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SUMMARY

The radiation dose from ^{252}Cf needles designed for use as a source of neutrons for radiotherapy has been measured. Neutron and gamma ray isodose lines around the source in tissue equivalent solutions have been determined. Neutron dose rates were measured with silicon solid-state dosimeters and activation foil techniques. Gamma ray dose rates were measured with ^{7}LiF dosimeters. Because the decrease in dose rate with increasing distance from the ^{252}Cf needle in tissue is more pronounced than with a radium source, the dose may be concentrated in a smaller volume. Neutron dose from ^{252}Cf is distributed more uniformly than gamma dose from radium because neutrons are attenuated less in the thicker ends of the needle than gamma rays. The advantages of neutron irradiation are maximized because gamma ray contribution to total dose from ^{252}Cf is only about 20%.

The dosimetry information presented in this paper will enable clinical studies of neutron radiotherapy with ^{252}Cf needles to be planned and begun.

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DOSIMETRY OF AN IMPLANTABLE ^{252}Cf SOURCE

Implantable californium-252 needles have been developed as neutron sources for radiotheraphy(1). The californium needles, designed as a versatile replacement for radium needles, have several theoretical advantages. The therapeutic effectiveness of fast neutrons, with their high linear energy transfer, may be greater than gamma rays on an equal dose basis(2). Fission spectrum neutrons provide a more localized dose to the tissue volume under treatment because of their low penetrability. Consequently, larger doses to the tumor can be given without an attendant increase in dose to surrounding healthy tissue. Californium, which emits 2.33×10^6 neutrons/(sec)(μg) by spontaneous fission and has an effective half-life of 2.566 years, may be prepared in a variety of source geometries. Sufficient ^{252}Cf for clinical use could be available by 1975 at a cost in the range of one dollar per microgram(3). The potential hazard associated with container rupture and release of contaminating materials is insignificant compared to that with radium sources.

Before californium can be clinically evaluated, detailed descriptions of the dose distribution near californium sources must be determined. Preliminary dosimetry studies have been reported(1). More comprehensive dosimetry studies have now been completed and are presented in this paper as neutron and gamma-ray depth dose curves and isodose charts for a typical ^{252}Cf needle.

MATERIALS AND METHODS

Neutron and gamma-ray doses were measured in close proximity to a 4.5-μg ^{252}Cf needle having a diameter of 1.65 mm and active length of 20 mm (Fig. 1). All dose rates were measured in a torso-shaped phantom (20 x 30 x 60 cm high) filled with tissue-equivalent (T-E) solution(4). Two systems, activation threshold materials and semiconductor diode dosimeters, measured the incident fast neutron fluence in the presence of thermal neutrons and gamma rays(5). An equivalent fast neutron dose was calculated using the kerma/fluence relationship described by Williams and Mitacek(6).

Activation threshold materials for detecting fast neutron fluence have been used for years in reactor technology and in dosimetry. An adaptation of the dosimetry techniques of Wright, Hoy, and Splichal(7) was used for these measurements, which simulate an in vivo situation. The threshold materials (foils), described in Table I, were selected for their response to neutrons in a desired energy range. If an effective cross section weighted for the incident neutron energy distribution is determined, these three materials can measure the incident neutron fluence between 2.0 eV and 8.0 MeV. The fluence calculated for this interval is converted to neutron dose by:

$$D(\text{rads}) = [1.44\ \phi_{Cu} + 2.88\ (\phi_{In} - \phi_S) + 3.9\ \phi_S] \times 10^{-9},$$

where ϕ_{Cu}, ϕ_{In}, and ϕ_S are the fluences in their respective energy ranges, and the coefficients are the average kerma/fluence factor, weighted for the californium fission spectrum. The foil system described has a minimum detectability limit of about 10 rads.

The semiconductor diode dosimeter is a silicon junction device that determines the integrated fast neutron fluence incident upon it(8,9). The small volume, ruggedness, convenience, and gamma-ray and thermal neutron insensitivity of these devices make them particularly useful in radiobiological applications. The few disadvantages include temperature sensitivity, nonlinear energy dependence, and slight annealing of the neutron-induced damage with time. Energy dependence of the device varies roughly as $E^{1/3}$ from 0.2 to 8.0 MeV, with the response dropping quickly below 0.1 MeV. Since the kerma/fluence relationship rapidly decreases with energies less than 0.1 MeV, the diode calculated dose represents the significant portion of the dose from neutrons of 2.0 eV to 8.0 MeV. The diodes have a practical minimum detectability limit of about 10 rads with the read out device used.

