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SOLID CHEMICAL RADIATION DOSIMETER

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PREFACE

This report presents the accumulated results of investigations carried out to determine the usefulness of the HAP solid chemical system for charged particle dosimetry. Protons from a 160 meV cyclotron and beta rays from a strontium -90 plaque were the radiations studied.

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PROTON DOSIMETRY USING THE HAP SYSTEM[*]

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The solid phantom chemical dosimeter, which contains halogenated compounds and azo dyes in a paraffin matrix, has been used primarily to measure ionizing electromagnetic radiation.[1-4] Some limited applications of the HAP system as a method of visualizing and determining dose distribution associated with charged particles have been previously reported.[5,6] This article presents more precise quantitative data about specific uses of these translucent tissues--approximating formulations in proton dosimetry. In addition to presenting the effect of specific gravity and effective atomic number, there are studies to illustrate dose distribution in phantoms irradiated with proton beams of different sizes. Analyses of the Bragg peak as well as the shaft of the proton beam are included in the experiments.

MATERIAL AND EQUIPMENT

Chloroform or bromoform was the halogenated compound dissolved in a paraffin matrix with one of three azo dyes: p-dimethylaminoazobenzene (PDAB), 4-phenylazodiphenylamine, (PADA), or p-phenylazoaniline (PPAA). Hexylresorcinol and p-phenylazophenol (PPAP) were employed as chemical modifiers or stabilizers.

The proton source was the Harvard synchrocyclotron with an external beam maximum intensity of about 10^{11} protons per second with an energy of approximately 160 meV. One-half of the protons could be focused by a quadrupole lens to pass through an area of one centimeter square. Calibration dosimetry was carried out with nitrogen-filled

ionization chambers and a Faraday Cup. In water the full range of
the protons was 17.5 centimeters. When actually used the range of
the beam was attenuated by various thicknesses of interposed water-
equivalent plastic.

The equipment for quantitative determinations of color intensity
in the HAP dosimeter was the same as described in detail in a pre-
ceeding paper.[3] It consisted of a constant-voltage-regulated fluores-
cent light source, a photoelectric cell to pick up the light trans-
mitted through the dosimeter, and a galvanometer to measure the light
intensity.

RESULTS

A. Effect of specific gravity and Z on sensitivity.

Disks of HAP dosimeter, 0.8 cm. thick and 12 cm in diameter,
contained 1.2×10^{-4} molal of p-dimethylaminoazobenzene with differ-
ent molal concentrations of chloroform or bromoform. These small
round slabs were placed at the front or beam entrance end of 10 cm.
more of HAP dosimeter, which constituted additional phantom material.
The experimental disks measured the radiation intensity of a 2 x 2 cm.
square proton beam as it entered the tissue-approximating material
which was also the dosimeter.

Chloroform and bromoform systems of equal specific gravity exhibited
color changes of similar intensity to a given dose of radiation. For
example, a 0.4 molal bromoform formulation and a 1.5 molal chloroform
system had identical densities of 0.95 and about the same sensitivities
(Figure 1), in spite of calculated effective Z values of 14 for the
bromoform system and 9 for the chloroform formulation. Under these

conditions Z had little effect on sensitivity.

B. Effect of chemical modifiers on sensitivity.

When hexylresorcinol in a 5×10^{-3} molal concentration was added to a chloroform system containing p-dimethylaminoazobenzene sensitivity was definitely enhanced as is pointed out by Figure 2. The addition of a 6×10^{-4} molal concentration of p-phenylazophenol to the same hexylresorcinol--chloroform--p-dimethylaminoazobenzene formulation further increased the sensitivity. To change the relative transmittance of the dosimeter from 100 per cent to 50 per cent required 2700 rad for chloroform alone, 920 rad when hexylresorcinol was included and only 730 rad when p-phenylazophenol was an additional modifier.

C. Effects of beam size on surface dose.

Protons passing through portals of 1 x 1 cm., 2 x 2 cm, and 4 x 2 cm. were used to irradiated dosimeter disks as described above under section A. The measured surface dose was not affected by the size of the proton beam. These results indicated little or no back scatter of protons to the surface, for the energies used in this study.

D. Effect of beam size on the geometry and dose at the Bragg peak.

For the remaining proton beam experiments the HAP system was used in the form of 20 x 20 cm. slabs that were 9.5 mm. thick. The protons were so directed into the sides of several closely-packed slabs that the central one, recording the whole shaft and Bragg peak, could be removed, the color intensities quantified and dose curves plotted (Fig. 3).

After irradiation the per cent relative transmittance was measured along the center of the beam. Dose distribution was determined from a standard curve (Figure 4) obtained by irradiating HAP disks of the same

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composition with known amounts of protons. Figure 5 shows the dose
distribution for three different-sized proton beams. The ratio of
absorbed dose at the Bragg peak to the dose at the entering or prox-
imal-most end of the beam was calculated from these data. As presented
in the table in Figure 6, there was less dose differential between the
shaft and the peak with narrower beams.

Figure 5 also shows that the position of the Bragg peak along the
axis of irradiation in the HAP dosimeter was not affected by changes in
proton beam size. However, the relative flairing or expansion of the
proton beams at their distal ends was greater for small beams. The
ratios of beam width at the Bragg peak to the beam width at the entering
surface of the phantom dosimeter are given in the table in Figure 7.
A very narrow beam manifested the spread of the distal end so much that
no point increase or peak dose was found. For such beam sizes the dose
distribution indicated the absence of any significant Bragg peak (Fig. 8).

E. Effect of Z on the position of the Bragg peak.

Chloroform formulations of the HAP dosimeter were calculated to
have an effective Z of 7 for 0.5 molal, 8 for 1.0 molal and 9 for 1.5
molal concentrations. For bromoform systems the effective Z was deter-
mined to be 12 for 0.2 molal and 18 for 0.8 molal concentrations. These
different concentrations of chlorinated and brominated hydrocarbons with
effective Z ranging from 7 to 18 did not alter significantly the posi-
tion of the Bragg peak as shown in Tables I and II. In all instances
the distal end of the proton beam was found to be at a 12.2 or 12.3 cm.
depth within the phantom dosimeter.

