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IN-PHANTOM DOSIMETRY
OF $^{147}\text{Pm}_2\text{O}_3$ HEAT SOURCE IN RELATION
TO CIRCULATORY SUPPORT SYSTEMS

June 1969

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IN-PHANTOM DOSIMETRY
OF $^{147}\text{Pm}_2\text{O}_3$ HEAT SOURCE IN RELATION
TO CIRCULATORY SUPPORT SYSTEMS

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IN-PHANTOM DOSIMETRY OF $^{147}\text{Pm}_2\text{O}_3$ HEAT SOURCES
IN RELATION TO CIRCULATORY SUPPORT SYSTEMS

I. INTRODUCTION

The overall objective of the in-phantom dosimetry program at the Pacific Northwest Laboratory is to develop the dosimetry of suitable implantable radioisotopes for circulatory support systems. The approach is a combination of experimentation and computation. The experimentation provides a measure of the dose-rates surrounding an implanted radioisotopic heat source while the latter is concerned with the development of a computational code(s) that can predict the measurements. The computational code allows dose-rate values to be generated for directions and locations in tissue that are not readily or easily measured. It is also useful for predicting dose-rates obtainable from other source-shield types and geometries, especially when prototypes cannot be measured.

The dosimetry of cold pressed and sintered Pm_2O_3 sources of nominal 15 watt thermal rating, containing about 44.1 kCi of ^{147}Pm and small quantities of ^{146}Pm impurity, is reported herein. The dosimetry of ^{238}Pu sources will be the subject of a future report. Various protocols in the predictions and measurements on implantable sources are included. They are expected to be generally applicable, the procedures changing only in minor respects depending on the type of radiations to be measured.

II. Procedure for Computing the Dose-Rates Surrounding an Implanted Radioisotopic Heat Source

The approach for characterizing the dose-rates surrounding an implanted isotopic power source was to borrow the procedures used in radiology. In radium therapy, for example, tabulations of mghr (an alternate way of stating the activity) to deliver 1000 rads to a point h cm from the center of a linear source of active length L with various amounts of filtration are available for determining the dosimetry from a single needle. Ground rules such as the Patterson-Parker⁽¹⁾ and Quimby⁽²⁾ systems are available for developing the dosimetry for planar and volume implants when a larger number of needles are used. Recently, to save time, computer codes such as the M. D. Anderson⁽³⁾ method have been developed that utilize the coordinates of the individual needles as determined by stereoroentgenograms to calculate the dose at various points on a superimposed three-dimensional grid system. The dose within any organ of interest would be determined by averaging the appropriate grid points. The development of computer codes was a necessary extension of the earlier work, mainly because of an increased patient load which increased the dosimetry effort, and to free the radiologist from the geometry

restrictions or ground rules referred to above. Although an attempt is usually made to place the individual sources in the configurations necessary for referral to tabulated doses, the sources are very often skewed from the intended positions.

Because only one source is used in the artificial heart system, there was no compelling reason to complicate the in-phantom dose-rate predictions by developing a computer-code that treats all the parameters needed to characterize the dose-rates from distributed sources. Therefore, a computer code was sought that would characterize the dose-rates surrounding a source placed in an "infinite" homogeneous tissue-like medium in order to predict the physical measurements on a source placed "centrally" in a phantom. The perturbations from placement near the phantom surface or near other density organs such as the lung or bone are handled by correcting the dose-rates predicted or measured for a homogeneous medium. The characterization consists of dose-rate tabulations or profiles as a function of source configuration and distance from the surface or geometric center of the source.

The methods are in keeping with the dose-rate tabulations and profiles presently used by the radiologist and radiation physicist. Knowing the source configuration and orientation from roentgenograms, the distances to the various points or organs of interest can be scaled and by consulting the tabulations or profiles, the dose-rates can be determined.