Gamma-ray exposure was measured with extruded ^{7}LiF thermoluminescent dosimeters (TLD) that were small rods, 1.4 x 1.4 x 7 mm. The rods have a tissue-equivalent response to gamma rays. No response of the TLD within the accuracy of the measurement is attributed to neutrons. The exposure measured was converted to absorbed dose in tissue.

The neutron measuring systems were calibrated to establish absolute dose values by using the fission neutron spectrum from the Health Physics Research Reactor at the Oak Ridge National Laboratory. A radium source, certified by the National Bureau of Standards (NBS), was used to calibrate the TLDs in air. Exposure values were converted to absorbed dose in tissue. All data were corrected for decay and normalized to dose rate per microgram.

RESULTS

First, the dose rate distribution was determined along a line perpendicular to the central axis of the californium needle at its center. A plot of this distribution for gamma rays and neutrons with increasing thickness of T-E material is shown in Fig. 2. Both curves are the best fit of the data at a 95% confidence level. A minimum of five neutron measurements were made every 0.50 cm from 0.5 to 4.0 cm. The neutron curve shows a continuous drop in dose rate reaching about 2% of the 0.5-cm dose rate at 4.1 cm. Average deviation for all points is ±15.7% for the diode system and ±55.0% for the foil system at the 95% confidence level.

Since the TLDs are so small, measurements (minimum of eight) were obtained at 0.25 cm and from 0.50 cm to 4.0 cm at 0.50 cm intervals. Average deviation of the data is ±13.5%. The neutron and gamma-ray curves are approximately parallel except for a slight convergence beyond 3.5 cm. The ratio of neutron to gamma-ray dose in rads, shown in Fig. 3 as a function of T-E material thickness, appears to be linear. By using this curve and by measuring the gamma-ray dose, the total physical dose may be estimated at a specified thickness.

A comparison of the total biological dose in rem from ^{252}Cf and from radium on a unit weight basis is shown in Fig. 4. For this comparison, an RBE of three was assumed for the neutrons. Although the californium curve is somewhat steeper, the observed dose from one microgram of californium approximately equals that from one milligram of radium.

Second, the dose rate distribution was determined over an 18-cm^2 area lying in the same plane as the needle. The semiconductor diode was used exclusively to define the fast neutron dose rate at 78 points in a 0.5-cm grid over the area (Fig. 5). A minimum of four measurements was averaged for each point. Standard deviations were from 3.0 to 37.0% with the total average deviation being 18.7%. The pattern of gamma-ray absorbed dose around the needle is shown in the isodose chart Fig. 6.

DEPTH DOSE DATA

The data from both depth dose curves fits an equation of the form

$$D_x/D_{0.5\ cm} = (B)\ (e^{-X/L})\ (1/X)$$

where D_x represents dose rate under the conditions established by any particular value of tissue thickness X; $D_{0.5\ cm}$ is the dose rate 0.5 cm from the source center; B is the buildup factor due to the tissue-equivalent material; and L is the relaxation length. When analyzed by a linear least squares method, the reported neutron data have a 99.3% correlation and the gamma-ray data have a 97.1% correlation.

The diode data deviated from a true fit possibly because the neutron energy spectrum was altered with increasing moderator thickness and this alteration effected the corresponding energy dependence of the diode devices. Degradation of all parts of the spectrum by scattering reduces the effective neutron energy; as a result, the diode response is slightly decreased. Conversely, the dose evaluated by the foil system is not affected by such alteration and is a better dosimeter, in this respect, at thicknesses greater than 2.5 cm. Close to the needle (less than 2.5 cm) the foil has poor exposure geometry due to the relative foil and source sizes. While the foils have a cross sectional area of 0.242 cm^2, the diodes have only 0.04 cm^2. The neutron data included in the curve of Fig. 2 are a best fit of a combination of the two methods considering these aspects. Such problems are not encountered with the small TLDs.

