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DESIGN OF A SOURCE FOR A LARGE-SCALE ENVIRONMENTAL GAMMA IRRADIATION TEST FACILITY USING MIXED ISOTOPES

THESIS

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PREFACE

When Robert T. Carpenter and David M. Ericson completed "An Analysis of the Requirements for Large-Volume, High-Intensity, Gamma Environmental Testing Facilities" in 1959, they established generally the nuclear and non-nuclear requirements of such a facility for the testing of components up to and including subsystems of nuclear air and space craft. The source parameters ascertained from their report are those which would best duplicate the gamma radiation source of such a system and include the energy spectrum, dose rate, variation in field, and angular distribution of the gamma rays. William W. Monday adequately solved the problem of source spectrum when he completed "The Feasibility of Mixing Isotopes to Simulate the Gamma Environment of Nuclear Systems" in 1960 and recommended that a three isotope mixture of Cobalt-60, Cesium-137 and Europium-152 in the activity proportions of 1.00/3.39/4.26 be used.

Since I had an interest in this field I decided to incorporate the results of these previous investigations in a conceptual design of a source for a large-volume, high-intensity, gamma, irradiation facility. No attempt was to be made to completely engineer the design, but enough properties were to be determined in order that such an engineering design could be completed. The data and results of William W. Monday were utilized in all cases in an attempt to lend continuity to the effort.

The author wishes to express his appreciation to Major E. J. Zawalick for his guidance in the planning and writing of this investigation, and to Major J. R. Bohannon, Jr for his valuable suggestions and comments. Also, the encouragement and assistance from the author's wife, Jeanne D. McGee, is gratefully recognized.

John J. McGee, Jr.

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ABSTRACT

A design of a source for a large-scale, environmental, gamma-irradiation, test facility using the isotopes Cobalt-60, Cesium-137, and Europium-152 has been accomplished. The source geometry is a six-foot diameter verical disk with 1,627 small sources mounted in the disk. These small sources are cylinders containing the three isotopes and are mounted with their axes parallel to the axis of the disk.

An arbitrary test item with a four foot diameter face, centered on this source, six inches away is exposed to a dose rate of 1.3 x 10^8 ergs/hr-g(C) at its center. The exposure rate is only eight percent less at the edge of the test item face two feet off the center line.

The source contains 705,000 curies of Co-60, 1,030,000 curies of Cs-137, and 545,000 curies of Eu-152 and generates heat at the rate of 49,800 BTU/hr. The Co-60 is irradiated Cobalt with a specific activity of 2.9 curies/gm.; the Cs-137 is a processed fission product formed into CsCl powder with a specific activity of 22.0 curies/gm.; and the Eu-152 is irradiated Eu_2O_3 with a specific activity of 14.8 curies/gm.

The advantages of this source are its unidirectional geometry which allows the test item to be tested in various orientations, its ability to irradiate large test item faces, its relative effectiveness since both sides of the source may be used, and its flexibility since various source strengths may be obtained by loading less of the small sources.

DESIGN OF A SOURCE FOR A LARGE-SCALE ENVIRONMENTAL GAMMA-IRRADIATION TEST FACILITY USING MIXED ISOTOPES

I. Introduction

The design of a source for a large-scale, environmental, gamma-irradiation test facility is the latest effort in a project first undertaken by Robert T. Carpenter and David M. Ericson in 1959. In their report (Ref. 1) entitled "An Analysis of the Requirements for Large-Volume, High-Intensity, Gamma Environmental Testing Facilities", they concluded that such a facility for testing airborne equipment for nuclear-powered aircraft was non-existent but was practical and would be valuable in future test programs. The project was continued in 1960 by William W. Monday with his report (Ref. 8) entitled "The Feasibility of Mixing Isotopes to Simulate the Gamma Environment of Nuclear Systems", in which he attempted to simulate the prompt gamma-ray fission spectrum of Uranium-235 with mixed gamma-emitting isotopes. Monday concluded his report with the recommendation that a three-isotope mixture of Cobalt-60, Cesium-137, and Europium-152 be used.

The purpose of this report is to design the source for the large-volume, environmental gamma test facility proposed by Carpenter and Ericson using the three-isotope mixture recommended by Monday. All data and results obtained by Monday will be used to retain continuity in the effort. Specific objectives to be accomplished are, (1) selection of the source geometry, (2) design of the source, (3) calculation of the various source properties, and (4) consideration of cell facilities necessary to handle the source.

The primary criteria used in selecting a source geometry were to obtain the maximum radiation level for a source of given strength and to obtain a high degree of uniformity of the radiation field on the test-item. With the assumption that the source was to irradiate the test-item from only one direction and that the maximum test-item area facing the source could be represented by a four-foot diameter circle, all geometries were eliminated from consideration except plane circular disks, and spherical segments. These two geometries were compared and the plane circular disk was judged the best from overall considerations. Various sizes of disks were compared analytically and from these comparisons a disk size was determined which gave the maximum uniform radiation level on the face of the test item for a source of given strength.

In the design of the source, consideration was given to the physical state of the isotopes, arrangement of the isotopes within the source geometry, and size and number of the isotope containers. The physical state of the isotopes selected was limited to those that were commercially available at the time. The arrangement and size of the containers selected was that which would give the best uniform distribution of the isotopes in the source geometry with the least distortion of the previously determined spectrum.

The various source properties determined were the number of curies of each isotope required, the specific activity of the isotopes, the exposure dose rate on a test item, the spectrum emitted by the source, the heat generated by the source, and the maximum source temperature. The total cost of the isotopes was also calculated.

In considering the cell facilities necessary to handle the source, the techniques required for loading and replenishing the source were discussed. Other problems considered included the provisions for storage of the source and access to the cell for handling of experiments. Source temperature control, requirements for the cell shielding, dosimetry, and cell safety in the event of source damage were also considered.

The source design, that was accomplished, satisfactorily met all the criteria set forth with the possible exception of dose rate. The gamma dose rate achieved with this source was almost two orders of magnitude less than that of a typical nuclear reactor and for this reason may not be considered feasible for use in conjunction with a reactor test facility as was originally proposed. The relatively low dose rate was due primarily to two factors, the source geometry and the spectrum limitation. The cost of the isotopes in the source based on present prices was found to be almost five million dollars, which should be considered prohibitive. It is felt that the cost could be reduced by a factor of ten when source material in these quantities is required.

II. Selection of Source Geometry

The determining factor in the selection of the source geometry for a gamma irradiation test facility is the purpose for which the facility is to be used. A research facility for reasons of economics requires that the maximum absorbed dose of radiation be delivered to the whole test item. A developmental test facility, on the other hand, requires that the important environmental parameter of test item orientation be duplicated. It must be possible to position the test item in the test facility in the same orientation that it maintains in relation to the radiation source in the system under development. Since this source is to be used in a developmental facility for equipment used in conjunction with nuclear powered air and space craft and since this equipment is usually located some distance from the source of radiation, it is necessary for the test facility source to irradiate the test item from one direction to enable as near as possible the duplication of the test item's orientation in the system. This decision limits the source geometry to geometries which focus the radiation on one face of the test item.

Of all the geometries which meet the above criteria, only plane surfaces and curved segments meet the additional criteria of uniformity of radiation on the test item and low self absorption. Of the plane surfaces available, a circle with its property of compact area delivers more radiation at the center of a test item face in front of it than any other plane surface of equal area.