In another similar experiment 3 centimeters of water was interposed
at the front or beam entrance end of the HAP dosimeter slab. Measurements

showed that the Bragg peak was now at a 9.2 cm. depth. Figure 9 illustrates that the distal end of the proton beam in the combined phantom material was at a depth of 12.2 centimeters. This evidently means that the energy loss coefficient for protons in water, certain plastics, and specific HAP dosimeter formulations is about the same.

REFERENCES

1. Potsaid, M.S., and Irie, G. Paraffin base halogenated hydrocarbon chemical dosimeters. Radiology, 77:61-65, 1961.

2. Lane, F.W., Jr., Johnson, N.M., and Bargoot, F.J. Technic of experimental dosimetry for intracavitary radium applicators. Radiology, 82:827-830, 1964.

3. Potsaid, M.S., and Umezawa, T. Ionizing radiation color measurements of the HAP dosimeter. Amer. J. Roentgenol., 93(3):715-724, 1965.

4. Potsaid, M.S., and Umezawa, T. The effects of chemical concentrations and chemical modifiers on the HAP dosimeter. Amer. J. Roentgenol., 93(3):725-732, 1965.

5. Potsaid, M.S., and Irie, G. An in-phantom radiation detector. New England J. Med., 265:1135-1139, 1961

6. Potsaid, M.S. Dosimeters: Solid "Phantom." IN: The Encyclopedia of X-rays and Gamma-Rays. Editor, G. Clark. Reinhold Publishing Corporation, New York, 1963, pp. 279-290.

TABLE I

EFFECT OF CHLOROFORM CONCENTRATION ON POSITION OF THE BRAGG PEAK

Chloroform (Molal)	0.5	1.0	1.5
Distance from surface (cm.)	12.3	12.2	12.2

TABLE II

ROLE OF EFFECTIVE ATOMIC NUMBER ON POSITION OF THE BRAGG PEAK

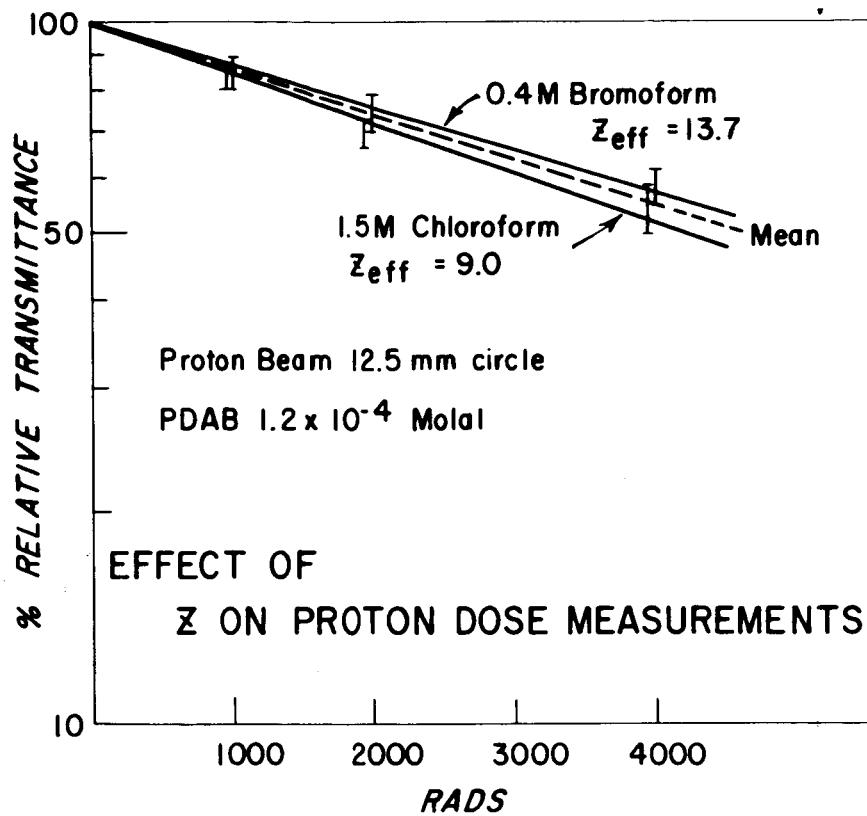| Z (effective)	8.17	11.82	17.74
Halogenated cpd (Molal)	1.0 chloroform	0.2 bromoform	0.8 bromoform
Specific gravity	0.93	0.93	1.0
Distance from surface (cm.)	12.3	12.3	12.2

Figure contents:

% RELATIVE TRANSMITTANCE (y-axis), RADS (x-axis)

100

0.4 M Bromoform
$Z_{eff} = 13.7$

1.5 M Chloroform
$Z_{eff} = 9.0$

Mean

50

Proton Beam 12.5 mm circle

PDAB 1.2×10^{-4} Molal

EFFECT OF
Z ON PROTON DOSE MEASUREMENTS

10

1000   2000   3000   4000

RADS

FIGURE 1

EFFECT OF ATOMIC NUMBER ON SENSITIVITY

EFFECTS OF
CHEMICAL MODIFIERS ON SENSITIVITY

Chloroform 1.0 Molal
PDAB: 1.2×10^{-4} Molal
Proton Beam $2 \times 2 \text{ cm}^2$