The foil and diode systems agreed well. The diode system exhibited greater precision and convenience. Relative error between them was 3.6 to 28%. Correction of room temperature isothermal annealing during and after exposure (especially extended exposures) would further improve the precision of diode measurements.. Small differences in readout values introduced errors to the calculated dose as high as 35%, depending on the dose level and the pre-exposure history of the individual diode. The large deviation for the foil data is caused primarily by the required method of calculation, in which the errors from each material are compounded.

A comparison of the thickness of T-E material required to reduce the dose rate by a factor of 2 is shown in Table II. The important point is that the total effective dose from a californium needle is more localized than the dose from a comparable radium needle.

Table III shows that the gamma-ray contribution to the biological dose close to the needle is about 20%, but because of the faster decrease in neutron dose will become more significant at greater distances.

CONCLUSION

For radiotherapy, small self-contained sources of ^{252}Cf have theoretical advantages over conventional gamma sources, and will allow versatility of treatment with neutrons in a form never before available. From the point of view of dose distribution and quality of radiation, ^{252}Cf may be a good substitute for radium and other implantable gamma-ray sources, although its shorter half-life is a slight disadvantage.

The dosimetry data presented will be used for radiation biology and clinical experiments to evaluate the effectiveness of ^{252}Cf for radiotherapy.

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TABLE I

CHARACTERISTICS OF MATERIALS USED IN ACTIVATION MEASUREMENTS

Foil Material	Nuclear Reaction	Effective Cross Section (barns)	Energy Range (MeV)	Product Half-Life
Copper (Cd clad)	$^{63}Cu(n,\gamma)^{64}Cu$	0.258	2.0 eV-1.0	12.8 hr
Indium (Cd clad)	$^{115}In(n,n')^{115m}In$	0.155	1.0-8.0	4.4 hr
Sulfur	$^{32}S(n,p)^{32}P$	0.229	2.5-8.0	14.2 d

TABLE II

COMPARISON OF THICKNESS OF T-E MATERIAL REQUIRED TO REDUCE THE DOSE RATE FROM CALIFORNIUM AND RADIUM BY A FACTOR OF TWO

	Thickness (cm)
Californium n	.30
Californium γ	.32
Californium n + γ	.30
Radium γ	.50

TABLE III

FRACTION OF ^{252}Cf TOTAL DOSE
DUE TO GAMMA RAYS

Distance into Tissue, cm	Percent Gamma-ray Contribution to Total Biological Dose, rem
0.5	19.9
1.0	19.0
1.5	19.5
2.0	20.5
2.5	20.5
3.0	23.9
3.5	21.9
4.0	24.5

