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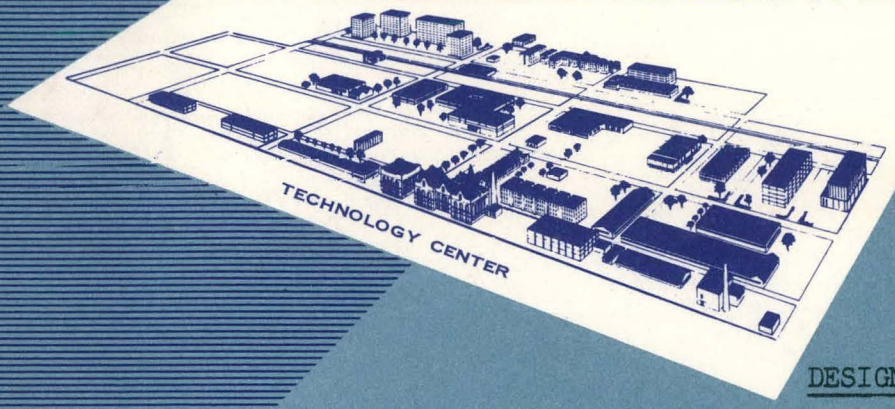

DESIGN STUDIES ON CESIUM-137 AS A SOURCE FOR HIGH LEVEL GAMMA IRRADIATORS

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on

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to

U. S. Atomic Energy Commission
Chicago Operations Office
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Research Contracts Division

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DESIGN STUDIES ON CESIUM-137 AS A SOURCE FOR HIGH LEVEL GAMMA IRRADIATORS

I. INTRODUCTION

The purpose of this investigation is to study the design of potential high level Cs-137 gamma irradiators, particularly from the standpoint of the radiation physics problems which are involved.

In the initial phase of this study the emphasis has been placed on analytical studies; establishing general relations from first principles for the performance of gamma irradiators, examining in what respects Cs-137 can be expected to offer advantages or show limitations as compared to other sources of penetrating radiation, and examining plaque source configurations which lead to favorable performance conditions for Cs-137. In parallel with these analytical studies has been the design and assembly of instrumentation for radiation field measurements with low-level experimental sources, and the exploration of techniques for preparing suitable test sources.

II. RADIATION PROPERTIES OF Cs^{137} SOURCES

A. Decay Scheme and Power Output

As reviewed by Strominger et al,[1] Cs^{137} decays primarily by beta emission with a maximum energy of 0.514 Mev, followed by a single gamma ray of 0.662 Mev from Ba^{137}. In 8 percent of the decays, there is a beta of 1.17 Mev maximum energy with no gamma rays. In the gamma decay of Ba^{137} from the 0.662 Mev level, which has a half-life of 2.6 minutes, 10 percent of the transitions occur by internal conversion, giving electrons of 624 Kev as well as characteristic barium x-rays.

The average energy of gammas per disintegration should then be $0.662 \times 0.92 \times 0.90 = 0.55$ Mev. This corresponds to a gamma power of

$$P_\gamma = 3.7 \times 10^{16} \times 0.55 \times 1.6 \times 10^{-6} \times 10^{-10} = 3.27 \text{ Kw/Megacurie.} \quad (1)$$

The average energy of the betas and conversion electrons per disintegration is 240 Kev. The corresponding beta power is $P_\beta = 1.43$ Kw/Megacurie, or 44 percent of the gamma power radiated. This high beta energy output of Cs^{137}, which is of concern in self-heating, is to be compared with the smaller fraction of only 4 percent of the gamma power in the case of Co^{60} sources.

The half life of Cs^{137} is $\sim$ 28 years, corresponding to an annual renewal requirement of $\sim$ 2.5 percent if the source strength is to be kept constant in an irradiator. Also, from the half life, the maximum possible specific activity for Cs^{137} sources is $S_m \sim 100$ curies/gm.

B. Absorption and Scattering Cross-Sections

At photon energy of 662 Kev, the values for the attenuation (μ) and energy absorption (μ_a) coefficients used in this investigation were obtained from Rockwell[2] and Grodstein[3] and are listed in Table I.