TABLE I

COMPARISON OF DOSE RATE*/AREA OF SURFACES EMITTING S_a (PHOTONS/SEC-CM^2)

SURFACE	DOSE RATE/AREA ($10^{-2} S_A/FT^2$)			
	DIAMETER–CHORD (FT.)			
	4.0	6.0	8.0	10.0
CIRCLE	5.63**	3.19	2.07	1.47
SPHERICAL SEG. RADIUS – 5 FT.	5.89	3.19	1.90	0.92
SPHERICAL SEG. RADIUS – 7 FT.	5.86	3.26	2.05	1.37
SPHERICAL SEG. RADIUS – 10 FT.	5.78	3.26	2.09	1.45
SPHERICAL SEG RADIUS – 15 FT.	5.77	3.23	2.10	1.47

* CALCULATED ON AXIAL CENTERLINE 6 IN. FROM SURFACE

**EXAMPLE · $5.63 \times 10^{-2} S_a / FT^2$

For this reason consideration is given only to plane circular surfaces and spherical segments in determining the source geometry. For comparison both geometries are assumed to be emitting Sa(photons/sec-cm^2) and the flux which is proportional to the exposure dose rate at a point on the source centerline six inches from the source is calculated (see appendix A). In order to compare these two geometries the dose rates are divided by the source area, since the area is a measure of the quantity of source required. When plane circular sources are compared to spherical segments whose chord is equal to the diameter of the circular source, (see Table I), the spherical segment is found to be slightly superior. This would seem to make the decision in favor of the spherical segment; but when it is considered that both faces of the plane circular source radiate equally while much radiation is lost on the convex side of the spherical segment, the decision is clearly in favor of the plane circular surface.

In determining the size of the circular source which is best suited for this facility, three factors form the criteria for judgement. They are the amount of source required, the dose rate achievable, and the uniformity of the dose rate on the face of a test item. To optimize the source size for these three criteria a test item size is required. A test item face represented by a four-foot diameter circle is selected as it is felt this area would include most subsystems which would be tested. Dose rates at a point on the centerline six inches from the face of the source are calculated for source radii from six inches to five foot three

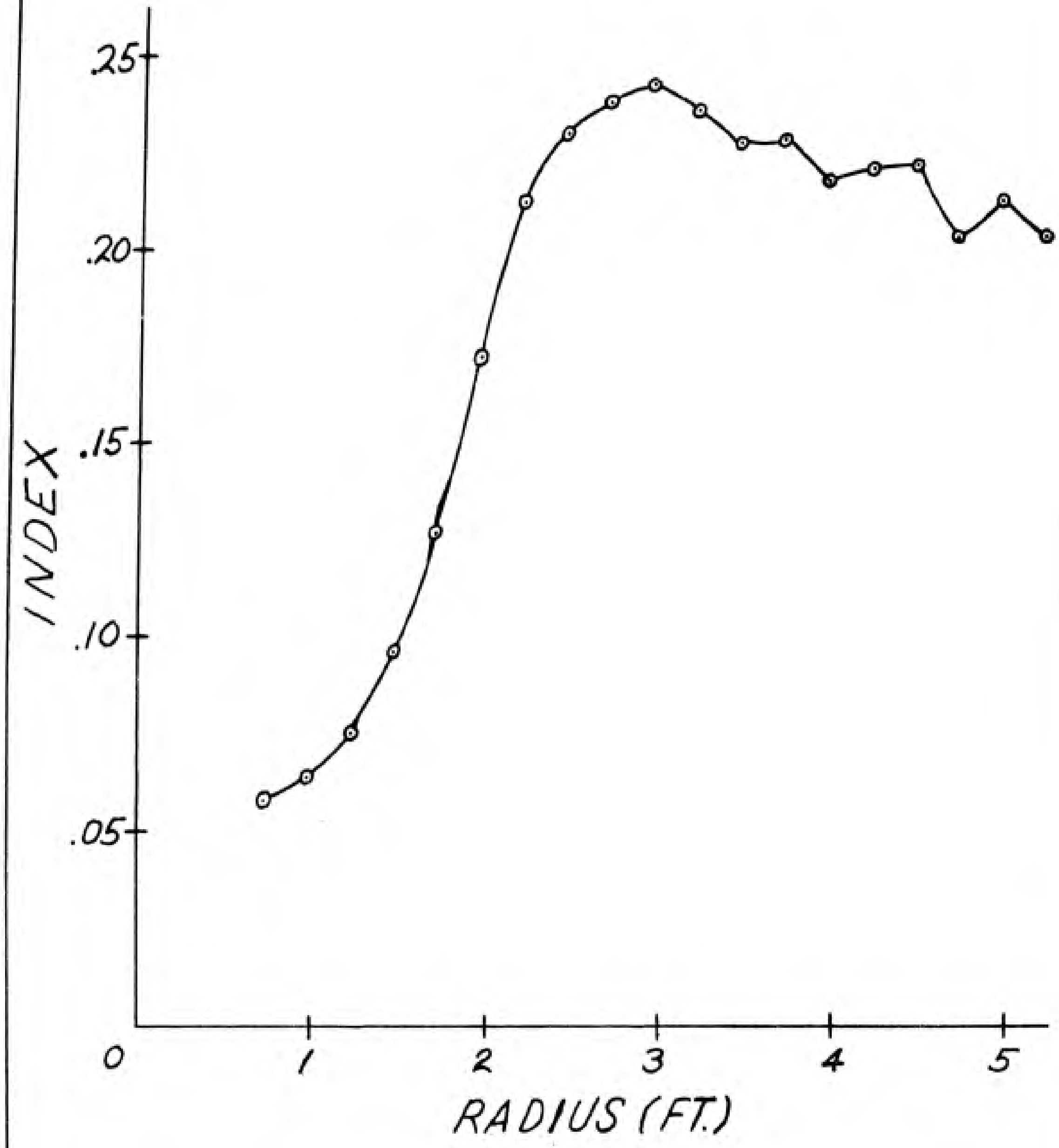

FIG. 1

THE OPTIMUM DISK RADIUS

inches in increments of three inches. For each of these 20 source sizes the ratio of the dose rate at the edge of the test item (a distance of two feet off the centerline) to the dose rate on the centerline both six inches from the face of the source is calculated (see appendix B). This ratio is calculated by replacing the circular source with a line source whose length is equal to the diameter of the circular source. This approximation gives a ratio that is always higher than that which actually exists. The error is greatest at the small source radii, is approximately 14% at a radius of two feet, and for all practical purposes vanishes at a radius of three feet. This ratio is the geometry factor of the particular source size. The geometry factor multiplied by the percentage increase in dose rate for each increment and divided by the percentage increase in area for each increment is the index by which source size is determined. The percentage increase is defined as the final value minus the initial value divided by the initial value. As the source size is increased from a radius of six inches, the geometry factor increases, the percentage of dose-rate-increase decreases, and the percentage of area-increase decreases. The index is plotted against source radius in Fig. I and reaches a maximum at a source radius of three feet. Thus, limiting the source size to a radius of three feet gives the best combination of uniformity of radiation on the test item face and highest percentage increase in dose rate per percentage increase in source required. The source geometry is now fixed as a three-foot radius circle.

III. Design of the Source

The design of the source is concerned primarily with arranging the three isotopes in the source geometry in such a way that maximum radiation on the test item face and minimum distortion of the spectrum result. The source geometry can now be considered to be a circular disk since some thickness is necessary to contain the source material. Many methods of arrangement of the isotopes are possible in this disk. The most practical method to minimize the distortion of the spectrum is to place the isotopes one behind the other and vary the individual isotope thicknesses to allow the self absorption and shielding effect to balance out for each gamma energy. The number of gammas of each energy which reach the test item (the spectrum) is determined by the amount of self absorption and attenuation which each gamma energy flux undergoes.