The perturbations of the dose-rate fields arising from interposed bone or lower density cavities such as the lung are accounted for by estimating the water (used to represent tissue) cm-equivalents of bone and lung tissue. For the 0.6 MeV average photon energy from ^{146}Pm , these are obtained from the relative electron densities of water and those of the perturbing medium. Thus, from an absorption viewpoint, 1 cm of bone is equivalent to 1.66 cm of water; 1 cm of air is equivalent to 0.0012 cm of water; and 1 cm of lung tissue is equivalent to about 0.30 cm of water. If there is no reduction in dose due to the inverse square effect, the correction to the depth dose (as estimated from the tumor-air ratios published in Johns⁽⁴⁾) per cm of tissue bolus is 6.4% at the ^{146}Pm energies. Thus, 1 cm of bone should reduce the depth dose by $(1.66-1)6.4 = 4.2\%$; 1 cm of air should increase it by $(1-0.0012)6.4 = 6.4\%$; and 1 cm of lung tissue should increase the depth dose by $(1-0.30)6.4 = 4.5\%$. These estimates are based upon data for sources outside the body at an "infinite" source-skin distance and for a radiation field size of 100 cm^2 . When applied to an implantable heat source it might be expected that the values would be appropriate to large source-dosimeter distances as the corrections depend on this parameter and the field size. Since the corrections are approximations, and rather small values at that, the choices might be -4%, +4%, and +6% per cm for bone, lung, and air, respectively.

The interpretation for bone is as follows: All depth dose-values beyond the interposed bone are reduced by about 4% per cm of bone from

the value that would be found at the same depth in tissue. Inside the bone, the dose will be altered by the ratio of $\bar{f}$ (bone) to $\bar{f}$ (tissue) or 0.963, interpolated from values listed in NBS Handbook 85⁽⁵⁾. An example of the use of this data follows: Suppose the depth dose-rate at 5 cm into tissue is 10% of that at the source surface and 2 cm of bone is interposed at 3 cm. The actual depth dose-rate at 5 cm is $0.92 \times 10\%$ or 9.2%. Inside the bone the dose is altered by 0.963 $D(\text{tissue})$. The dose-rate just inside the bone at about 5 cm, therefore, is $0.963 \times 9.2\%$ or 8.8% of the source surface dose-rate. In view of the overall uncertainty in the depth dose-rates, these small corrections can probably be neglected except when the interposed bone thickness amounts to a few centimeters. The same may be said for air cavities. The entire lung would significantly perturb the dose-rate fields and if dose-rate values for the cranium are desired, the values determined for the homogeneous medium should be increased about 4% for each cm of interposed lung tissue. However, the cranium dose-rate values should be negligible for a source placement near the pelvic girdle.

In summary: The dose-rates in a non-homogeneous phantom such as the human body can be determined by applying the corrections -4%, 4% and 6% per cm of interposed bone, lung and air, respectively, to the dose-rate values determined for a homogeneous tissue-like phantom. It is recognized that these corrections apply to points located far enough from the source that inverse-square effects are minimal, but in view of the small percentages; the fact that the source might eventually be "buried" within a blood-pump subsystem and thus be located "sufficiently far" from any interposed perturbing materials in the body; and the relatively large overall uncertainty in the true dose-rate values; these corrections are sufficiently accurate. If the perturbing medium is smaller than a few centimeters thick, the correction factor can be neglected altogether.

Finally to aid in estimating the integrated dose-rate within the body, the dose-rate can be averaged for various tissue volumes surrounding the source. For a centrally placed source in the abdominal cavity, for example, most of the energy will be deposited in the gastro-intestinal system or any one organ or organ system that may lie closest to the source. For this reason it is necessary to know the eventual placement of the source. Otherwise the average dose-rates within the surrounding volumes may be over-estimated if some of the energies are lost to the body and absorbed by the surrounding air. That amount not lost to the surrounding air is estimated from the solid angle subtended by the source in the body.

III. Procedure for Measuring the Dose-Rates Surrounding an Implanted Radioisotopic Heat Source

A number of tissue-equivalent (to radiation) phantoms was utilized to accommodate the various doismeters used in the measurements program.

These were a non-homogeneous REMAB or man-simulating phantom, which contains an actual skeleton, and two homogeneous (water and polystyrene) phantoms. The former phantom is used for estimating the effect on the tissue dose-rates from interposed bone or lower density cavities, such as the lung. It also provides a grasp of the dose-rates that would be found at various locations in the body of an individual of similar size and contour; this being the U. S. Air Force 50th percentile male. The latter two phantoms are used for accurate scaling of source to dosimeter distances and, therefore, allow more accurate measurements of dose-rate versus thickness of interposed tissue. The polystyrene phantom, in particular, is most useful for measurements with dosimeters that are adversely affected by moisture.