The scattering cross section σ_s and the ratio σ_s/μ_a shown in Table 1 were derived for estimating build-up effects.

C. Dose Conversion Factors

Using the energy absorption coefficients μ_a in Table I, the expected specific dose rates for Cs^{137} point sources are

$$k_r = \left(\frac{3.7 \times 10^{10}}{4\pi}\right) \times (0.55 \times 1.6 \times 10^{-6}) \times 3600 \times \left(\frac{0.0295}{87}\right)$$

$$= 3.15 \times 10^3 \text{ r/hr/curie at 1 cm in air} \qquad (2)$$

$$k_E = \left(\frac{3.7 \times 10^{10}}{4\pi}\right) \times (0.55 \times 1.6 \times 10^{-6}) \times 3600 \times \left(\frac{0.0328}{100}\right)$$

$$= 3.05 \times 10^3 \text{ rads /hr/ curie at 1 cm in water.} \qquad (3)$$

D. Source Material

The fission product Cs^{137} source material, as described in the Radioisotope Catalogue and in a brochure by the Isotopes Division of ORNL, is presently made available in the form of CsCl with a specific activity S_m = 22 curies per gram of solid. The density of source material is expected to approach $\rho_s \sim 3$ gm/cm^3. From its similarity to the composition of sodium iodide, source attenuation coefficients for CsCl have been assumed to approximate those shown for NaI at the bottom of Table I.

E. Comparison with other Gamma Sources

Table II lists the more important Cs^{137} characteristics which have been found of interest for irradiator analysis, as well as the corresponding features for several other gamma sources.

TABLE I

CROSS SECTIONS FOR Cs^{137} GAMMA RAYS (0.662 Mev)

Material	Z	μ cm^2/gm	μ_a cm^2/gm	$\sigma_s = \mu - \mu_a$ cm^2/gm	σ_s/μ_a
H	1	0.152	0.059	0.093	1.57
C, N, O, Air	6-8	0.0765	0.0295	0.047	1.60
Tissue	-	0.0825	0.0320	0.0505	1.58
Water	-	0.0855	0.0328	0.0527	1.60
Al	13	0.0755	0.0287	0.0468	1.62
Fe	26	0.0715	0.0270	0.0445	1.65
Cu	29	0.069	0.0255	0.0435	1.72
Sn	50	0.0715	0.0332	0.0383	1.15
Ta	73	0.098	0.059	0.039	0.66
Pb	82	0.113	0.074	0.039	0.53
U	92	0.135	0.098	0.037	0.38
NaI	-	0.073	0.032	0.041	1.28

TABLE II

SOURCE CHARACTERISTICS FOR GAMMA IRRADIATORS AND WATER EQUIVALENT ABSORBERS

Isotope	$T_{1/2}$	E Mev	P_γ Kw/Mc	μ gm/cm^2	μ_a gm/cm^2	σ_s/μ_a	k_E rads/hr/c at 1 cm
Cs^{137}	28 yr.	0.66	3.27	0.086	0.033	1.6	3.05
Co^{60}	5.2 yr.	1.17 1.33	14.8	0.063	0.030	1.1	12.6
Na^{24}	14 hr.	1.38 2.76	24.5	0.050	0.026	0.9	17.8
Ir^{192}	74 d.	$\sim$ 0.4	$\sim$ 5.9	0.11	0.033	2.4	$\sim$ 5.2

III. IRRADIATOR DESIGN PROBLEMS

A. Source Economics

In reviewing the factors governing the economic use of Cs-137 in high level gamma irradiators, the earlier study by Beeley[4] has been found to be a convenient point of reference.