Control

A

B

% RELATIVE TRANSMITTANCE

RADS
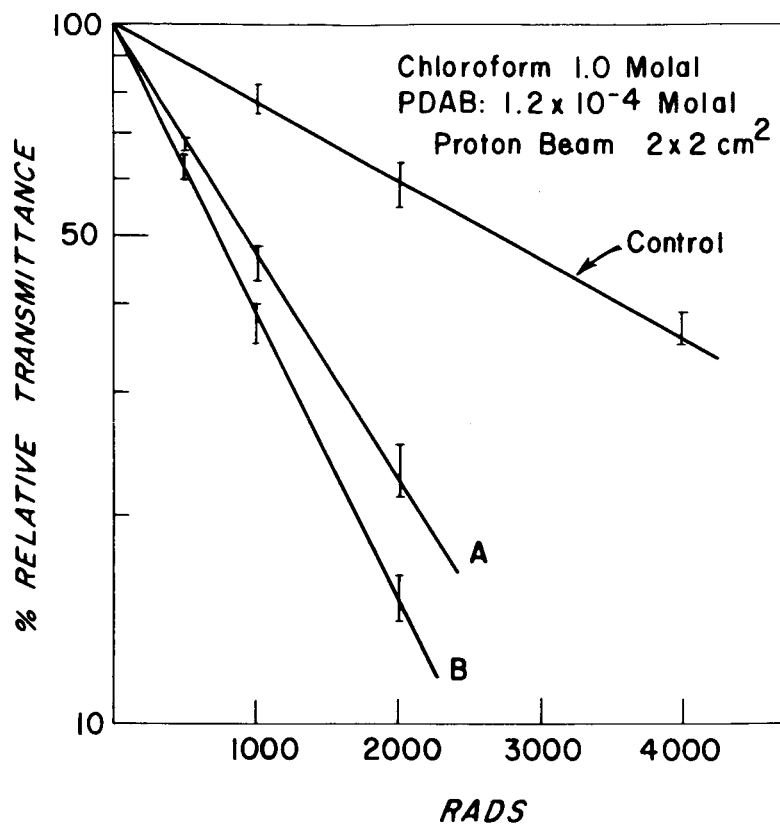
FIGURE 2

MODIFICATION OF DOSIMETER RESPONSE

A has 5.0×10^{-3} molal hexylresorcinol.
B has the same concentration of hexylresorcinol
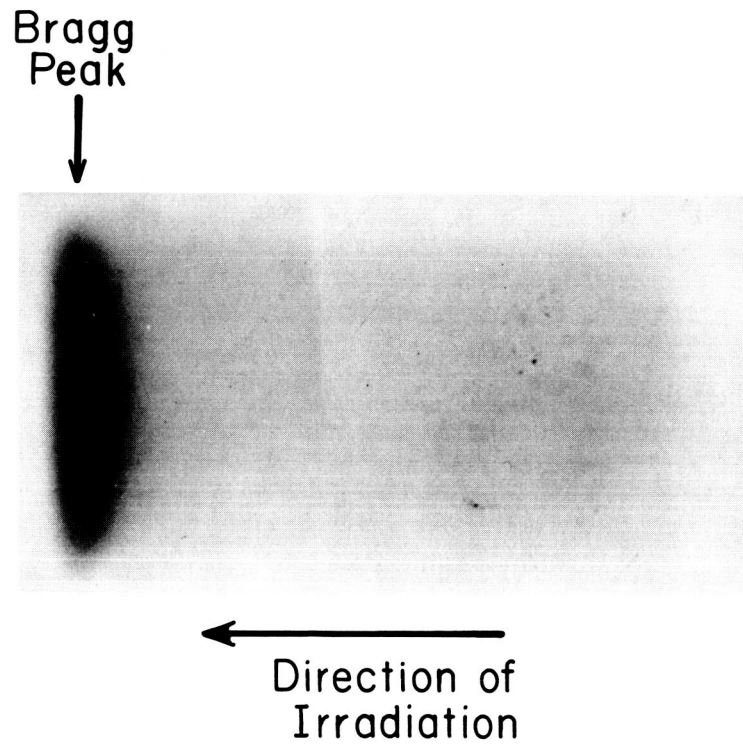plus 6.0×10^{-4} molal p-phenylazophenol (PPAP).

**Bragg
Peak**

↓

←

**Direction of
Irradiation**

FIGURE 3.

Photograph of the terminal end of a 160 meV
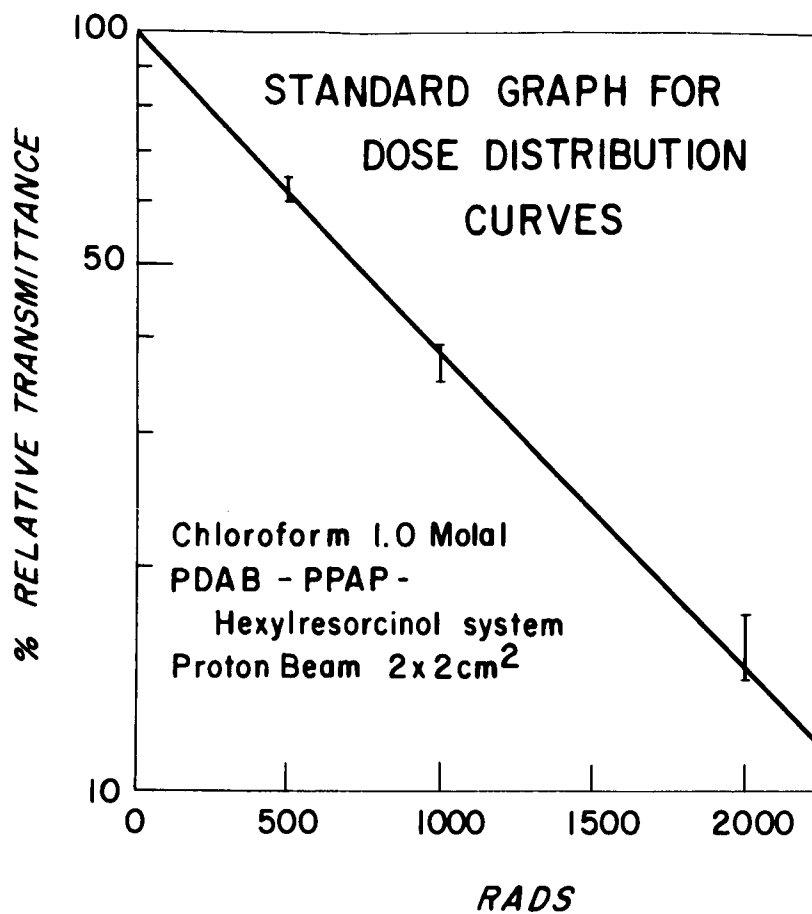proton beam as demonstrated by the HAP dosimeter.

FIGURE 4

REFERENCE FOR MEASURING DOSE

In addition to the chloroform this 9.5 mm thick formulation contained 1.2 X 10^{-4} molal p-dimethylaminoazobenzene (PDAB), 6.0 X 10^{-4} molal p-phenylazophenol (PPAP) and 5.0 X 10^{-3} molal hexylresorcinol.