The dosimeters found most useful for the promethium source measurements were small thermoluminescent (TLD) blocks 0.125" square by 0.035" thick; various pencil-type ionization chambers; and an extrapolation-ionization chamber. The most accurate measurements were made by placing the TLD and the extrapolation-ionization chamber on a thin platform of polystyrene which was in turn placed upon the water surface in the water phantom. The back plate of the extrapolation-ionization chamber was thick enough to provide adequate backscatter for simulating a dosimeter that is "buried" within tissue. The TLD blocks and pencil-type chambers also were backed with adequate thicknesses of tissue-like material. Accurate scaling of source to dosimeter distance was accomplished by adjusting the height of the polystyrene platform via attached nylon threaded rods. The water level was continually adjusted to eliminate any air gaps. Figures 1, 2, 3 and 4 portray some of the dosimeters and phantoms that were used in the measurements. In order to cool the promethium heat source, a heat exchanger of aluminum, coated with fiberfax and silastic insulation, was fabricated. Water coolant was passed through a portion of the heat exchanger which was not in contact with the source. The source, some shields, and the heat exchanger are also portrayed in the Figures.

Since one of the purposes of the promethium program was to develop a suitable computational code that could predict the measurements, little thought needs to be given to the proper choice of materials for the source shields and heat exchanger. Whichever choice(s) was made it was still to be demonstrated that the dose-rates measured in the phantom could be predicted with sufficient accuracy. Thus a combination of materials was utilized and their efficacy in removing the radiations while keeping the overall weight of the source at a minimum was determined.

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FIGURE 1. Remab or Man-Equivalent Phantom and Various Ancillary Equipment Used in the In-Phantom Dosimetry Circulatory Support Program. The dosimeters (left to right), are pencil ionization chambers (one is projecting out of the cranium), thermoluminescent dosimeters or TLD (some are taped to the surface of the phantom) and tissue-equivalent or TE ionization chambers for measuring total absorbed dose in mixed radiation fields.

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FIGURE 2. Close-up of Remab Phantom With The Source Positioned On The Inside Surface Of The Left Ilium. Various dosimeters are placed on the surface of the Phantom.

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FIGURE 3. *Tissue-Equivalent Phantoms and Various Dosimeters Used in The In-Phantom Dosimetry Circulatory Support Program. The Remab Phantom Contains an Actual Skeleton and Tissue-Equivalent (to radiation) Fluid. Dosimeters are placed within and around the Phantoms. The heat exchanger, in which the radioisotopic heat source is placed, is shown out of the body.*

Neg 0683126-2

FIGURE 4. Various Tissue-Equivalent Phantoms and the Extrapolation-Ionization Chamber Used in the In-Phantom Dosimetry Circulatory Support Program. The extrapolation-ionization chamber is a standard for measuring surface dose values after interposing various kinds and thicknesses of material between the source and detector.

IV. Shielding and In-Phantom Dose Predictions

A. Description of Codes

Two computer codes (Isoshld-II, a PNL Code [6,7] and QAD-P5A, a LASL Code [8,9] were adapted for use in the prediction program. The PNL-code has the advantage in determining the contribution to the dose-rate from the ^{147}Pm bremsstrahlung radiations. If the bremsstrahlung spectrum is known, QAD can also compute this contribution but in any event, this contribution becomes negligibly small ($<1/2\%$) after interposition of about 1/4 cm of high atomic number shielding material. A heat source-blood pump subsystem will most likely contain this amount. The remainder of the dose is from the ^{146}Pm radiations of about 0.6 MeV average energy, and has been found to be more accurately predicted by the QAD code, although the differences may be more attributed to the parameters in the code libraries, such as interaction cross-sections and buildup factors. The greatest advantage to the QAD-code is that dose-rates can be computed for all points in phantom space, whereas Isoshld is restrictive to certain geometries. In addition, QAD is a more rapid code but requires more time in programming a given situation.

