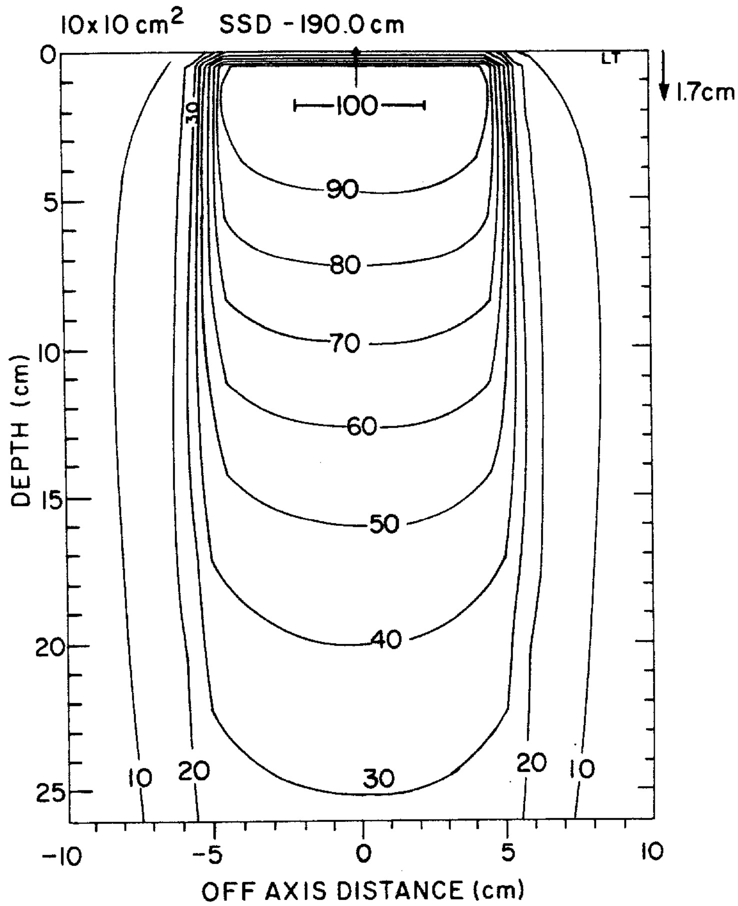
10x10 cm^2 SSD - 190.0 cm
LT
1.7cm
100
90
80
70
60
50
40
30
20
10
DEPTH (cm)
OFF AXIS DISTANCE (cm)
0
5
10
15
20
25
-10
-5
0
5
10

FIGURE 7

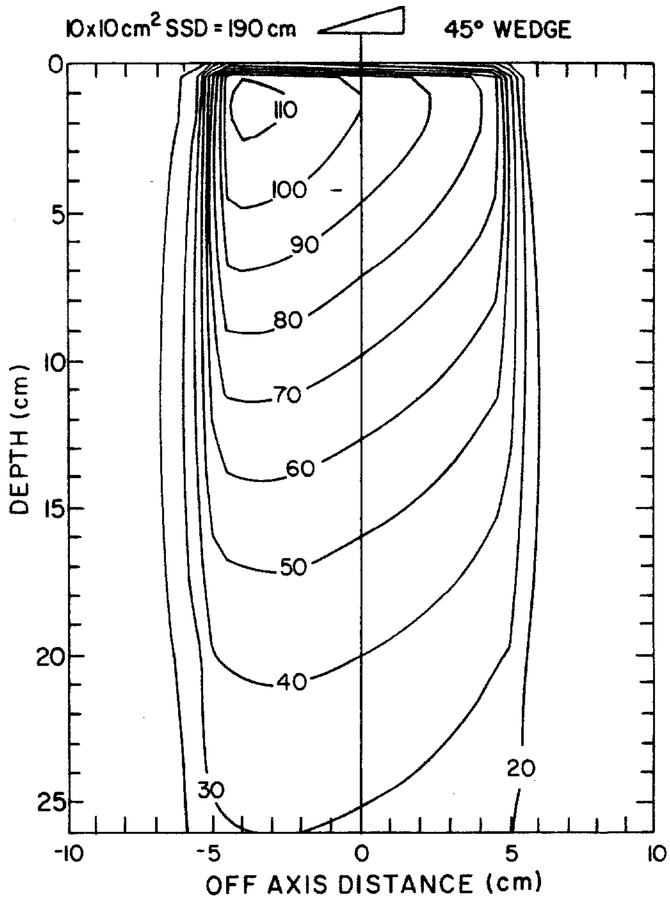

FIGURE 8

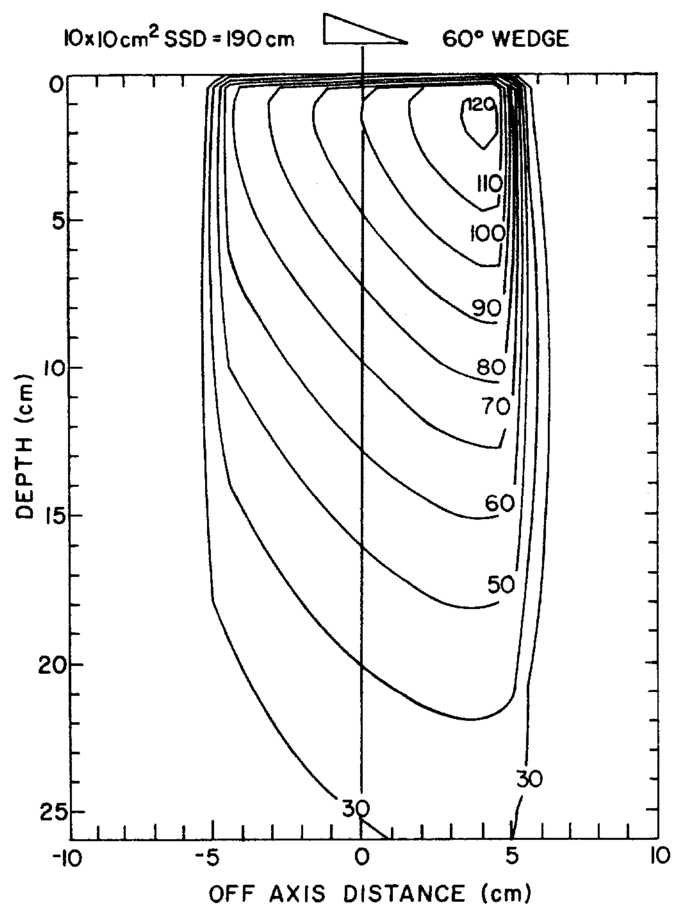

FIGURE 9