EFFECT OF PROTON BEAM SIZE ON
DOSE ALONG THE CENTRAL AXIS

CHLOROFORM – PDAB – PPAP – HEXYLRESORCINOL SYSTEM
Bragg peak at 12.2 cm depth
Thickness 9.5 mm

4 x 2 cm

2 x 2 cm

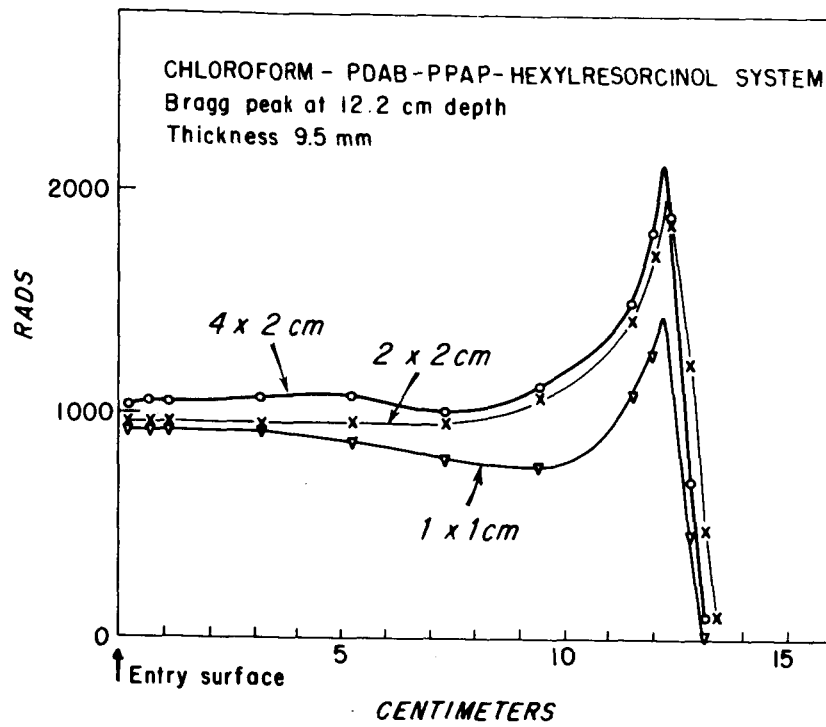1 x 1 cm

Entry surface

CENTIMETERS

FIGURE 5

DOSE DISTRIBUTION ALONG THE CENTRAL AXES
OF PROTON BEAMS

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EFFECT OF BEAM SIZE ON RATIO OF DOSE
AT BRAGG PEAK TO DOSE AT ENTRY SURFACE

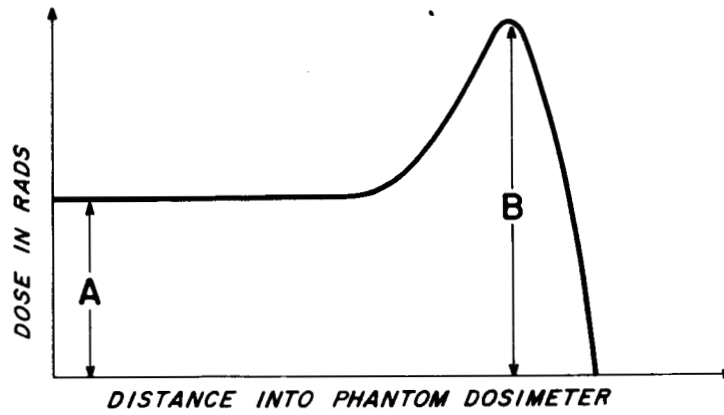| BEAM SIZE	1 x 1cm	2 x 2 cm	4 x 2cm	5 cm circle
B/A DOSE RATIO	1.50	2.00	2.00	3.10

FIGURE 6

SURFACE-BRAGG PEAK DOSE RATIO AS AFFECTED BY PORTAL SIZE

EFFECT OF BEAM SIZE ON RATIO OF BEAM WIDTH
AT BRAGG PEAK TO WIDTH AT ENTRY SURFACE

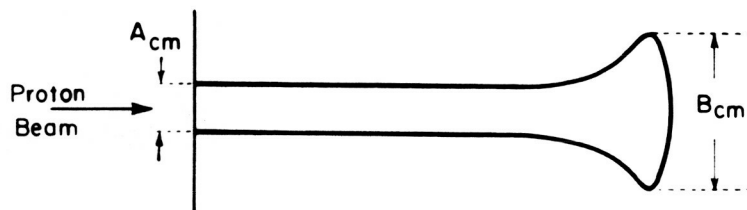| BEAM SIZE		1 x 1 cm	2 x 2 cm	4 x 2 cm	5 cm Circle
WIDTH IN CM.	A	1.0	2.0	4.0	5.0
	B	1.3	2.4	4.6	5.5
B / A RATIO		1.30	1.20	1.15	1.10