Both codes require the user to specify the proper buildup medium to represent all media between source point and dosimeter point. In essence, the user must determine which intermediate atomic number materials to use in the buildup computations for the surface dose-rates and the first few centimeters into tissue, and at which tissue-thickness and beyond to use water in the buildup computations (this is because a photon experiences scattering within the promethium source material and all other materials between the source point and the dosimeter).

B. Computations

1. Shielding Computations

The shielding effectiveness of uranium, tungsten and iron, for ^{147}Pm - ^{146}Pm heat sources, was studied using the computational code Isoshld-II. As expected, the higher Z (atomic number) materials were much more effective in removing the bremsstrahlung radiations. Uranium and tungsten were about equally effective in this regard (based on the absorption coefficients in the code library). These computations merely emphasize the usefulness of the higher Z materials as the primary cladding, particularly for the photoelectric absorption region. In the Compton absorption region (^{146}Pm energies fall mainly within this region), iron is about 15% better than uranium, tantalum or tungsten on a per gram basis. On a cm basis, uranium, tantalum and tungsten are about twice as effective as iron.

2. Tissue Dose-Rate Computations

The computer codes QAD and Isoshld-II were used to compute the photon dose in tissue from a 15 watt $^{147}\text{Pm}_2\text{O}_3$ heat source and shields of the same dimensions used in the measurements program. Assuming 11.9 mCi of ^{146}Pm impurity, the ^{147}Pm bremsstrahlung contribution to the dose is less than 2%; the remainder of the dose is due to the higher photon energies from ^{146}Pm .

Figure 5 compares some of the predicted dose-rates of the two codes. Many other phantom points were calculated but these values along the source axis serve to illustrate the differences in the two codes. The source and shield dimensions (from center) for all reported data are shown in Figure 6.

Briefly, the QAD code agrees more closely with the measurements. Selecting iron as the dose buildup medium, a divergence from the measurements starts at about 8 cm into tissue. Beyond 8 cm, water is a better, and certainly more logical choice, for the dose buildup medium. Throughout the distances measured, the QAD code predicted the measurements to within the experimental errors ($\pm 20\%$) whereas the Isoshld-II code over-predicted the dose-rate values. In fact, the agreement is better than what is indicated in Figure 5 as the predictions, because of an early error, are based on 11.9 mCi of ^{146}Pm rather than the actual amount measured, or 11.0 mCi. At 8 cm tissue thickness, the dose-rates are only about 5% of the surface values thus the departures of the predictions and measurements beyond 8 cm become less significant.

3. Integral Dose-Rate Computation

The integral dose-rate of a spherical 15 watt $^{147}\text{Pm}_2\text{O}_3$ source containing 0.25 ppm ^{146}Pm and shielded similar to the sources measured, was approximated using the equation

$$\Sigma = \rho \sum_i V_i \bar{D}_i$$
 where ρ , the tissue density, is unity. If the source is placed centrally in a 30 cm diameter sphere of tissue, $\Sigma \approx 2600 \text{ gm rad hr}^{-1}$. For a source not placed centrally in a similar size body, the integral dose-rate is approximated by multiplying Σ by the fractional tissue volume subtended by the source.

C. Corrections for Dose Buildup

An attempt was made to develop a correcting equation as a function of atomic number that would be general (i.e., apply to any source-shield configuration) and correct all phantom predictions that were based on, say, iron as the buildup medium. No one satisfactory equation was developed and in retrospect it appears that the rule of thumb utilizing iron for the first 8 cm and water for the rest, would yield satisfactory agreement with the promethium measurements. Of course, for the particular source and shields studied, precise buildup factors, as determined by the ratio of the experimental and the unbuildup dose-rate values, could be used. This is the more satisfactory approach if closer agreement is desired, and also emphasizes the usefulness of measurements on the prototypic heat source-blood pump subsystems.