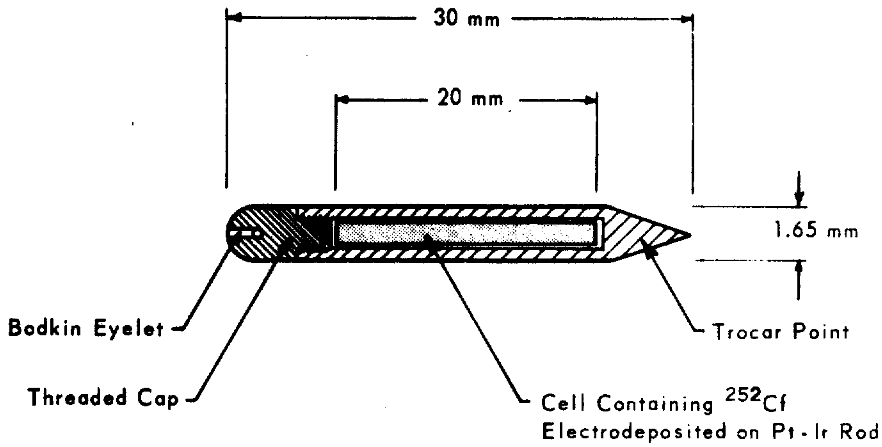

FIG. 1 ^{252}Cf NEEDLE

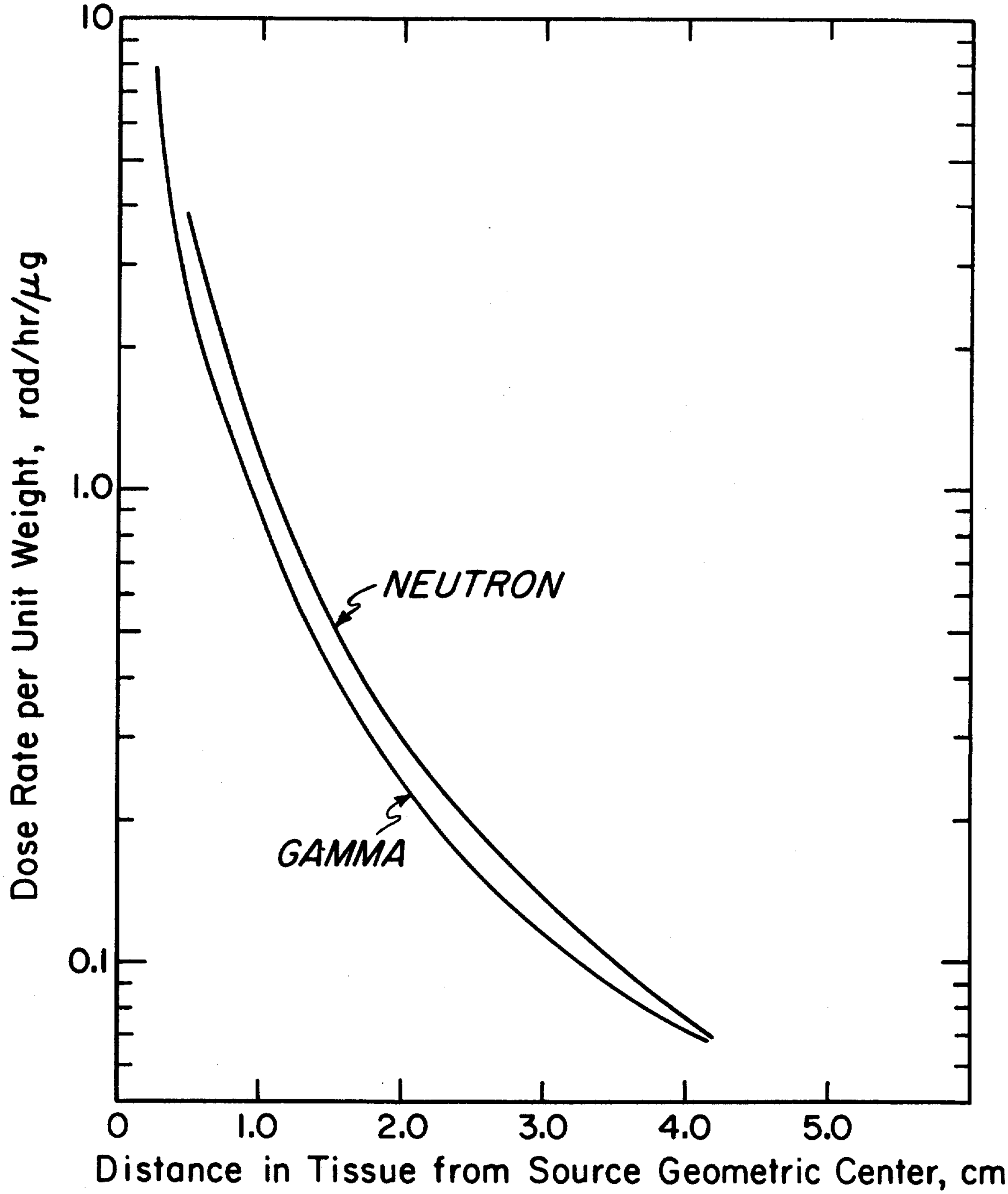

FIG. 2 DISTRIBUTION OF FAST NEUTRON AND GAMMA-RAY DOSE RATE FROM ^{252}Cf AS A FUNCTION OF TISSUE DEPTH