An irradiation cost of 0.15 cents per megarad lb (or $1.20 per Kwh of absorbed energy) was estimated by Beeley for capital charges and maintenance, exclusive of source costs, for a radiation cell containing 7.8 megacuries of Cs-137; irradiation was assumed to be on a continuous basis (90% plant factor or 8,000 hours per year). Taking 0.36 cents per megarad lb as the competitive total irradiation cost for a Na-24 reactor gamma facility (which is also near the mean of the estimated values for projected electron accelerator costs), the allowance permitted for competitive Cs-137 source costs in an irradiator with 20 percent efficiency came out to 3.7 cents per curie. The latter figure was based on 12 percent annual capital charges, plus 2.3 percent per year to make up for radioactive decay. Considering that the costs of source fabrication, shipping and installation will likely be at least several cents per curie, we see that Cs-137 source material has very little economic attraction on this basis.

The situation is drastically altered if Cs-137 gamma irradiators can be designed for high efficiency. Keeping all other factors the same, but assuming an improved irradiator to give 67 percent conversion efficiency, which is the value used by Beeley for projected high energy electron accelerators, the Cs-137 radiation cell charges drop from 0.15 to 0.045 cents per megarad lb. The allowance permitted for source costs then increases from 3.7 to 22 cents per curie of Cs-137 in the example above. In the limiting

case of 100 percent irradiator efficiency the allowances for source costs in this example would approach 35 cents per curie Cs-137.

More systematic study of process radiation economics and realistic conditions for the use of high level Cs-137 sources are under way by improved analysis and review of the literature.

The following simple relation has been derived for comparison of different gamma sources;

$$Y = \frac{4}{3} \cdot \left(\frac{p_\gamma}{P_\gamma}\right) \frac{A}{F} \text{ X dollars/Kwh absorbed}$$

where Y is the irradiation cost component for the source itself,

p_γ is the fractional charge per year for capital charges and source makeup due to radioactive decay,

P_γ is the isotopic gamma power (Table II)

A is the plant factor as a fraction of the time the irradiator is in use,

F is the irradiator efficiency, and

X is the source cost, in cents per curie.

For Cs-137 and Co-60, with capital charges amortized over 8 years and a plant factor of 90 percent in both cases, allowed source costs for Y=$2/Kwh (absorbed) come out on this basis to be X = 38 F cents/curie for Cs-137 and X= 78 F cents/curie for Co-60.

Cs-137 source costs as high as 25 to 50 cents per curie appear, so far, to be economically attractive for large scale radiation processing, but only in high efficiency irradiators.

B. Comparison of Cs-137 and Co-60 for HIFI

The approximate method of analysis used previously[5] for the Co-60 source and efficiency requirements in the HIFI program have been applied to

Cs-137. For a large area uniform rectangular source with tightly packed 6 inch water equivalent package absorbers on either side, the total source activity required for irradiation of 3 megarad tons/hr, or useful energy absorption at the rate of 7.6 Kw, the total activity required was found to approach

$$S \simeq 8.9 \times 10^4 / \overline{G} \text{ megacuries.} \qquad (1)$$

The effective dose rate, at half-depth in the absorber, is

$$\overline{D} = S_a \overline{G} = S_m h \overline{G} \qquad (2)$$

where S_m is the mass specific activity, h the source thickness, and $\overline{G}$ is a specific dose rate. The degree of dose uniformity was expressed as

$$U = I_{max}/I_{min} \simeq (G(0) + G(t)) /2 G(t/2) \qquad (3)$$

where G(0) and G(t) are the specific dose rates at the entrance and exit surfaces of the absorber as viewed from the source, and $G(t/2) = \overline{G}$ is the dose rate at half-depth which determines the minimum dose.

For an irradiator approaching infinite geometry, as above, it was found that with an equivalent plane source approximation

$$G(b) = k_E \; Q(b) \; B(b)$$

$$\simeq 2\pi k_E E_1(b) (1 + 2 (\sigma_s/\mu_a) b) \qquad (4)$$

where k_E is the dose rate conversion factor and $b = b'_s + \mu q$ is the total attenuation length for the source assembly (b'_s) and depth q in the absorber. For convenience in assessing the absorption and scattering variations, we have examined here the irradiator performance in terms of a reduced energy flux parameter G', where

$$G'(b) = G(b) /2\pi k_E \, . \, E_1(b) \left[1 + 2 (\sigma_s/\mu_a)_s b'_s + 2 (\sigma_s/\mu_a) \mu q\right] \qquad (5)$$