V. Shielding and In-Phantom Dose Measurements

The measurements were performed on two cylindrical (height to diameter ratio approximately 1:4) 58 gram $^{147}\text{Pm}_2\text{O}_3$ sources, each of nominal 15 watt rating, with ^{146}Pm impurities of 0.25 and 3.5 ppm, or about 11 and 154 mCi of ^{146}Pm , respectively. Photon spectrum analysis revealed no other radioisotopic impurities were present in significant

FIGURE 5

COMPARISON OF PREDICTED AND MEASURED IN-PHANTOM
DOSE-RATES ALONG AXIS OF 15 WATT CYLINDRICAL
 $^{147}\text{Pm}_2\text{O}_3$ SOURCE (0.25 ppm ^{146}Pm)

amounts. The dosimetry measurements included: (1) "surface" dose-rates on stainless steel clad surfaces, the first source covering, and on the surfaces of various combinations of tantalum, uranium, and aluminum shields; (2) "tissue" dose-rates in the homogeneous phantoms along the source axis and at right angles or in the radial direction; and (3) "tissue" dose-rates in the REMAB phantom (source location on inside surface of left ilium) for both sources with minimal or no shielding other than the stainless steel cladding and an aluminum heat exchanger. The latter measurements were made before the full complement of shields was fabricated, and were mainly for the purposes of intercomparing the various dosimeters that might be used in the measurements program. More extensive use of the REMAB phantom is planned in the forthcoming plutonium program.

The "surface" dose-rates are presented in Table 1. They were taken at about 1/16 inch in air from the source-shield end surfaces and through a tissue thickness of 7 mg/cm² or about 0.007 cm; this depth representing the front window thickness of the extrapolation-ionization chamber. The "true" surface dose-rates are estimated to be within 10% of these tabulations for either source having four or more shields and a minimum of 30 to 40% larger than these tabulations for two or fewer shields. It is experimentally difficult to determine window correction factors for mixed radiation containing low-energy bremsstrahlung and photoelectrons which come from the metal surfaces. To a good first approximation, the measurements in tissue can be interpolated from these tabulations and those in Tables 2, 3, 4 and 5 which represent dose-rates at various depths in tissue for one source-shielded configuration. In order to ascertain the effect of the total source-shield weight on the dose-rates, the mass values are also included in Table 1. It should be kept in mind, however, that the dose-rates tabulated are those occurring from the end surfaces of a 4 to 1 cylinder (ht. = 0.800 cm and dia. = 3.632 cm) and thus, are higher than what would be found for a 1 to 1 cylinder or those measured out the radial direction of a 4 to 1 cylinder. It is estimated that the dose-rates found for the latter two cases would be reduced by a factor of 2.

Most of the "tissue" dose-rates were taken with thermoluminescent dosimeters (TLD) of size 0.125" x 0.125" x 0.035" which were distributed on planes throughout a homogeneous water phantom and exposed to the source containing 0.25 ppm ¹⁴⁶Pm. The exposure conditions simulated full buildup and are comparable to a centrally placed source in a torso with the dosimeters completely surrounded by tissue. Tables 3, 4 and 5 present data in planes perpendicular to the source axis, the bisecting radial plane, and in planes parallel to the source axis, respectively. The phantom measurements for other shielding configurations or ¹⁴⁶Pm impurities can be interpolated from the ratios of the surface values presented in Table 1 and the impurity ratios. As an example, if part of the uranium shielding and the aluminum heat exchanger were omitted from the present source, giving a total source-shield weight of about 0.5 pound, all dose-rates would be increased about 20 times. It might be noted that the TLD values are slightly higher than the extrapolation-ionization chamber values presented in Tables 1 and 2. This is because the TLD more closely represent the dose-rates at a point in the phantom. The diameter of the chamber is 3 cm and thus its measurements are an average over a much larger area. When the TLD values are averaged to represent the area seen by the chamber, the two measuring systems agree to within the experimental errors.

The data in Tables 3, 4 and 5 are condensed in Figure 6 which profiles the dose rates in the perpendicular bisecting plane and in perpendicular planes 0, 2-1/2, 5, 10 and 20 cm along the source axis. If this particular source were implanted in a patient, the dose accrued by any organ or organ system would be determined by consulting either the tabulated values or the profiles once the distances from the source surface or center of geometry were determined.