FIGURE 7

RATIO OF SURFACE-BRAGG PEAK BEAM WIDTH AS
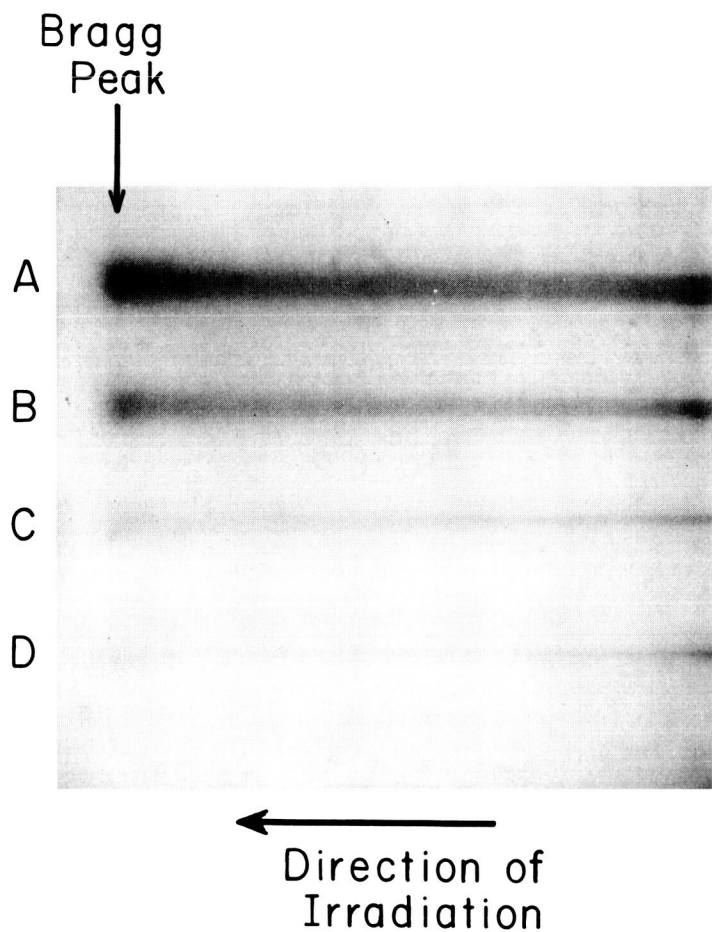AFFECTED BY PORTAL SIZE

FIGURE 8.

Photographic patterns of dose distribution of 160 meV protons resulting from entrance beam widths of A(4.8 mm.), B(3.2 mm.), C(1.6 mm.), and D(0.9 mm)., showing a gradual spread of the beam within the HAP dosimeter with an ultimate loss of the Bragg Peak for the narrowest portals of entry. Arrow indicates the beam direction.

COMPARISON OF STOPPING POWER
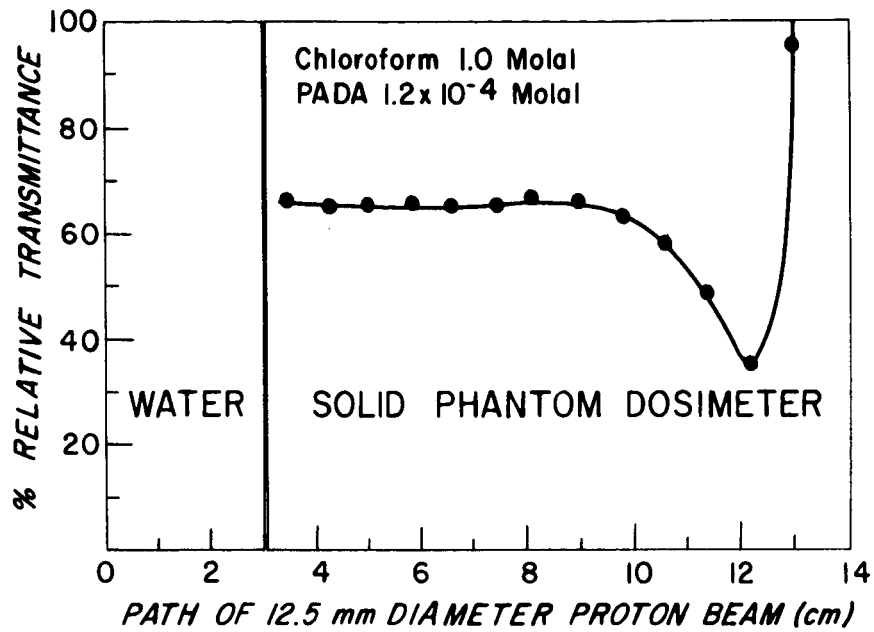## OF HAP DOSIMETER AND WATER FOR 160 MEV PROTONS

FIGURE 9

THE SOLID DOSIMETER COMPARED TO WATER
AS AN ABSORBER OF PROTONS

BETA RAY DOSIMETRY USING THE HAP SYSTEM*

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2. Research Fellows, Massachusetts General Hospital, Boston.

In earlier papers the solid chemical dosimeter containing halo-genated compounds and azo dyes in a paraffin matrix had been shown to be a valuable method of visualizing radiation effects due to charged particle ionization.[1-3]

This part of the report pursues applications of similar techniques to dose problems associated with beta ray sources and covers effects of light-source size in the measuring device and of dosimeter thickness on sensitivity. Patterns of beta ray scatter as well as the density on the range of beta rays in the HAP system are included.

MATERIAL AND EQUIPMENT

Chloroform or bromoform was the halogenated compound dissolved in a paraffin matrix with the azo dye, 4-phenylazodiphenylamine (PADA). Hexylresorcinol was employed as a chemical modifier.

The beta ray source was a strontium-90 skin-therapy applicator having a 5 mm. active diameter on a 12.7 mm. diameter overall base and a dose rate of 1250 rep per minute at the surface.

The equipment for quantitative determinations of color intensity consisted of a constant-voltage-regulated fluorescent light source, a photoelectric cell to pick up the light transmitted through the dosimeter, and a galvanometer to measure the light intensity. It was the same as described in a previous paper except that a more sensitive photoelectric cell was used for the beta ray dose measurements.[4]

RESULTS

A. Effect of light-source aperature size on sensitivity.

The HAP dosimeter was made into 2 mm. thick disks containing 0.8 molal bromoform and 2.3×10^{-4} molal 4-phenylazodiphenylamine and irradiated with various doses by the strontium-90 applicator. Color changes in the disks were then quantified. All components and geo-metries of the light source and light measuring device were kept constant except the size of the aperature at the light source. Accord-ing to the results as presented in Figure 1 dosimeter sensitivity was greater for the smallest light window. To obtain 70% relative transmittance required a dose of 9500 rep for a 10 mm. diameter cir-cular measuring light beam and only 4650 rep for a 0.7 mm. square light beam.

B. Effect of dosimeter thickness on sensitivity.

Disks containing 1.0 molal chloroform, 2.3×10^{-4} molal 4-phenylazodiphenylamine and 5.0×10^{-3} molal hexylresorcinol were exposed for different periods to the strontium-90 source. Color change was measured as before by determining the ability of each disk to transmit light. In these experiments, both the light-source window and the aperature at the phototube were 0.7 mm. square. Figure 2 shows that for an accurate measure of dose sensitivity was improved up to 5 mm. thickness of HAP dosimeter. When thicker disks were used as dosimeters the sensitivity was not much improved. Primarily this reflected the fact that beta rays from a strontium-90 applicator have a maximum range of only 8 mm. in soft-tissue phantom materials.