To completely fill the disk with a single source is impractical since the handling and safety problems would be impossible to tolerate. Therefore, it is necessary to fill the disk with an optimum number of small sources in which the isotopes are arranged one behind the other. The optimum is that number which gives the maximum area coverage with the minimum of handling difficulty. For ease of loading, the small sources are now considered to be cylinders each containing a cylinder of the three isotopes. The problem is now to determine the optimum size of these cylinders. Since the faces of these cylinders are parallel to the face of the circular disk,

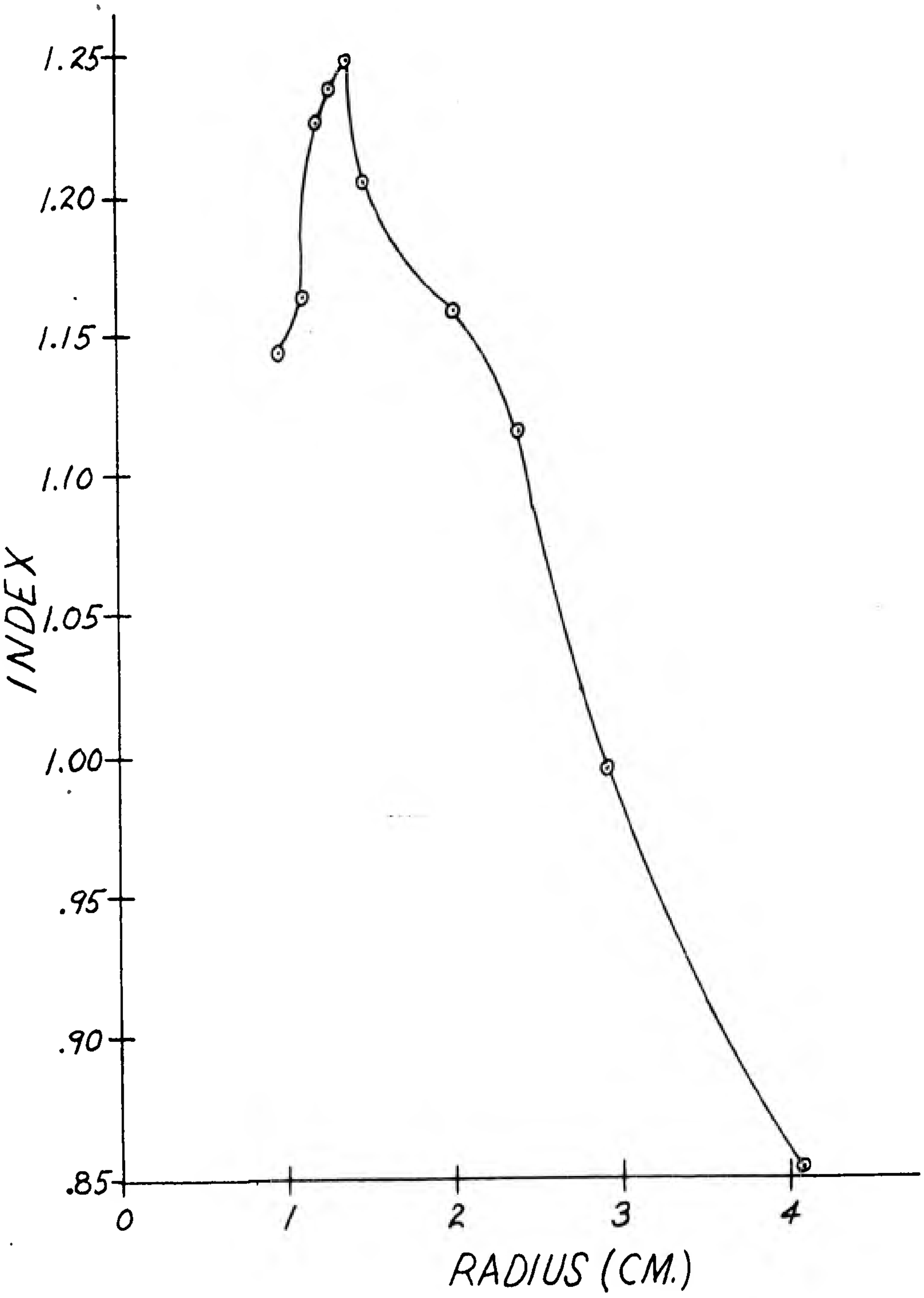

FIG. 2

THE OPTIMUM SMALL SOURCE RADIUS

the problem evolves into determining the optimum number of circles which will fit into the three-foot radius circle. First by utilizing a triangular unit cell of circles, the number of circles and their radius is determined by analytical and graphical methods (see appendix C) for a number of different size circles. A clearance distance to allow for handling of the small sources and source encapsulation is subtracted from the small circle radii. This clearance distance is constant and is assumed to be .75 cm. This new radius squared and multiplied by the number of circles is proportional to the frontal area of the small sources. A handling and difficulty factor is assumed to be equal to the square root of the number of sources. This factor is necessary so that the small sources will not contain an excessive amount of activity. The product of these two factors is the index used for selection of the small source radius. The area factor decreases continually as the number of sources increases while the difficulty factor increases as the number of sources increases. A plot of the index against small source radius (see Fig. 2) shows a definite peak at a radius of 1.38 cm. This is the optimum radius of the small sources for the arrangement and corresponds to 1627 sources.

Before the thickness of each isotope in these small sources can be calculated, the physical state of the isotopes must be determined. No attempt is made to use isotopes in a state or with a specific activity which is not commercially available at the present time. Only solid states are considered because of the very low specific activities of liquid solutions and the difficulties involved

TABLE II

LINEAR ATTENUATION COEFFICIENTS (μ_T cm^{-1})

ENERGY(MEV)	AL	Co	CsCL	Eu_2O_3	MIXTURE
0.12	.415	2.78	5.68	16.50	2.51
0.35	.270	.880	.572	1.40	.540
0.66	.207	.638	.304	.640	.367
0.78	.189	.585	.274	.566	.333
1.17	.154	.474	.224	.445	.270
1.33	.133	.445	.182	.410	.244
1.42	.138	.430	.166	.388	.239

TABLE III

LINEAR ABSORPTION COEFFICIENTS (μ_A cm^{-1})

ENERGY(MEV)	AL	Co	CsCL	Eu_2O_3	MIXTURE
0.12	.100	1.63	4.22	11.25	1.57
0.35	.078	.289	.356	1.01	.219
0.66	.078	.228	.152	.350	.144
0.78	.076	.228	.132	.296	.138
1.17	.070	.210	.106	.220	.122
1.33	.068	.202	.100	.204	.117
1.42	.068	.198	.097	.193	.115

in handling and replacement. Oak Ridge National Laboratory (Ref 9) lists Co-60 available as metallic Cobalt with a maximum specific activity of 50 curies/gm and Cs-137 available as Cesium Chloride (CsCl) with a maximum specific activity of 22 curies/gm and William W. Monday (Ref. 8:51) reports that Atomic Energy of Canada, Limited can produce Eu-152 as Europium Oxide (Eu_2O_3) with a specific activity of 29.5 curies/gm. These represent the best states and maximum specific activities of the isotopes for the purpose of this report. Attenuation and absorption coefficients of the three isotopes for each of the seven energy gammas are now calculated using interpolations from the data of Gladys White (Ref. 15) and are presented in Tables II and III.