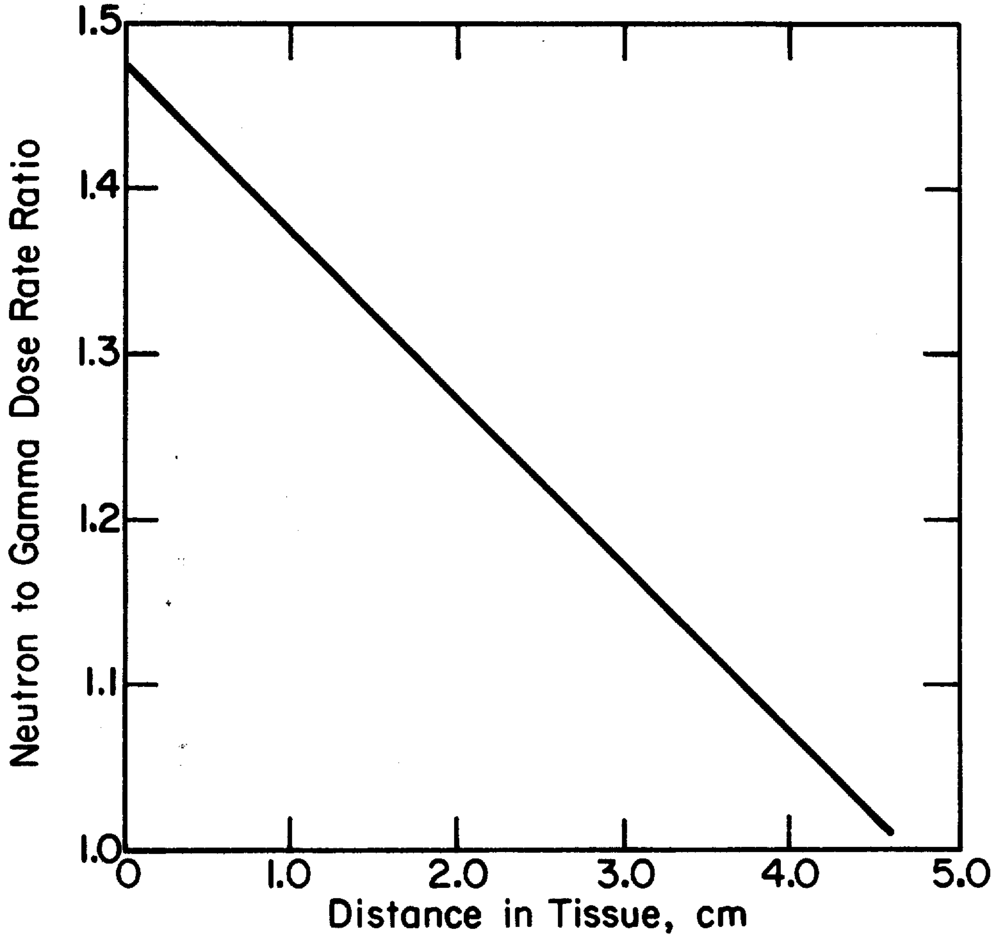

FIG. 3 NEUTRON TO GAMMA-RAY PHYSICAL DOSE RATE RATIO AS A FUNCTION OF TISSUE DEPTH FOR ^{252}Cf

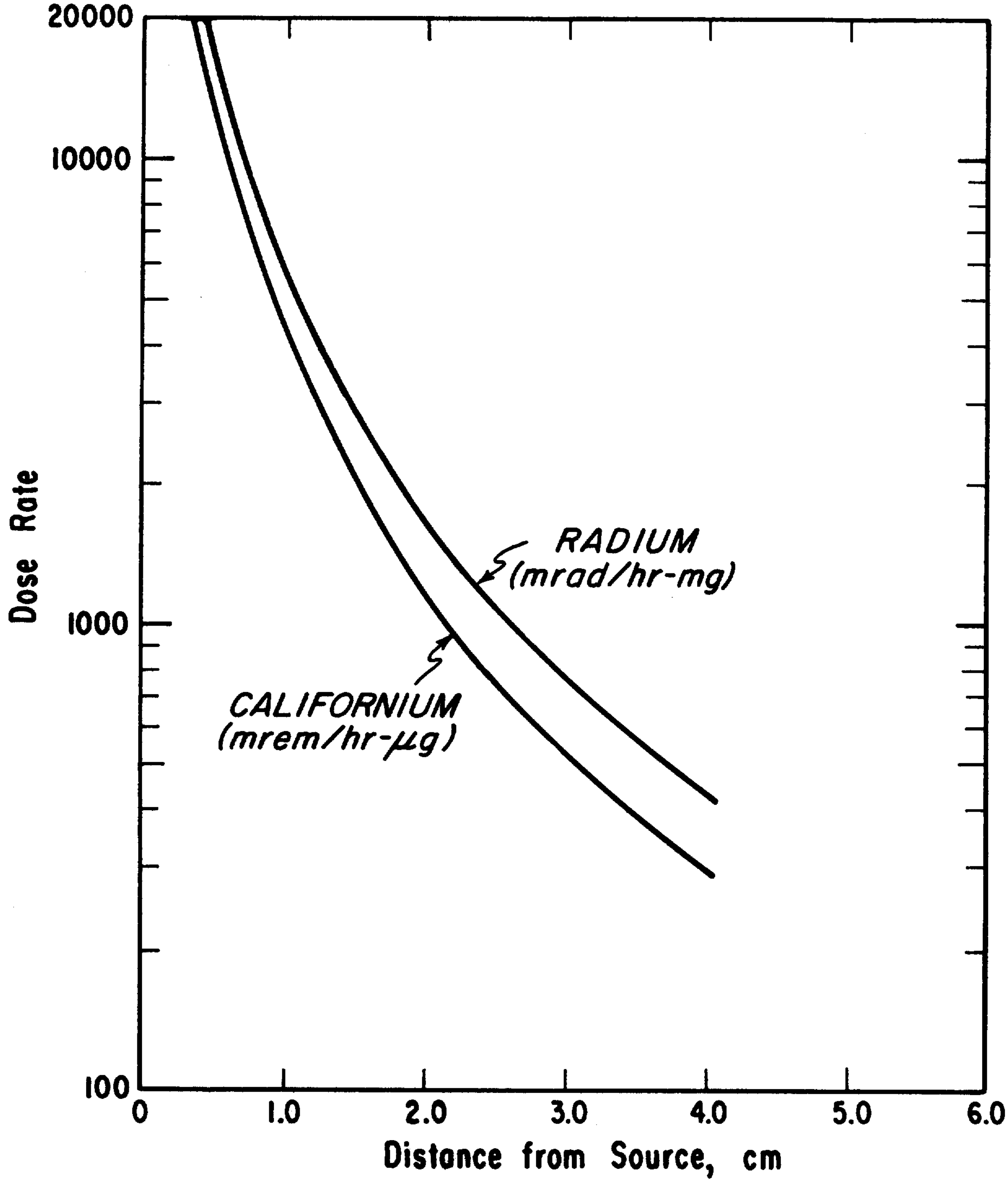