C. Effect of density on the range of beta rays in the HAP dosimeter.

Two millimeter thick slabs having different concentrations of chloroform and bromoform, but all with 2.3×10^{-4} molal 4-phenylazodiphenylamine and 5.0×10^{-3} molal hexylresorcinol constituted the dosimeters for these studies. One sheet of dosimeter was placed between 10 mm. thick paraffin slabs and the whole sandwich was held firmly between plastic plates. The sheet and slabs were then irradiated end on for 0.33, 0.66, 1.0, 3.0, 6.0, 12, 24, and 36 hours. This arrangement permitted the full depth of beta ray penetration to be recorded on the central sheet of dosimeter as would be evidenced by a measureable color change. Figure 3 relates the exposure time to the depths at which radiation-induced color changes stopped and where 100 per cent relative transmittance reappeared along the central axis of irradiation. The maximum depth of beta ray penetration in a 1.0 molal concentration of chloroform was found to be 8 mm. and was reached in 24 hours of exposure.

The absolute beta ray range in HAP dosimeters having different values of density was then determined for the strontium-90 applicator. These were determined in the same way as described above and are presented in Table I. Without much question the maximum range of penetration is lower for dosimeters having the highest densities.

D. Effect of beta ray scatter.

Figure 4 is a photograph of the horizontal planar and vertical cross section patterns obtained for a chloroform system with 4-phenylazodiphenylamine and hexylresorcinol. Measurements indicated that

the greatest diameter of color change was at a depth of 2 millimeters. Area of color changes plotted against exposure time are seen in Figure 5, which shows saturation in 24 to 36 hours. These saturation diameters were 18.0 mm. for 1 molal chloroform systems, 17.5 mm. for 2 molal chloroform and 0.2 molal bromoform systems and 14.0 mm. for 0.8 molal bromoform systems.

Beta ray back scatter was studied using 1 mm. thick HAP formulations containing 1.0 molal chloroform, 2.3×10^{-4} molal 4-phenylazodiphenylamine and 5.0×10^{-3} molal hexylresorcinol. These thin sheets of dosimeter were irradiated with different thicknesses of phantom placed behind as illustrated in Figure 6. Relative transmittance was determined for each 4 minute exposure. Also included in Figure 6 is the equivalent exposure dose for each point on the curve. These data indicate that saturation occurred from back scattering beta rays with a 5 mm. thickness of phantom and that the amount of back scattering was 30% of the given exposure.

REFERENCES

1. Potsaid, M.S., and Irie, G. Paraffin base halogenated hydrocarbon chemical dosimeters. Radiology, 77:61-65, 1961.

2. Potsaid, M.S., and Irie, G. An in-phantom radiation detector. New England J. Med., 265:1135-1139, 1961.

3. Potsaid, M.S. Dosimeters: Solid "phantom". IN: The Encyclopedia of X-rays and Gamma-Rays, Editor, G. Clark. Reinhold Publishing Corporation, New York, 1963, pp. 279-290.

4. Potsaid, M.S., and Umezawa, T. Ionizing radiation color measurements of the HAP dosimeter. Amer. J. Roentgenol., 93(3):715-724, 1965.

TABLE I

ATTENUATION OF STRONTIUM-90 RADIATION
BY DIFFERENT HAP FORMULATIONS

CHLOROFORM SYSTEM			BROMOFORM SYSTEM		
Molal	Density	Range (μm)	Molal	Density	Range (mm)
0.5	0.93	8.0	0.5	0.98	8.0
1.0	0.94	8.0	1.0	1.05	7.5
2.0	0.98	7.5	2.0	1.17	6.5
4.0	1.03	7.5	4.0	1.38	5.5
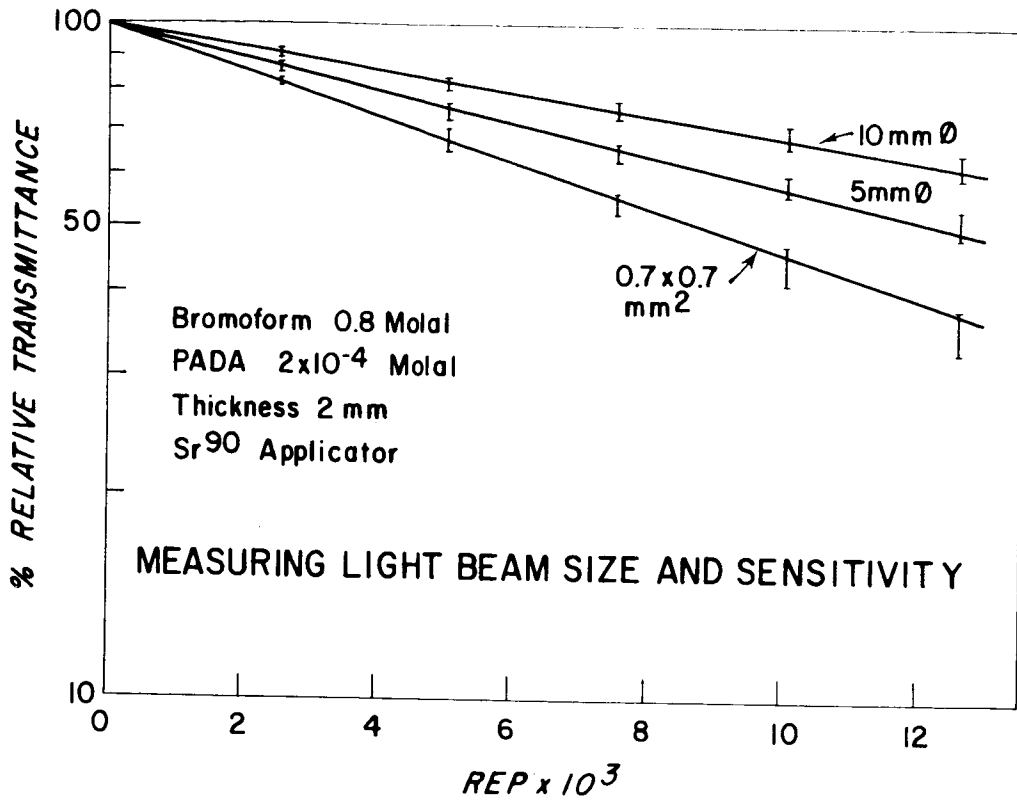
FIGURE 1

Effect of light-source aperature
size on sensitivity.