TABLE III

APPROXIMATE DOSE RATE VARIATIONS FOR A LARGE AREA Cs-137 PLAQUE SOURCE AND 6-INCH WATER ABSORBER

	b'_s	0	0.15	0.20	0.25	0.35
	$\mu_s h$	0	0.10	0.20	0.30	0.50
	h (cm^2/gm)	0	1.37	2.75	4.1	6.9
	G'(t/2)	1.25	1.10	1.05	1.0	0.9
Case A	U	∞	1.26	1.24	1.21	1.21
	G'(t/2)	1.25	1.00	0.90	0.80	0.75
Case B	U	∞	1.13	1.10	1.05	1.0

1. Dose Rate Variations for Infinite Sources

Table III lists the results derived for $G'(t/2)$, which governs the dose rate and final dose at half-depth in a 6 inch water absorber, and the depth dose uniformity $U=\left[G'(0) + G'(t)\right] / 2\, G'(t/2)$. The estimates were made for two limiting types of composition for Cs-137 source assemblies; case A for a dilute source in a low Z source mixture and cladding material, and case B for high Z (lead equivalent) source and cladding combination. It was also assumed that the source cladding thickness $b_c \simeq 0.10$ relaxation lengths, such that the source attenuation thickness $\mu_s h \simeq 2(b'_s - 0.10)$.

The dose uniformity figures in Table III indicate that relatively small values of b'_s, with Cs-137 source thickness of several gm/cm^2, should remove most of the depth dose non-uniformity if large area sources are employed. Under these conditions $U \lesssim 1.25$ and $G'(t/2) \simeq 1.0$.

2. Source Activity and Efficiency

To estimate the HIFI source activity requirements, we now find $\overline{G} \simeq 2\pi k_E\, G'(t/2) = 1.9 \times 10^4$ rads/hr/curie/cm^2, and $S \simeq 4.7$ megacuries Cs-137. The gamma power required is thus $SP_\gamma = 4.7 \times 3.27 = 15.3$ Kw, with a useful efficiency of 7.6/15.3 = 50 percent expected for an "infinite geometry" single plaque-two pass irradiator.

From an identical analysis for Co-60, we also find $U \lesssim 1.25$ and $G'(t/2) \simeq 1.0$ when b'_s is in the region of 0.20 relaxation lengths. For the HIFI conditions, in this approximation, $\overline{G} = 2\pi k_E\, G'(t/2) \simeq 8.0 \times 10^4$ rads/hr/curie/cm^2, $S \simeq 1.1$ megacuries Co-60, $SP_\gamma = 16.3$ Kw and the useful efficiency expected is 47 percent.

Similar estimates were also made for the more penetrating radiation from Na-24 and the softer radiation from Ir-192, listed in Table II.

Again the depth dose uniformity and efficiency values appeared from this type of analysis to be nearly independent of the initial photon energy. In fact, values for G' at 3" XX in water slab absorber appeared to be constant at G'≃ 1.2 for thin infinite plane sources over the whole Compton absorption region from 70 Kev to 4 Mev photon energies. At the same time the differences in σ_s/μ_a values for different source assembly compositions and photon energies appear to allow good dose uniformity to be achieved for both soft and hard gamma sources with b'_s values which keep the resultant value of G'(t/2) near unity.

Although the source assembly attenuation and scattering results here are not sufficiently reliable for accurate determinations of G'(t/2) and U values, there does appear to be a net trend favoring the lower photon energy sources, such as Cs-137, as being more efficient. (When a high degree of dose uniformity is not required, the softer gamma sources appear particularly favored.)