Before calculating the individual isotope thicknesses the order of the isotopes must be determined. Rough calculations substantiate the obvious fact that the isotope emitting the low energy gammas should be closest to the test item while the highest-energy-gamma emitter should be the farthest away. This orders the isotopes and places them, in the direction away from the test item, in the following order: Eu-152, Cs-137, and Co-60. Assuming each isotope is a three-foot radius disk of variable thickness and contains Sv(photons/sec.-cm^3) in the proportions determined by Monday, it is possible by trial and error to balance the thicknesses of the three isotopes using Rockwell's equation (Ref. 10:364) so that the spectrum at a point six inches from the face of the source on center line is distorted the minimum amount. To insure that Sv is in the correct

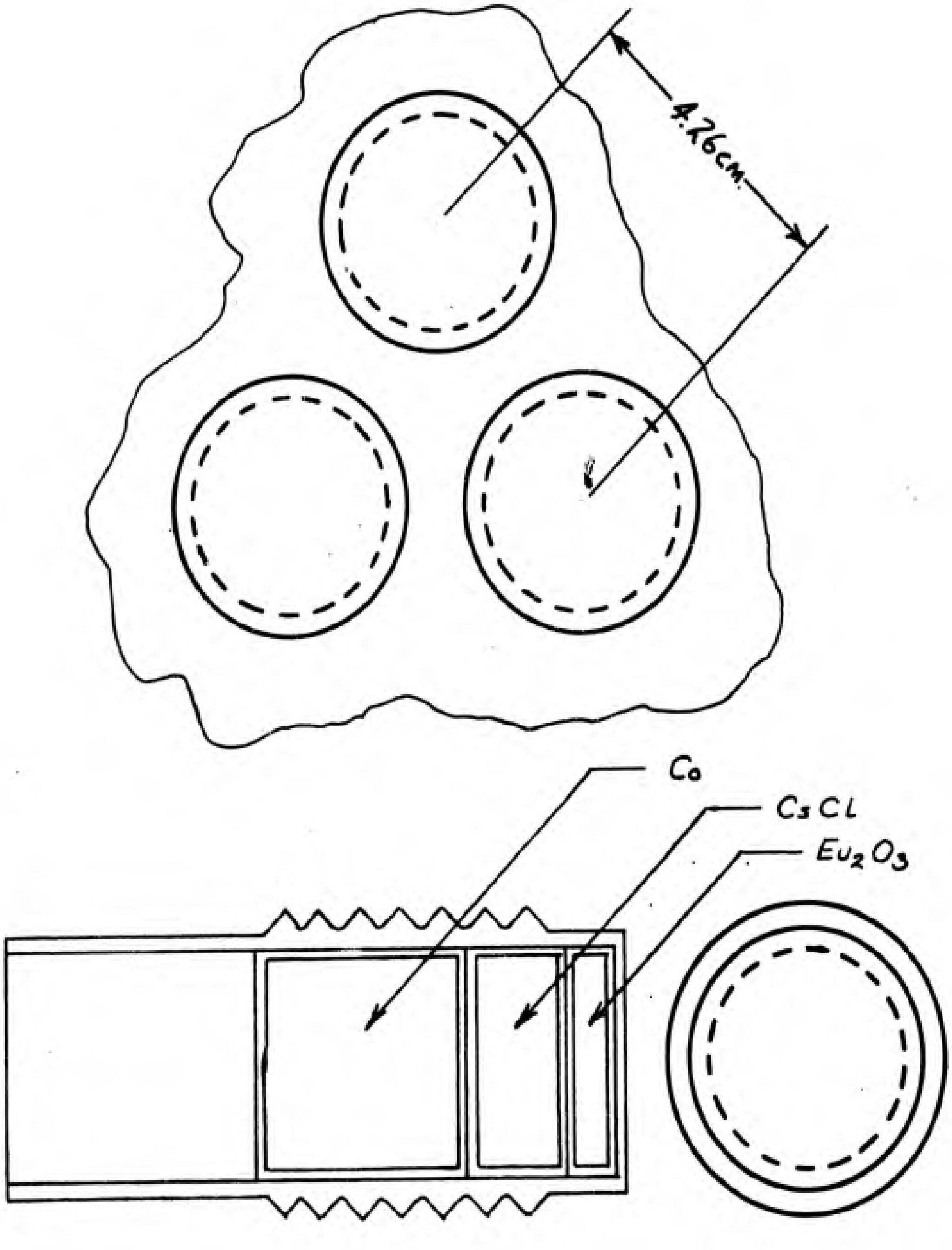

FIG. 3

SMALL SOURCE CONSTRUCTION & ARRANGEMENT

proportions the activity per unit volume must be in Monday's proportions. This method gives the following thickness Eu,.5cm; Cs 1.2cm, and CO,2.8cm. The number fluxes in photons/sec-cm^2 of the various energies at the calculation point are; .12 Mev-.025Sv, .35Mev-.21Sv, .66Mev-.33Sv, .78 Mev-.32Sv, 1.17 Mev-.33Sv, 1.33 Mev-.35Sv, and 1.42 Mev-.35Sv. The spectrum is distorted somewhat at the two lower energies but remains relatively uniform at the five higher energies. The source design parameters have now been determined and consist of 1627 cylinders of 1.38 cm. radius and 4.5 cm. height. This height is made up of .5 cm. of Eu_2O_3, 1.2 cm. of CsCl and 2.8 cm. of Co. The isotopes are individually encapsulated in 1.0 mm. thick type 316 stainless steel as recommended by Oak Ridge National Laboratories (Ref. 9) and are loaded in threaded aluminum cylinders (see Fig. 3) and screwed into the three-foot diameter 4.5 cm. thick disk as illustrated. Because of the complexities involved the shielding effect of the stainless steel is neglected. Aluminum is chosen as the source holder material because of its low gamma absorption cross sections and high structural strength.

TABLE IV

SOURCE PROPERTIES

ISOTOPE	γ ENERGY (MEV)	YIELD	SP. A. (CURIES/GM)	ACTIVITY (CURIES)	FLUX* (γ/SEC-CM^2)	DOSE RATE* (ERGS/HR-G(C))
Co-60	1.17	1.00	2.9	705,000	1.17×10^{11}	2.12×10^{7}
	1.33	1.00			1.24×10^{11}	2.56×10^{7}
Cs-137	0.66	0.92	22.0	1,030,000	3.70×10^{11}	3.78×10^{7}
Eu-152	0.12	0.67	14.8	545,000	$.262 \times 10^{11}$	$.049 \times 10^{7}$
	0.35	0.27			$.885 \times 10^{11}$	$.480 \times 10^{7}$
	0.78	0.11			$.550 \times 10^{11}$	$.667 \times 10^{7}$
	1.42	0.27			1.47×10^{11}	3.26×10^{7}

ISOTOPE	FORM	DENSITY (GM/CM^3)	VOLUME (CM^3)	MELT. P. (°F)	β HEATING (BTU/HR)	γ HEATING (BTU/HR)
Co-60	Co	8.90	34,050	2723	4,400	19,000
Cs-137	CsCl	3.97	9,730	1195	11,800	7,200
Eu-152	Eu_2O_3	7.42	7,300	3690	3,300	4,100
AL	AL	2.70	67,420	1220		

HEAT GENERATION (BTU/HR)	MAXIMUM TEMP. (°F)
49,800	1000 + T(AMBIENT)

DENSITIES & MELTING POINTS (REF 5)
MELTING POINT Eu_2O_3 (REF 16:51)
GAMMA ENERGIES & YIELDS (REF 8)
*ON CENTER LINE 6 IN FROM SOURCE

IV. Calculation of Source Properties

With the source parameters determined, the various source properties can now be calculated. These properties are: the specific activities of the isotopes, the number of curies of each isotope, the exposure dose rate on a test item, the spectrum emitted by the source, the heat generated by the source, and the maximum source temperature. The total cost of the isotopes in the source is also calculated. A tabulation of the source properties appears in Table IV.