DOSIMETER THICKNESS AND SENSITIVITY TO BETA RAYS
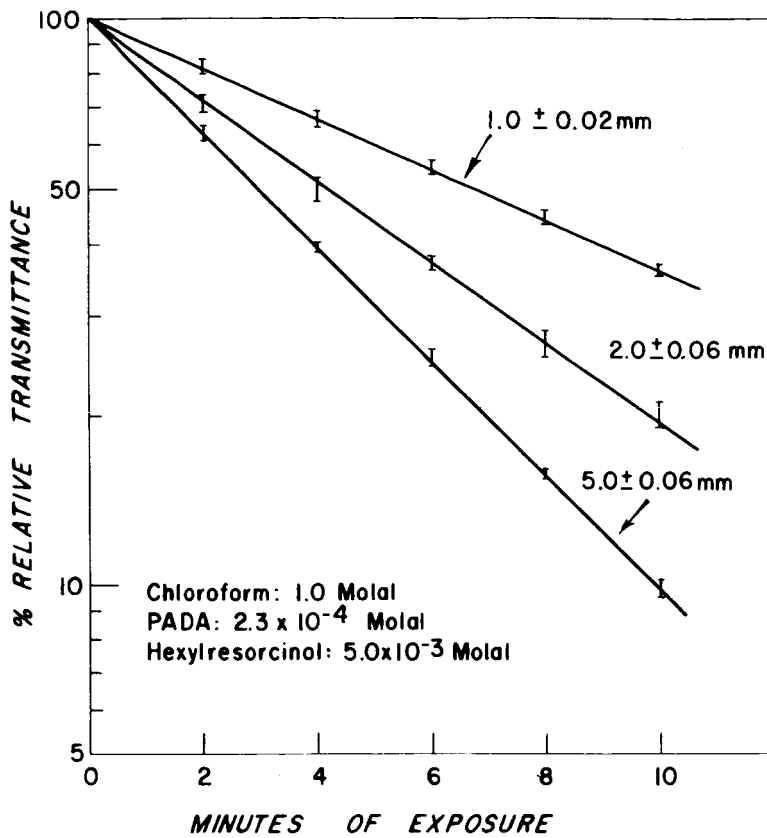
FIGURE 2

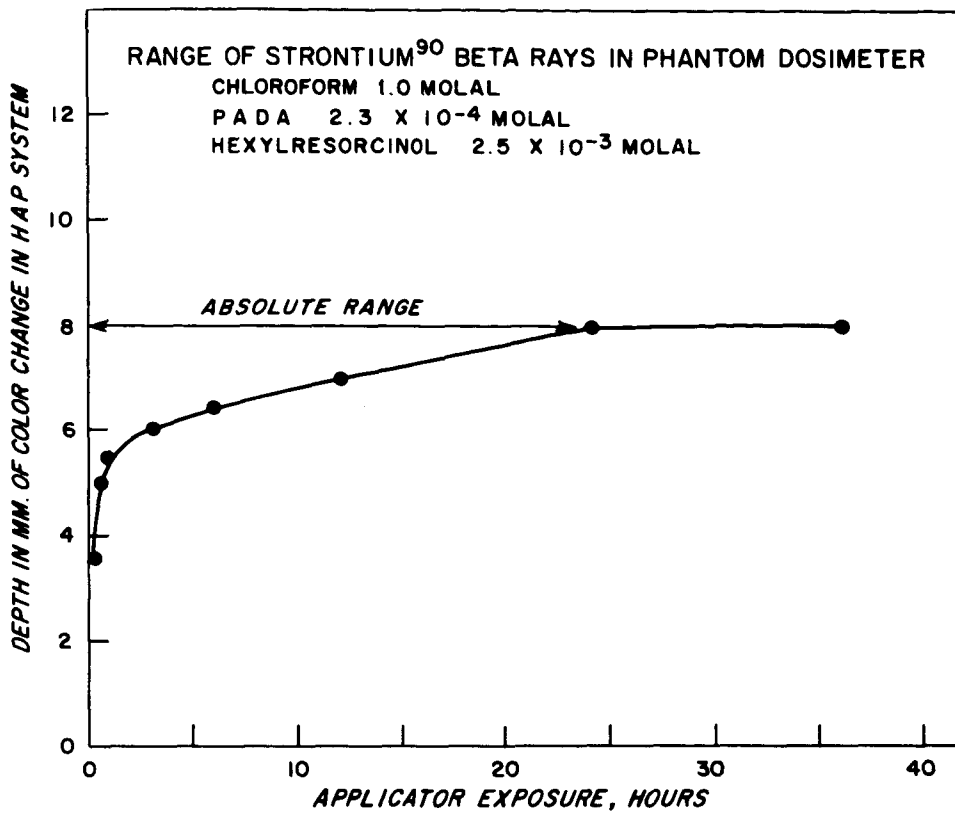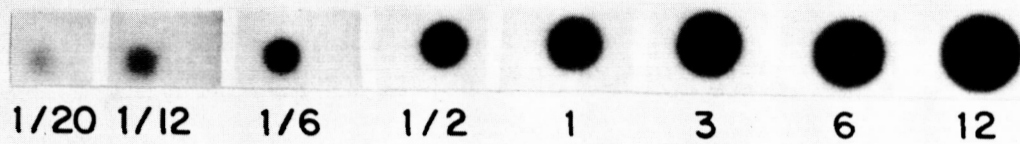Effect of Dosimeter
thickness on sensitivity

RANGE OF STRONTIUM^{90} BETA RAYS IN PHANTOM DOSIMETER
CHLOROFORM 1.0 MOLAL
PADA 2.3 X 10^{-4} MOLAL
HEXYLRESORCINOL 2.5 X 10^{-3} MOLAL

ABSOLUTE RANGE

DEPTH IN MM. OF COLOR CHANGE IN HAP SYSTEM

APPLICATOR EXPOSURE, HOURS

FIGURE 3.