TABLE 1. Extrapolation-Ionization Chamber Measurements on $^{147}\text{Pm}_2\text{O}_3$
Source-Shield Ends

<u>Shields (thickness and Total Source and Shield Weight)</u>	<u>Source #1*</u>	<u>Source#2†</u>
Stainless Steel (S.S.), 0.249 cm 131 gm	422 rads/hr $\pm$ 20%	658 rads/hr $\pm$ 20%
S. S. + 1 Uran. (U), 0.076 cm, 211 gm	84.6	299
S. S. + 2U, 0.152 cm, 291 gm	21.9	206
S. S. + 3U, 0.229 cm, 371 gm	13.0	148
S. S. + 3U + Al Heat Exchanger, 0.635 cm, 540 gm	3.66	50.7
S. S. + 1 Tantalum (Ta), 0.076 cm, 201 gm	60.2	321
S. S. + 2Ta, 0.152 cm, 271 gm	18.1	218
S. S. + 3Ta, 0.229 cm, 341 gm	14.6	164
S. S. + 3Ta, + Al, 0.635 cm, 510 gm	4.52	61.0

* Source #1 Nominal 15 watt source with 0.25 ppm ^{146}Pm

† Source #2 Nominal 15 watt source with 3.5 ppm ^{146}Pm

(% decay per day: 0.0343% ^{146}Pm , 0.0724% ^{147}Pm)

TABLE 2. Central Axis Tissue Depth Dose-Rates From End Surface Of
 $^{147}\text{Pm}_2\text{O}_3$ Source #1*

<u>Tissue Thickness</u>	<u>Dose-Rate</u>
0 cm	4.0 rads/hr $\pm$ 15% (estimated error)
1/2	2.5
1	1.9
2	1.2
3	0.82
4	0.60
5	0.46
6	0.35
7	0.28
8	0.22
9	0.18
10	0.15
11	0.12
12	0.10
13	0.086
14	0.070
15	0.062
20	0.027

* The tabulations are interpolated from a plot of dose-rate versus depth in a water phantom as the actual thicknesses measured do not always correspond to the indicated values. (The interpolated "surface" value agrees within the experimental errors, with the value listed in Table 1.) The source shields are 0.249 cm S.S. (Fe), 0.299 cm U, and 0.635 cm Al. The measurements were taken with an extrapolation-ionization chamber.

TABLE 3
DOSE-RATE MEASUREMENTS (rads/hr) IN PLANES PERPENDICULAR TO THE SOURCE AXIS *

Tissue Depth (d)	Lateral Displacement (ℓ)				
	0 cm	1 cm	2 cm	5 cm	10 cm
0.475 cm	3.4	3.3	2.5	0.75	0.34
1.11	2.1	2.2	1.8	0.64	0.29
1.74	1.5	1.5	1.3	0.53	0.24
2.38	1.1	1.1	0.90	0.44	0.22
3.65	0.65	0.65	0.57	0.36	0.17
4.92	0.46	0.44	0.40	0.27	0.14
7.46	0.26	0.25	0.23	0.17	0.095
12.54	0.10	0.10	0.092	0.080	0.049
21.43	0.028	0.028	0.027	0.029	0.020

* Source dimensions are the same as in Figure 6 - The estimated accuracy of the dose-rate values is $\pm 20\%$.

TABLE 4
DOSE-RATE MEASUREMENTS (rads/hr) IN BISECTING RADIAL PLANE *

Tissue Depth (d)	Lateral Displacement (ℓ)				
	0 cm	1 cm	2 cm	5 cm	10 cm
0.475 cm	1.5	1.34	1.1	0.75	0.23
1.11	1.0	0.93	0.83	0.56	0.21
1.74	0.75	0.73	0.66	0.45	0.17
2.38	0.57	0.56	0.53	0.37	0.15
3.65	0.38	0.37	0.36	0.26	0.12
4.92	0.25	0.25	0.25	0.19	0.092
7.46	0.13	0.13	0.13	0.099	0.056

* Source dimensions are the same as in Figure 6 - The estimated accuracy of the dose-rate values is $\pm 20\%$.