FIG. 4 COMPARISON OF DOSE RATES FROM UNIT WEIGHTS OF ^{252}Cf AND RADIUM

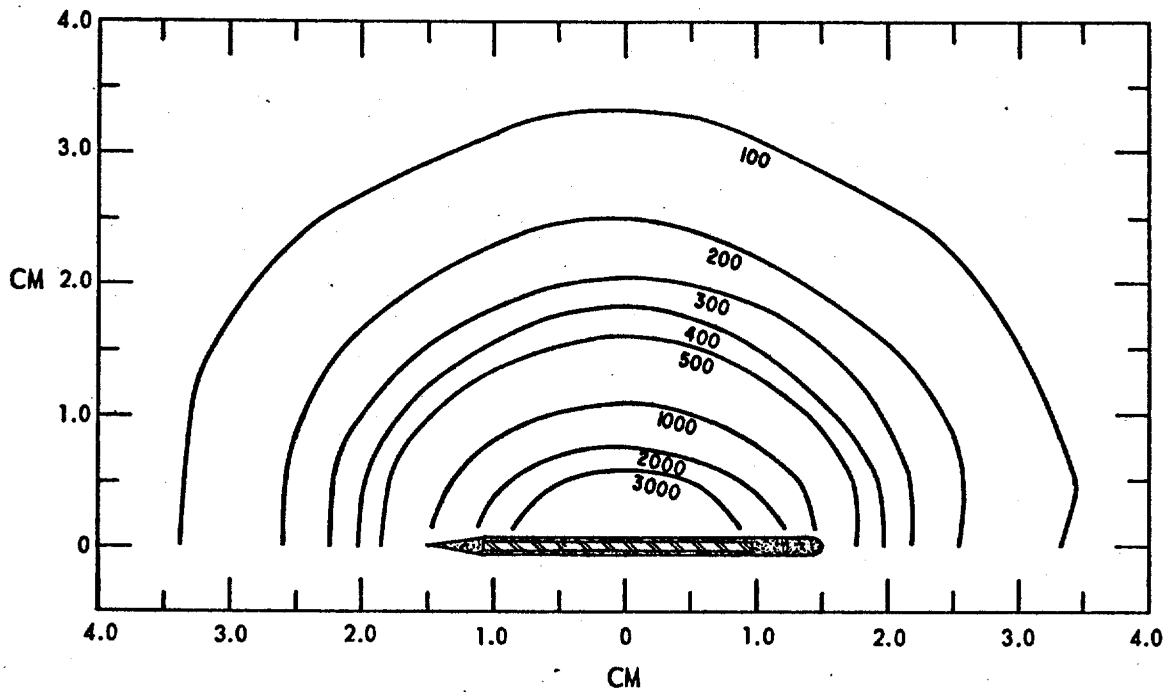

FIG. 5 FAST NEUTRON ISODOSE CHART FOR A ^{252}Cf NEEDLE IN TISSUE-EQUIVALENT SOLUTION