Specific Activities

If the activity per unit volume of each isotope is divided by its proportional constant the result is a constant which is equal for the three isotopes. The activity per unit volume is the product of the density which is known and the specific activity which is unknown. The three activities per unit volume divided by the individual proportional constants are equated; the limiting specific activity of the three maximums is determined; and the other two specific activities are then calculated (see appendix D). The limiting specific activity is that of the Cs-137, 22.0 curies/gm. This value causes the specific activity of Eu-152 to be 14.8 curies/gm and that of Co-60 to be 2.9 curies/gm. These values give Sv(photons/sec-cm^3) of each energy gamma in the proportions necessary for the spectrum determined by Monday (Ref. 8:31) and since the fraction of Sv arriving at the test item was made equal for most of the gamma energies minimum distortion of the spectrum will result.

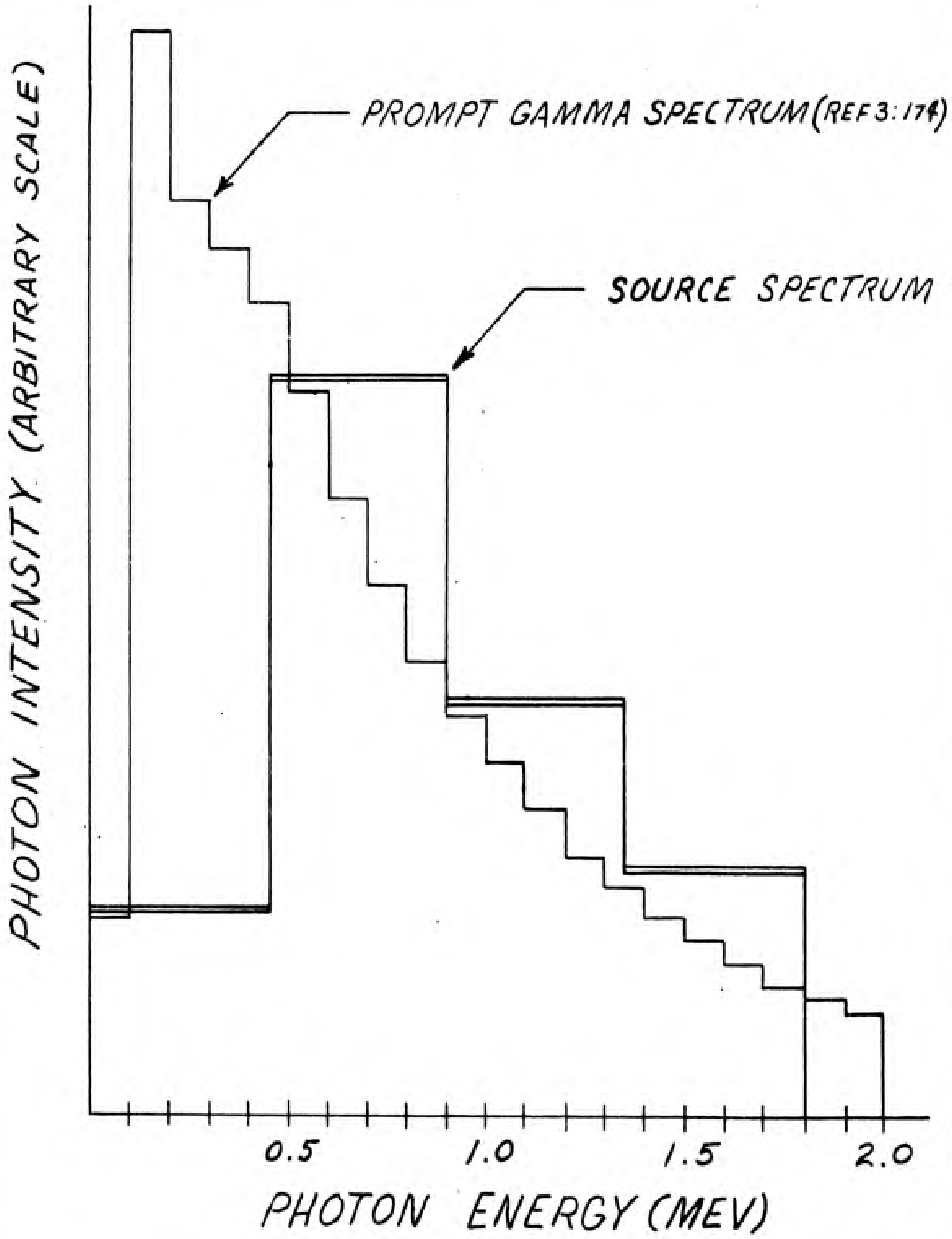

FIG. 4

SPECTRUM COMPARISON

Exposure Dose Rate

The exposure dose rate in erg/hr-g(C) on the center of a test item face six inches from the face of the source is calculated using the fractions of Sv at this point that have already been determined. in minimizing spectrum distortion (see appendix E). The dose rate at this point from the uncollided flux is 1.3 x 10^8 erg/hr-g(C). Using the geometry factor previously determined the dose rate two feet off the centerline is 1.2 x 10^8 erg/hr-g(C).

Spectrum

The spectrum emitted by the source is determined for a point six inches from the face of the source on the centerline by using the fractions of Sv arriving at this point, previously determined in minimizing the spectrum distortion. The numbers of photons/sec-cm^2 are placed in energy groups of .45 Mev and are plotted on an arbitrary scale against photon energy (see Fig. 4). The prompt gamma spectrum of U-235 as determined by Gamble (Ref. 3:174) is plotted for comparison.

Heat Generation

The heat generated by the source is determined by assuming that all Beta particles emitted on decay of the isotopes are absorbed and then adding this energy to that absorbed by the source from gamma radiation. Beta energies and yields are Co-60, .306 Mev-1.00, Cs-137, 1.17 Mev-.08, .51 Mev-.92, and Eu-152, 1.46 Mev-.15, 1.00 Mev-.01, .68 Mev-.11 (Ref. 9). Gamma attenuation and absorption coefficients were determined by the use of volume fractions which, in effect, homogenizes the heterogeneous source. These are presented in Tables II and III under the column entitled mixture. Uncollided gamma fluxes calculated using Rockwell's equations (Ref. 10:365) are found to be, for all practical purposes, constant for each energy gamma on the center plane of the disk. These fluxes are used to calculate the absorbed energy from gamma radiation (see appendix F). The heat generated is found to be 49,800 BTU/hr.

Source Temperature

The maximum source temperature is calculated using the heat generation rate (see appendix G). For free convective cooling, assuming no radial heat dissipation, the maximum source temperature at the center is found to be 1000°F above the environmental temperature. This temperature is excessively high since the lowest material melting point in the source is that of aluminum at 1220°F. This temperature would critically limit the environmental temperature but since free convective cooling was assumed, it could be lowered by a method of forced cooling.

Isotope Cost

William W. Monday reports the cost of the three isotopes (Ref. 8:32) as Co-60, \$2.00 per curie; Cs-137, \$1.50 per curie; and Eu-152, \$3.40 per curie. These prices yield a total cost of the isotopes as \$4,805,000.