3. Effective Dose Rate

From the data above the dose rate $\overline{D}$ in 6 inch water absorbers due to a Cs-137 plaque source of large dimensions is expected to approach

$$\overline{D} \simeq S_a \overline{G} \simeq (2\pi k_E S_m)\, h\, G'(t/2) .$$

As indicated previously $S_m \simeq 100$ curies/gm if Cs-137 could be prepared as a pure source. From Table III, $h \sim 3$ gm/cm^2 and $G'(t/2) \simeq 1.0$ for good dose uniformity and efficiency. The resultant dose rate would then be $\overline{D} \simeq 6$ megarads/hour, satisfying the HIFI requirements. Because of the larger k_E value for Co-60 (Table II), with this source material a specific activity in the region of 25 curies/gm should give comparable results.

With the Cs-137 source material presently available the specific activity is $S_m \simeq 22$ curies/gm and an effective dose rate $\overline{D} \simeq 1.3$ megarad/hour is indicated. To obtain dose rates in the region of 6 megarads/hour with this source material it is estimated that two tall parallel plaque sources could be used with a single absorber pass but the resultant efficiency would be in the vicinity of 15 percent and a total activity near 16 megacuries of Cs-137 would be required. However, there appear to be very few potential applications of high level Cs-137 irradiations where dose rates in excess of 1 megarad/hour are essential.

C. Extensions of Design Analysis

In order to explore more fully the effect of design parameters for Cs-137 or other gamma irradiators, and also to provide a more explicit basis for a close comparison of experimental results with design theory, further modifications have been explored in the existing methods of analysis.

1. Efficiency

It has been found convenient to consider the fractional irradiator efficiency F, for any irradiator treating an absorber of thickness t, in the following forms

$$F = WI/SP$$

$$= \mu_a t \cdot C \lesssim 1 - e^{-\mu t}$$

where the rate of useful energy absorption WI and source power are both expressed in the same units, e. g., in kilowatts, and C is a design parameter which includes all the specific factors for the source and absorber configurations, dose rate and dose uniformity requirements, etc.

For the single plaque, two pass irradiator with infinite geometry discussed above, it turns out very simply that the configuration Factor C=

$G'(t/2)$ in the previous notation. It has also been found that $G'(t/2) \simeq 1.2$ for all gamma sources when the source attenuation length b'_s is negligible and $t/2$ corresponds to 3" of water. By adjusting the source and cladding thicknesses and their atomic compositions, appropriate values of b'_s are further anticipated to yield closely similar values of $G'(t/2)$ with comparable depth dose uniformities over a considerable range of absorber thickness t. From Table II we also see that the higher values of μ_a and μ favor the lower energy gamma emitters for better efficiency.

Estimates made for the "see-through" factor in successive parallel slab absorbers also show little variation with primary photon energy. In the infinite plaque geometry and 6" water slab absorbers the efficiency F is expected to increase by a factor of ~ 1.20 for two passes on either side, and by ~ 1.25 for three passes on either side, whether the source is Cs-137, Co-60 or Na-24. For sterilization applications with good dose uniformity, large plaque sources are expected on this basis to approach a useful conversion efficiency for 6 inch water absorbers of $F \sim 62$ percent. For chemical processing, where the average dose is relevant rather than the minimum dose, the efficiency of the same irradiators approaches $F \sim 80$ percent. (Similar high efficiencies can also be expected for other irradiator configurations in which several relaxation lengths of absorbing material closely surround the gamma source.)

2. Finite Source Corrections

For real irradiators we have approached the problem of detailed analysis by considering the correction factors necessary in the cases where the source configuration comes closest to one of three ideal geometries, viz. infinite plaque, infinite line or rod, and point source. In terms of $\overline{\mu}$, the

linear attenuation coefficient for primary source photons in the absorbing material, these three geometries become relevant for different "plaque" source heights H_s, lengths L_s and thicknesses h. Also, for good utilization of scattered radiation the air gaps should be small, i. e., $g \ll 1/\bar{\mu}$.

On this basis a high level gamma irradiator with small source dimensions approaches the point source condition when $\bar{\mu} H_s \ll 1$ and $\bar{\mu} L_s \ll 1$. A long source ($\bar{\mu} L_s \gg 1$) approximates either a line geometry if $\bar{\mu} H_s \ll 1$, or an infinite plaque geometry if $\bar{\mu} H_s \gg 1$.