The units are millirad/hr/μg of Cf

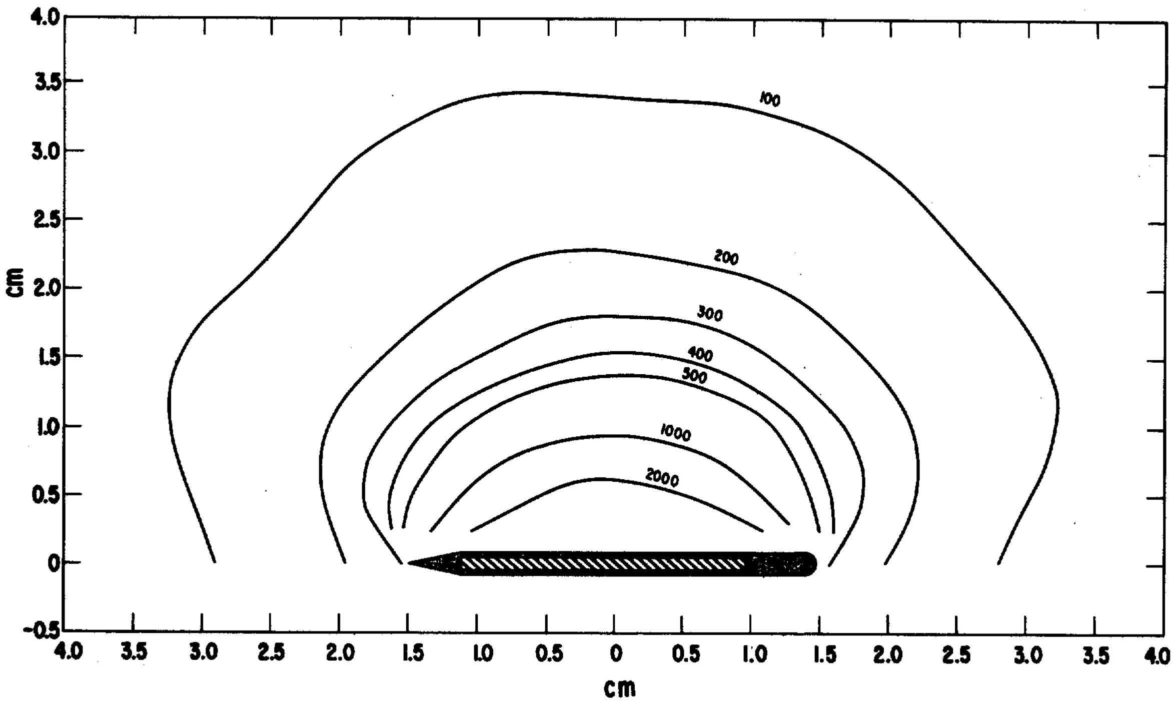

FIG. 6 GAMMA-RAY ISODOSE CHART FOR A ^{252}Cf NEEDLE IN TISSUE-EQUIVALENT SOLUTION
The units are millirad/hr/μg of Cf