V. Cell Facilities

There are six important problems to consider in the design of a test cell to accommodate this source. They are source temperature control, source loading and replenishment, source storage, shielding requirements, dosimetry, and cell safety in the event of source damage.

Source Temperature Control

The environmental conditions attainable in any facility utilizing this source are curtailed by the large amount of heat which is generated. The source temperature under free convective cooling is 1000°F above the environmental temperature. Some method must be determined which will remove heat from the source at a high enough rate to lower this temperature appreciably. This heat could be used to raise the environmental temperature of the test cell. This implies that the source is insulated from the environment of the test cell and should cause many problems which would have to be solved.

Source Loading and Replacement

The source can be loaded only by remote means; but since a great deal of experience has been obtained in the remote handling of radioactive materials, no great problem is envisioned. One method which seems quite practical is to use a loading machine which is able to install the small sources into the aluminum disk and a remote position indicator. Techniques would have to be developed and practiced with dummy sources before actual loading could commence.

Replenishing the individual isotopes would consist only of removing one of the small sources and replacing the cylinder of isotope. Each small source consists of 435 curies of Co-60, 635 curies of Cs-137, and 335 curies of Eu-152 or a total of 1405 curies per small source. This relatively small amount of activity should be easy to handle in a test cell. The Cobalt and Europium slugs can be reradiated but the Cesium must be reprocessed or replaced.

Source Storage

The source must be removed from the cell to allow for access to the cell for handling of experiments. Normally this is accomplished by shielding the source from the test cell. The most practical method would seem to be to lower the source into a large pool of water while experiments are being set up in the test cell. The heat generated by the source must of necessity, be dissipated by the water which would require flowing water with associated cooling equipment.

Shielding Requirements

The shielding requirements for a source of this activity are great; but in comparison with some of the power reactors now in operation, they represent only a small problem. Consideration should be given to the necessary access to the cell of personnel and equipment including the required power lines and dose measuring equipment.

Dosimetry

Rather than attempt to measure the radiation field while the test is in progress, periodic plotting of the field in the test cell should be done to define the field. Individual test items will have to be instrumented to determine the absorbed dose.

Cell Safety

The cell facility must be designed first to prevent source damage through failure of the source temperature control mechanism or malfunction of the handling equipment and second to allow repair to be initiated under all conditions which could possibly occur.

VI. Conclusions and Recommendations

The source that has been designed should prove valuable in the testing of nuclear aircraft components under dynamic test conditions. It should be pointed out that the exposure dose rate of this source on a test item is only one order of magnitude less than that attainable in existing small volume gamma irradiation facilities (Ref. 13), and two orders of magnitude less than that attainable in the Air Force Nuclear Engineering Test Facility (Ref. 13:29). A number of factors are responsible for this. The low average energy of the photons caused by duplicating a spectrum which is largely composed of low energy photons reduces the dose rate by at least a factor of two compared to using only Cobalt-60. Limiting the thickness of the source to minimize spectrum distortion also limits the dose rate. The dose rate could also be increased by increasing the specific activities of the isotopes. Increasing the specific activities of Cobalt-60 and Europium-152, which were limited by that of Cesium-137, up to their maximums would ruin the spectrum previously determined, but would increase the dose rate by a factor of four. The source geometry also does not lend itself to high dose rates. Surrounding a point with this source, while seriously curtailing the test cell volume, would increase the dose rate at this point by a factor of three. Therefore the nuclear parameters of spectrum duplication and radiation field representation have limited the dose rate attainable with this source.

The test cell volume corresponding to this source is limited only by the degradation of radiation field which is tolerable. Both sides of this source may be used for test purposes; and although it was only calculated for one side, the dose rates should be comparable on either side. The spectrum on the side opposite the one for which calculation were made should be considerably different though. Large items may be tested dynamically with various faces towards the source to determine their best position for mounting to take advantage of self shielding.

The dose rate may be varied in this source by simply loading less of the small sources. This provides a flexibility which is not available in other facilities. With the proper loading equipment the job of changing the dose rate should not be tedious or difficult. It is felt that the source, through automation, could be loaded and unloaded in less than a day.

The upper environmental temperature of the NETF of 800°F (Ref. 13:29) would not be possible in a facility using this source unless the source was individually cooled. An ambient temperature of 800°F would raise the source temperature under free convective cooling to above the melting point of the aluminum source holder.

Although the cost of the isotopes at present prices, almost five million dollars, is considered prohibitive, it is felt that the purchase of this quantity of source material should lower the price by a factor of ten especially when higher flux reactors are available for irradiation.

It is felt that this source possesses the advantages of unidirectional geometry which allows the test item to be tested in various orientations, ability to irradiate large test item faces, effectiveness in using both sides of the source, and flexibility since the source strength may be varied over a wide range. It is recommended that this source be used in any further effort to design a large-scale environmental gamma irradiation test facility.

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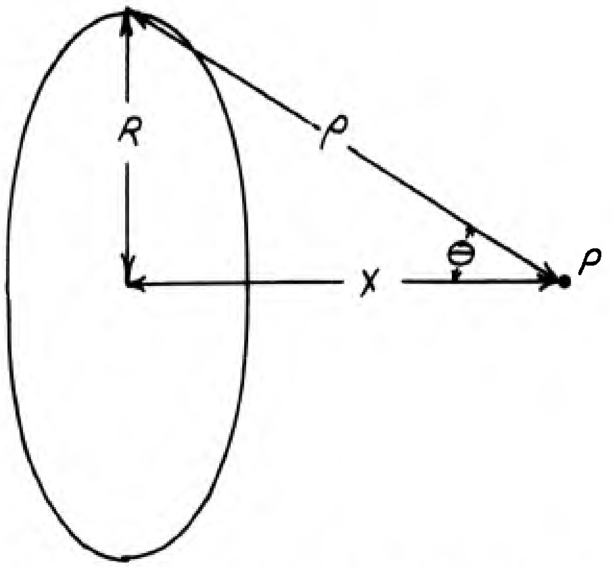
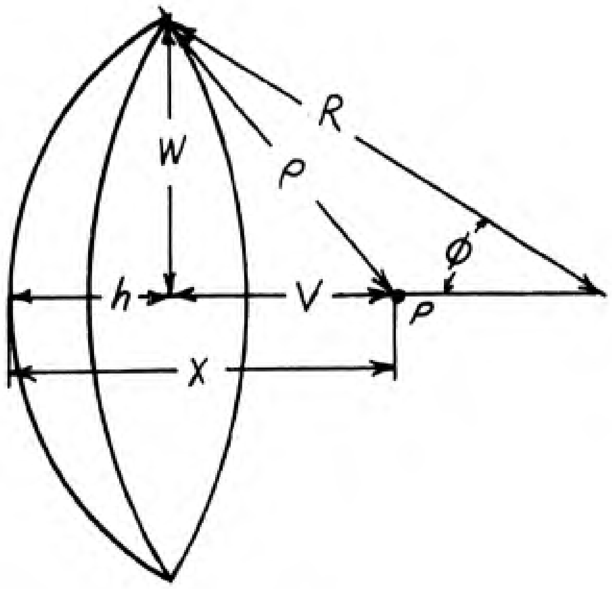


PLANE CIRCULAR SURFACE



SPHERICAL SEGMENT SURFACE

FIG. 5

SURFACE GEOMETRIES

Appendix A

Dose Rate Calculation

The dose rate at a point on the centerline of a plane circular surface any distance away is calculated as follows.