Preliminary correction factors have been estimated for the effect of finite height H_s for plaque irradiators, based both on theory and examination of the Co-60 HIFI experimental data.[6] The depth dose appears to approach the infinite geometry value corresponding to G'(t/2), following the form $K\, G'(t/2) \simeq (1 - a_1/\bar{\mu} H_s)\, G'(t/2)$. To avoid non-uniformity in the vertical dose distribution by the source overlap method, the irradiator efficiency is reduced further by a factor (H_t/H_s), where H_t is the useful height of absorber target. Since the fringe field drops off primarily over distances comparable to $1/\bar{\mu}$, the efficiency reduction with source overlap is expected to be $(H_t/H_s) \simeq (1 - 2/\bar{\mu} H_s)$.

Table IV shows values for K and (H_t/H_s) derived in this way for finite Cs-137 and Co-60 plaque sources. Assuming small air gaps, we have put $K \simeq 1 - 1/\bar{\mu} H_s$. The interesting feature here is that for given irradiator dimensions, Cs-137 appears more favorable than Co-60. For Na-24, with $1/\bar{\mu} \simeq 7.6$ inches in water, the finite source corrections are considerably more serious still, while for Ir-192, with $1/\bar{\mu} \simeq 3.9$ inches water, even a source as small as 40 inches in length and height can be considered as an infinite plaque.

A closer examination of these source corrections will be made for

TABLE IV

FINITE PLAQUE SOURCE HEIGHT CORRECTION FACTORS (L_s 1/)

	H_s - inches	∞	72	48	24
Cs-137	H_t/H_s	1.0	0.87	0.80	0.60
$1/\mu$ = 4.75 inches	K	1.0	0.93	0.90	0.80
Co-60	H_t/H_s	1.0	0.83	0.74	0.48
$1/\mu$ = 6.25 inches	K	1.0	0.91	0.87	0.74

comparison with available experimental data, which presently looks very attractive indeed, and for comparison in our own experimental program.

3. Radiation Field Distribution

Another problem area which we have begun to explore is the separation of the radiation field explicitly into two components, one for the uncollided source photons and the other for scattered radiation. The absorbed dose rate D(b) at any attenuation depth b in a plaque source irradiator is expressed as

$$D(b) = 2\pi k_E S_a (K_o G_o'(b) + K_s G_s'(b))$$

where $G_o'(b) = E_1(b)$ governs the dose rate variation for the uncollided photons in the equivalent plane source approximation, and K_o is a correction factor for finite source and absorber dimensions;

$G_s'(b) = (\sigma_s/\mu_a) e^{-b}$ governs the dose rate variation for the scattered photons, again based on the infinite plane source approximation, and K_s includes both normalizing and correction factors for a real plaque source. For comparison with experiments, the analysis in this form will be chiefly concerned with the factors K_o and K_s. The former is chiefly of interest for shallow penetration, when $b \sim b_s'$ and the dominant term is the uncollided flux ($G_o'(b)$). The scattered radiation factor K_s is of particular interest for deep penetration, where in order to attain good efficiency and dose uniformity with soft photon source such as Cs-137, we expect $G_s' \gtrsim G_o'$ and the depth dose variation to fall off as e^{-b}.

Estimates of the relative dose contributions due to primary and scattered photons at 3 inch depth in water give approximately equal effects in the case of Co-60, whereas for Cs-137 the scattered component is indicated

to be predominant even at this shallow penetration with plaque source geometry. Small source dimensions and large air gaps are the main factors which we see as of concern for reducing the factor K_s, and hence the effective dose rate $\overline{D}$ and irradiator efficiency F for realistic Cs-137 high level sources.

IV. EXPERIMENTAL PROGRAM

A. Radiation Field Mapping Instrumentation

Because of its high sensitivity and the small detector dimensions possible, the scintillation method was chosen in preference to ionization chambers. A further advantage of scintillators here is the greater possibility for analyzing the dose distribution by taking into account variations in the photon spectrum due to scattered Cs-137 gammas.