TABLE 5
DOSE-RATE MEASUREMENTS (rads/hr) IN PLANES PARALLEL TO THE SOURCE AXIS *

Tissue Depth (d)	Lateral Displacement (ℓ)				
	0 cm	1 cm	2 cm	5 cm	10 cm
0.475 cm	1.5	1.5	1.3	0.58	0.22
1.11	1.0	0.99	0.81	0.47	0.20
1.74	0.75	0.73	0.62	0.38	0.18
2.38	0.57	0.57	0.47	0.30	0.16
3.65	0.38	0.37	0.32	0.23	0.13
4.92	0.25	0.25	0.22	0.16	0.097
7.46	0.13	0.13	0.12	0.10	0.072

* Source dimensions are the same as in Figure 6 - The estimated accuracy of the dose-rate values is $\pm 20\%$.

FIGURE 6

IN-PHANTOM MEASUREMENTS ON 15 WATT CYLINDRICAL
 $^{147}\text{Pm}_2\text{O}_3$ SOURCE (0.25 ppm ^{146}Pm IMPURITY)

VI. Summary and Conclusions

This report presents the in-phantom predictions and measurements on two cylindrical $^{147}\text{Pm}_2\text{O}_3$ radioisotopic heat sources of nominal 15 watt rating and containing 0.25 and 3.5 ppm ^{146}Pm impurity. The protocol for characterizing the dose-rate fields is discussed. A comparison of two computer codes is included - the conclusion being that the more versatile QAD-code is somewhat more accurate in predicting the measurements and, in fact, is capable of predicting the phantom measurements to within the experimental error of $\pm 20\%$. If the total source-shield weight is restricted to about 0.5 pounds, the ^{146}Pm impurity would need to be reduced an order of magnitude or to about 0.02 ppm for promethium heat sources to be competitive with the estimated dose-rates from electrorefined ^{238}Pu heat sources. This comparison is for a promethium heat source of twice the thermal rating of a plutonium heat source. For a total source-shield weight of 1.2 pounds (the full complement of shields utilized in the phantom measurements), the 0.25 ppm ^{146}Pm source produced dose-rates at 20 cm into tissue (the approximate location of the spleen if the source is placed on the left iliac) of about 35 mrem/hr. This could be reduced to about 20 mrem/hr by rotating the source 90° , taking advantage of the dose reduction from source self-absorption.

It is perhaps misleading to compare "bare" sources rather than sources placed within a blood-pump subsystem as it is recognized that a significant dose reduction takes place by distance shielding alone. The first tissues encountered by the radiations emanating from a subsystem would probably be at distances greater than those in contact with a "bare" source. This will reduce the source "surface" dose-rate and thus the integrated dose-rate in the body. However, the dose to any one organ, like the spleen, may not change appreciably unless there is an interposed thickness of higher atomic number materials from the subsystems.

A more logical comparison of promethium with plutonium would be the computation of dose-rates accrued by tissue from sources placed within a subsystem. Once suitable prototypes are developed, this comparison should be made.

VII. REFERENCES

1. Paterson, R., Parker, H. M., and Spiers, F.W. (1936). A system of dosage for cylindrical distributions of radium. Brit. J. Rad. 9 487.
2. Quimby, E. H. (1944). Dosage table for linear radium sources. Radiology 43 572.
3. Shalek, R. J., Stovall, M. and Batten, G. W. Jr. (1968). The M. D. Anderson method for the computation of isodose curves around interstitial and intracavity radiation sources. Am. J. Roentgenol., Rad. Therapy & Nuclear Med. 102 662.
4. Johns, H. E. (1966). The Physics of Radiology, Charles C. Thomas, Springfield, Illinois, 2nd Ed., 3rd Printing.
5. ICRU, (1964). Physical aspects of irradiation. NBS Handbook 85, U. S. Government Printing Office, Washington.
6. Engel, R. L., Greenborg, J. and Hendrickson, M. M. (1966). Isoshld - a computer code for general purpose isotope shielding analysis. BNWL-236.
7. Simmons, G. L., Regimbal, J. J., Greenborg, J., Kelly, E. L. Jr., and Van Tuyl, H. H. (1967). Isoshld-II: code revision to include calculation of dose rate from shielded bremsstrahlung sources. BNWL-236 Supl.
8. Malenfant, R.E. (1967). QAD: A series of point-kernal general-purpose shielding programs. LA-3573.
9. Lahti, G. P. (1967). QAD-HD point-kernal radiation shielding computer code to evaluate propellant heating and dose to crew. NASA TM-X-1397.

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