$$dI = \frac{S_A \, dA}{4\pi \rho^2}$$

$$dA = 2\pi R \, dR$$

$$R = X \, TAN\,\theta$$

$$dR = X \, SEC^2\theta \, d\theta$$

$$\rho = X \, SEC\,\theta$$

$$dI = \frac{S_A (X TAN\theta)\, 2\pi X SEC^2\theta \, d\theta}{4\pi X^2 SEC^2\theta}$$

$$dI = \frac{S_A \, TAN\theta \, d\theta}{2}$$

$$I = \frac{S_A}{4} \ln\left(1 + \frac{R^2}{X^2}\right)$$

I = Dose rate (photons/sec-cm^2)

S_A = Source strength (photons/sec-cm^2)

A = Source area (cm^2)

ρ = Distance from element of area to calculation point (cm)

X = Distance from source center to calculation point (cm)

θ = Angle between centerline and line from element of area to calculation point

R = Radius of source (cm)

The dose rate at a point on the centerline of a spherical segment on the inside any distance away is calculated as follows.

$$dI = \frac{S_A \, dA}{4\pi \rho^2}$$

$$dA = 2\pi R^2 SIN\phi \, d\phi$$

$$W = R SIN\phi \qquad V = X - h$$

$$h = R(1 - COS\phi) \qquad \rho = \sqrt{V^2 + W^2}$$

$$dI = \frac{S_A \, 2\pi R^2 SIN\phi \, d\phi}{4\pi \{[X - R(1 - COS\phi)]^2 + (R SIN\phi)^2\}}$$

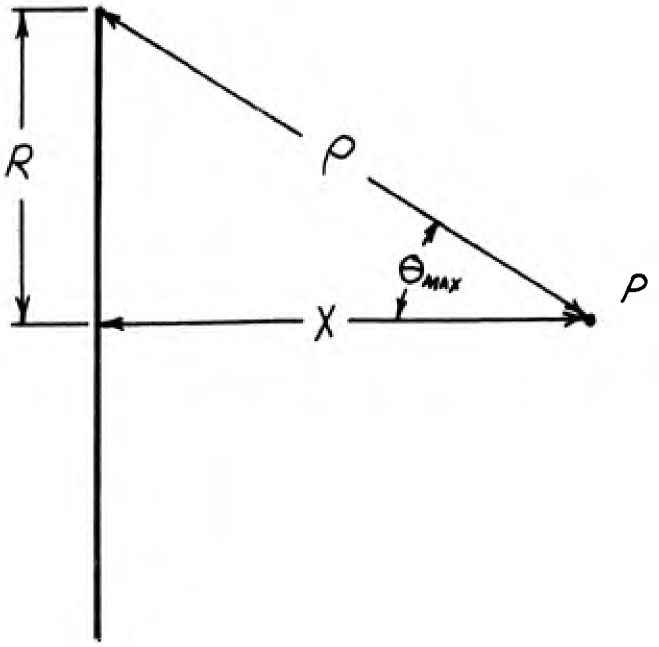
$$I = \frac{S_A}{4\left(1 - \frac{X}{R}\right)} \ln\left[1 - \frac{2R}{X} + \frac{2R^2}{X^2} + \left(\frac{2R}{X} - \frac{2R^2}{X^2}\right) COS\left\{SIN^{-1}\left(\frac{W}{R}\right)\right\}\right]$$

ϕ = Angle between centerline and spherical segment radius

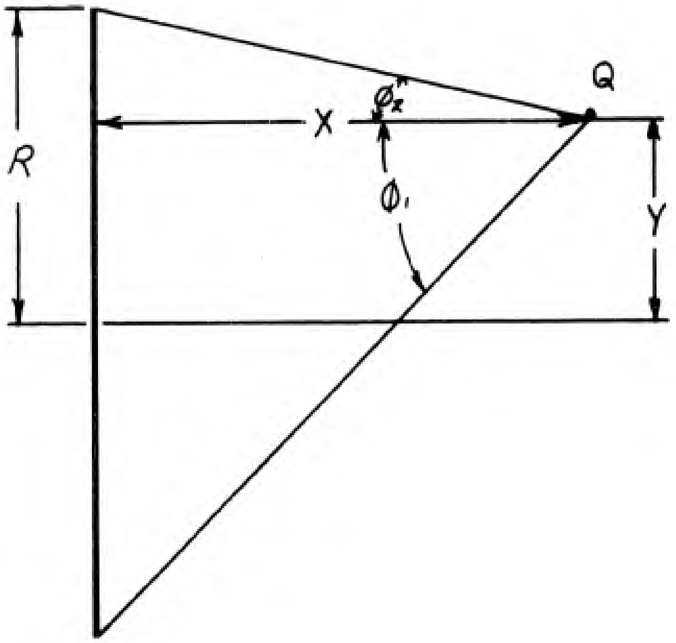
R = Radius of source (cm)

W = One half the chord of spherical segment (cm)

h = Depth of spherical segment (cm)



ON CENTERLINE



OFF CENTERLINE

FIG. 6

LINE GEOMETRY

Appendix B

Geometry Factor Calculation

An approximate method of calculating the ratio of the dose rate at a point off the centerline to that on the centerline both the same distance from the face of a plane circular source is to represent the surface source by a line source whose length is equal to the diameter of the circular source

ON CENTERLINE:

$$dI_P = \frac{S_L\, dL}{4\pi\rho^2}$$

$$\rho = X\,\mathrm{SEC}\,\theta$$

$$L = X\,\mathrm{TAN}\,\theta$$

$$dL = X\,\mathrm{SEC}^2\theta\, d\theta$$

$$dI_P = \frac{S_L\, X\,\mathrm{SEC}^2\theta\, d\theta}{4\pi X^2\,\mathrm{SEC}^2\theta}$$

$$I_P = \frac{S_L}{4\pi X}\, 2\int_0^{\theta_{MAX}} d\theta$$

$$I_P = \frac{S_L}{4\pi X}\, 2\,\theta_{MAX}$$

OFF CENTERLINE:

$$I_Q = \frac{S_L}{4\pi X}\int_{-\phi_1}^{\phi_2} d\phi$$

$$I_Q = \frac{S_L}{4\pi X}\,(\phi_2 + \phi_1)$$

I_P = Dose rate at point on centerline (photons/sec-cm^2)

I_Q = Dose rate at point off centerline (photons/sec-cm^2)

S_L = Source strength (photons/sec-cm)

θ_{MAX} = Angle from centerline point to end of line source

ϕ_2 = Angle from point off centerline to top of line source

ϕ_1 = Angle from point off centerline to bottom of line source

X = Distance from centerline point to center of line source (cm)

R = Radius of circular source (cm)

Y = Distance off centerline of point Q (cm)