Two probe assemblies have been selected, both using 3/4 inch diameter phototubes, and designed for immersion in fluid absorbers.

The first probe acts as a dose rate meter in connunction with a conventional Keithley D. C. amplifier or Beckman electrometer for reading the phototube current. An additional read-out circuit has been built to balance the phototube dark current and also provide further current amplification by a factor of 30 so that signal currents as low as 10^{-11} amps can be readily measured. With a selected 10 stage DuMont phototube which shows a low dark current of only 2×10^{-9} amps when operated at 1200 volts, coupled to a 5 mm thick anthracene crystal 10 mm in diameter, initial calibrations with a known Cs-137 source have been made for fields down to 0.1 mr/hr. It appears unlikely that still smaller crystal dimensions will be necessary even for "point" dosimetry, or at interfaces where the radiation field shows steep gradients. To reduce the field perturbations, a 4 inch long lucite light pipe 1/2 inch in diameter is used for coupling the scintillator and phototube.

The second probe, of the type commonly used for gamma ray counting in medical applications, is being obtained from National Radiac Inc. Scintillator pulses from this unit will be fed into a 256 channel pulse height analyzer, for studying changes in spectral distribution, and for following

the uncollided 0.66 Mev source photons independently of the dose measurements.

The two principal scintillating materials to be used are anthracene for dose rates and NaI(Tl) for photon spectra. Preliminary estimates indicate that relatively large correction factors may be required for converting anthracene XX current readings to roentgens, or rads in water, when there is an appreciable contribution of Cs-137 scattered photons degraded below 100 Kev. If this leads to sufficiently large uncertainties in the derived distribution of absorbed dose rate in water absorbers, we intend to investigate the use of air-equivalent or water-equivalent mixtures of anthracene and chloroanthracene, as was done by Breitling.(7)

B. Design of Experimental Sources

At the beginning of this investigation it was expected that suitable low level sources could be readily prepared by the Isotopes Division at Oak Ridge; diluted CsCl source material would be compacted into standard rectangular tubing. With such tubes we planned to make linear arrays to simulate "rod" sources and rectangular arrays for plaque sources in the field mapping determinations.

After reviewing the source fabrication techniques at Oak Ridge and carrying out further analytical studies on the effect of source thickness, it became clear that the tube filling method, with hot cell techniques, presented considerable difficulties for source thicknesses of only a few gm/cm^2 which are of particular interest to us (see Table III). Thicker sources, such as $h \sim 8$ gm/cm^2, or ~ 1" in thickness, are more convenient to prepare by the tube filling method.

To obtain thinner sources, and test whether the efficiency and dose uniformity improvements suggested in the analytical studies can be realized, a number of alternative source fabrication techniques are being investigated.

The first method, which has also been favored by E. Beauchamp at ORNL, would use thin wafers of compressed CsCl stacked next to each other in rectangular tubing. The method is now under study at Oak Ridge and the first tests will be made with a 1" x 1" die to see if the wafers in the thickness range 1/4" to 1/2" can be compressed satisfactorily.

A second method is under study here, based on the use of metallurgical techniques for producing thin plane sources by means of either rolling or pressing on suitably designed Cs-137 containers whose initial dimensions allow convenient filling in hot cells.

A third method is also being pursued. In this case thin flat trays would be filled with simulated source mixtures and diluted Cs-137.

V. CONCLUSIONS

In this phase of the study on Cs-137 High Level Irradiators a systematic basis has been developed for identifying the pertinent problem areas which affect the economics, the efficiency, and the dose distribution for material undergoing process irradiation. Comparison of Cs-137 with Co-60 gamma sources by approximate analytical methods now indicates, in the case of irradiators specifically designed for high efficiency of useful energy conversion, that the performance of Cs-137 source material should be at least comparable to the performance of Co-60 source material.

The general design parameters which have now been formulated are being applied to the design of specific experiments which will also lend themselves to close analysis and comparison with theoetical predictions.

Respectfully submitted,

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