Relationship of depth of penetration to
radiation exposure time.

TOP VIEW

1/20 1/12   1/6   1/2   1   3   6   12

CROSS-SECTIONAL VIEW

1/3   2/3   1   3   6   12   24   36

HOURS   OF   EXPOSURE
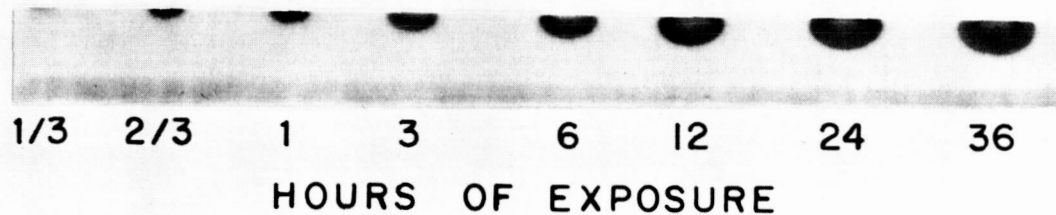
FIGURE   4.

Photograph of actual dosimeter sections
showing the range of lateral scatter as
well as the depth penetration.

FIGURE 5.

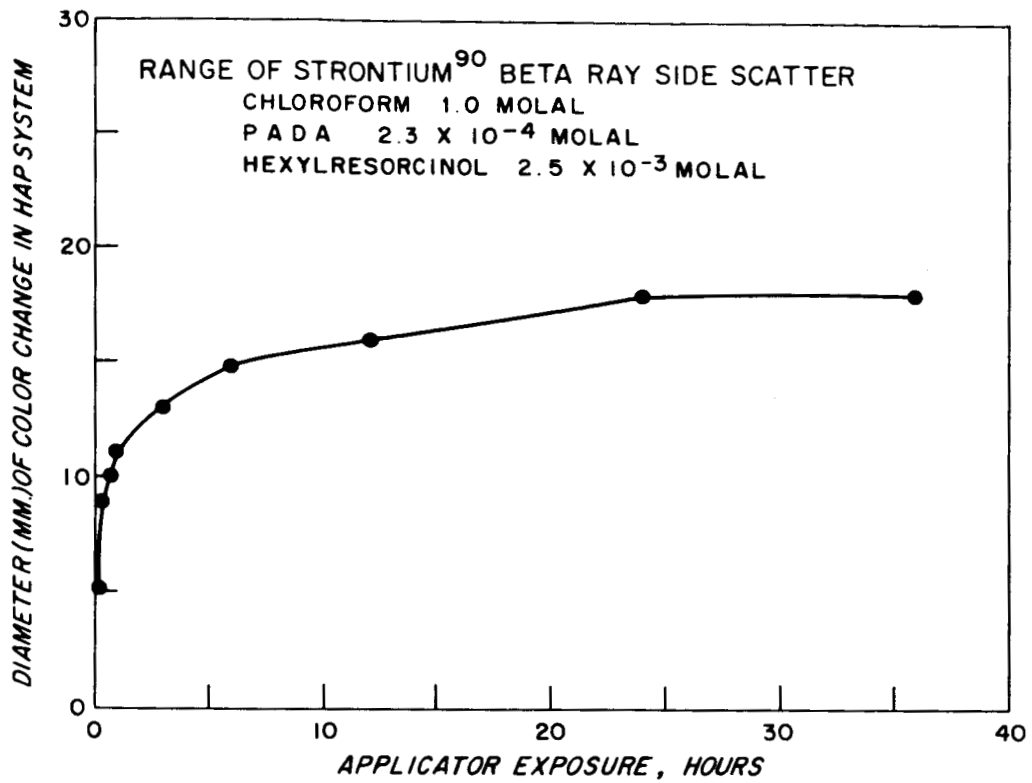The area of color change
plotted against exposure time.

RANGE OF Sr⁹⁰ BETA RAY BACKSCATTER
CHLOROFORM 1.0 MOLAL
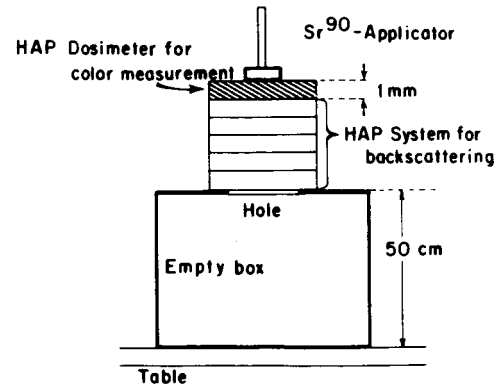PADA 2.3 X 10⁻⁴ MOLAL
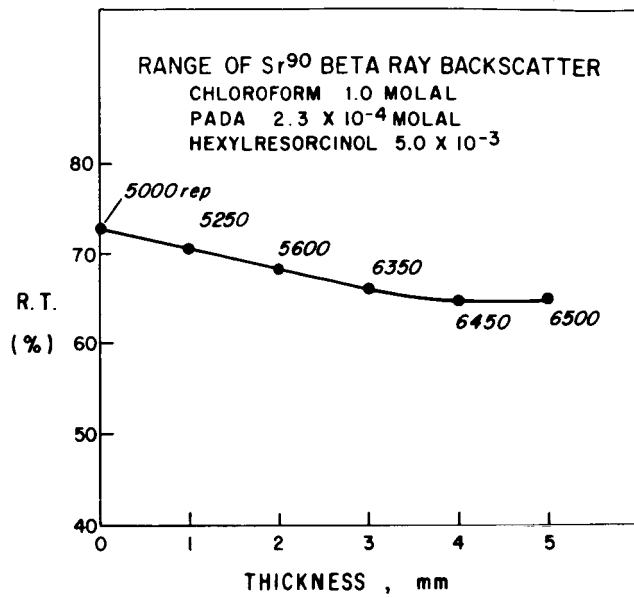HEXYLRESORCINOL 5.0 X 10⁻³

FIGURE 6.

Schematic diagram of dosimeter geometry
used in studying beta ray backscatter.

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