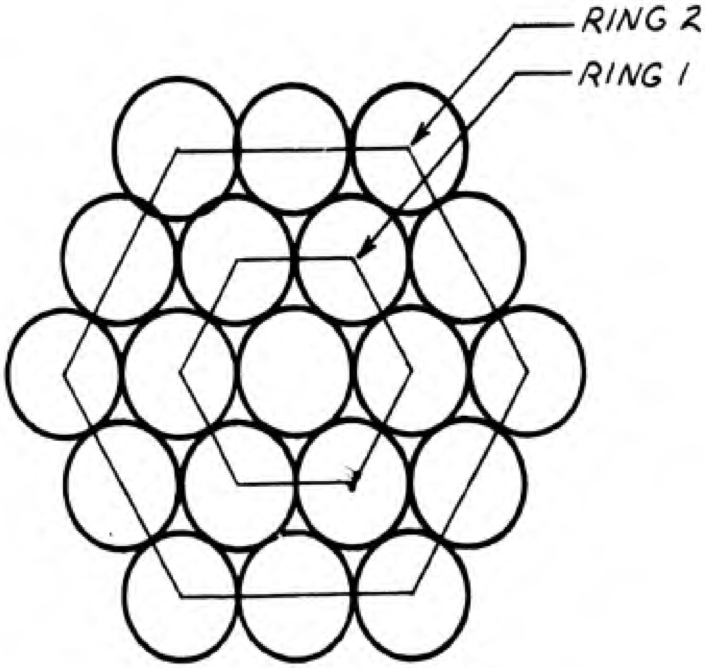
$$\text{GEOMETRY FACTOR } (G) = \frac{I_Q}{I_P}$$

$$G = \frac{\phi_2 + \phi_1}{2\,\theta_{MAX}} = \frac{\mathrm{TAN}^{-1}\left(\frac{R-Y}{X}\right) + \mathrm{TAN}^{-1}\left(\frac{R+Y}{X}\right)}{2\,\mathrm{TAN}^{-1}\left(\frac{R}{X}\right)}$$

Appendix C

Geometry Calculation

The number of circles which will fit into a larger circle can be determined by a combination of analytical and graphical methods. A triangular unit cell of circles best utilizes the area available. Most of the area of the large circle will be contained in the areas of the small circles. To fit into the large circle these unit cells will form a hexagonal pattern.



The number of circles in the hexagon is determined by:

$$N = 1 + \sum_{R=1}^{M} 6R$$

N = Number of circles

R = Ring number

M = Number of hexagonal rings

The radius of the small circle is determined by:

$$r = \frac{R}{2M+1}$$

R	Radius of big circle
r	Radius of small circle
M	Number of hexagonal rings

The hexagon will not completely fill the large circle so a graphical method is used to find the additional circles that fit between the hexagon and the perimeter of the large circle.

Appendix D

Specific Activity Calculation

William W. Monday (Ref 8: 31) determined the activity ratios of the isotopes to be Co/Cs/Eu- 1.00/3.39/4.26. Therefore the activity per unit volume of each isotope can be set equal to each other using his ratios.

$$\left.\frac{\rho\ Sp.A.}{1.00}\right]_{Co} = \left.\frac{\rho\ Sp.A.}{3.39}\right]_{CsCl} = \left.\frac{\rho\ Sp.A.}{4.26}\right]_{Eu_2O_3}$$

ρ = Density of compound (gm/cm^3)

$Sp.A.$ = Specific activity of compound (curies/gm)

Isotope	Sp.A.max. (curies/gm)
Co-60	50.0
Cs-137	22.0
Eu-152	29.5

One of the maximum specific activities will limit the equation. After this is determined the other two specific activities can be calculated.

Appendix E

Exposure Dose Rate Calculation

The exposure dose rate on the center of the test item face is calculated by summing the energy fluxes of the different energy gammas and multiplying by the absorption coefficient for air, then converting this dose rate Mev/sec-cm^3 (air) to ergs/hr-g (C). The absorption coefficient for air is 3.5×10^{-5} cm^{-1} (Ref 11: 197) and is assumed constant from 0.1 Mev. to 2.0 Mev. Utilizing the relationship that 7.07×10^{4} Mev/cm^3 (air) is equal to one roentgen and that one roentgen equals 87.1 ergs/g (C) (Ref 12: 3), the following equation results.

$$D = 1.55 \times 10^{-4} \sum_{i=1}^{7} E_i f_i S_{v_i}$$

$$S_{v_i} = \frac{3.7 \times 10^{10} Y_i A_i}{V_i}$$

D = Dose rate (erg/hr-g (C))

E_i = Energy of ith gamma (Mev.)

f_i = Fraction of Sv at calculation point (cm)

S_{v_i} = Number strength of ith gamma (photons/sec-cm^3) in source

Y_i = Number of ith gammas per disintegration

A_i = Number of curies of isotope emitting ith gamma

V_i = Volume of isotope producing ith gamma (cm^3) (THREE FOOT RADIUS DISK WITH ISOTOPE THICKNESS)

Appendix F

Heat Generation Calculation

The heat generated by the source is composed of both beta and gamma absorption. All betas emitted by the isotopes are assumed to be absorbed. Thus the beta heating is merely the number of betas emitted (the product of the activity and the number of betas per disintegration) multiplied by the energy of the beta and converted to BTU/hr.

The gamma heating is more complicated and is the integrated energy flux multiplied by the absorption coefficient for the material. The uncollided flux on the center plane of the disk is calculated for each energy gamma using Rockwell's equations (Ref 10: 365) and is found to be practically constant for each energy on the center plane. This energy flux is then assumed to be constant throughout the volume of the source, a conservative assumption. These fluxes multiplied by the appropriate mixture absorption coefficient give a lower limit on the amount of energy a particular energy gamma deposits in a unit volume of the source. The sum of these energy depositions multiplied by the source volume gives the lower limit of the gamma heating. The upper limit is determined by using the attenuation coefficient rather than the absorption coefficient. This assumes that each gamma attenuated deposits all its energy. The average of the upper and lower limit was assumed to be the gamma heating in the source. This was necessary to account for build up since the uncollided flux was used throughout the calculation.

Appendix G

Source Temperature Calculation

The maximum source temperature is calculated using the known heat generation rate of 49,800 BTU/hr and assuming that there is no heat rejection through the radial edges. Free convective cooling is also assumed for a vertical disk as the most conservative assumption. Since aluminum constitutes over 50% of the source volume, the thermal conductivity of aluminum is used in the calculation. For a flat plate:

$$T_o = T_s + \frac{q''' L^2}{2k} \quad (\text{REF. } 4{:}658)$$

$$\frac{q}{2} = hA(T_s - T_A)$$

$$h = .3(T_s - T_A)^{.25} \quad (\text{REF. } 7{:}215)$$

$$\frac{qL}{2AL} = .3(T_s - T_A)^{1.25}$$

$$q''' L = .3(T_s - T_A)^{1.25}$$

$$T_s = T_A + \left(\frac{q''' L}{.3}\right)^{.8}$$

$$T_o = T_A + \left(\frac{q''' L}{.3}\right)^{.8} + \frac{q''' L^2}{2k}$$

T_o = Temperature (center)

T_s = Temperature (surface)

T_A = Temperature (air)

q = Heat generation (BTU/hr)

q''' = Heat generation (BTU/hr-ft^3)

A = Area of plate (Ft^3)

L = One half thickness (Ft)

h = Heat transfer coefficient (BTU/hr-ft^2-oF)

k = Thermal conductivity aluminum (BTU/hr-ft-oF)

Vita

John J[redacted] McGee, Jr. was born [redacted], [redacted], the son of John and Catherine McGee. After graduation in 1952 from the [redacted] Institute of Technology with the degree of Bachelor of Mechanical Engineering, he was employed by the Shell Oil Company. He entered the United States Air Force Pilot Training Program as a Second Lieutenant in 1952 receiving his wings in 1953. He completed All Weather Interceptor Training and served in various Fighter Interceptor Squadrons for the next two years. In 1956 he completed the Nuclear Weapons Officer Course and served as a Nuclear Weapons Officer in an Aviation Depot Squadron until assigned to the Institute of Technology.

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This thesis was typed by Mrs. Judy A. Adams.