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RADIATION CHARACTERISTICS AND SHIELDING REQUIREMENTS OF ISOTOPIC POWER SOURCES FOR SPACE MISSIONS

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ABSTRACT

The radiation and shielding characteristics of 200 to 20,000 thermal watt radioisotope power sources of Cs^{137}, Sr^{90}, Pu^{238}, Cm^{244}, Pm^{147}, Ce^{144}, Cm^{242}, and Po^{210} are described. Space applications are stressed, radiation backgrounds in space are given, and possible levels of tolerable radiation from power sources are summarized. Shield weights and unshielded separation distances for a possible 5-year mission life are given.

CONTENTS

CONTENTS (continued)

INTRODUCTION

Isotopic power sources for use in some space missions require shielding or a degree of isolation to prevent excessive radiation doses to personnel handling the source, to prevent radiation damage to instrument systems associated with the mission, and to prevent interference with experimental measurements utilizing radiation detection instruments.

This paper describes the types of radiation that are encountered in isotopic power sources of current interest, methods of evaluating radiation levels and shielding requirements, radiation tolerances that may be applicable, and radiation levels in space. Also, correlated results of radiation and shielding calculations for Cs^{137}, Sr^{90}, Pu^{238}, Cm^{244}, Pm^{147}, Ce^{144}, Cm^{242}, and Po^{210} are presented. Practical applications will be stressed as much as possible, and references will be given to calculational techniques that are presently widely available.

TYPES OF PENETRATING RADIATION FROM ISOTOPIC POWER SOURCES

The types of radiation that must be considered in the design of shields for isotopic sources of present interest are summarized in Fig. 1.

Decay Gamma

Characteristic gamma rays are formed in the decay of most radioisotopes since alpha, beta, and positron decay and electron capture generally leave the product nucleus in an excited state, which subsequently decays to the ground state with the emission of one or more photons. These gamma rays vary widely in energy and abundance from one isotope to another. For example, abundant 1 to 2 Mev gamma rays accompany decay of Co^{60} or Ce^{144}, while there is little, if any, gamma accompanying the decay of Pm^{147}.

Scattered Gamma

Gamma rays interact with matter primarily by three mechanisms: photoelectric effect, pair production, and Compton scattering. In the photoelectric effect an incident photon transfers all of its energy to one of

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PREDOMINANT SOURCES OF PENETRATING RADIATION FROM ISOTOPIC POWER SOURCES

TYPE OF RADIATION	COMMENTS
DECAY GAMMA	CHARACTERISTIC ENERGY SPECTRUM. MAY ACCOMPANY ALPHA OR BETA DECAY.
SCATTERED GAMMA	COMPTON SCATTERING. MOST IMPORTANT WHEN LOW ENERGY GAMMAS INTERACT WITH LARGE MASS OF LIGHT ELEMENTS.
BREMSSTRAHLUNG	CONTINUOUS GAMMA SPECTRUM FROM CHARGED PARTICLES DECELERATED IN ATOMIC ELECTRIC FIELD. MOST ABUNDANT AND ENERGETIC WHEN ENERGETIC BETAS INTERACT WITH HEAVY ELEMENTS.
PROMPT SF GAMMA	CONTINUOUS SPECTRUM (0.1 - 8 MEV) FROM SPONTANEOUS FISSION.
SF-FP DECAY GAMMA	FROM FISSION PRODUCTS FORMED IN SPONTANEOUS FISSION.
SF NEUTRONS	CONTINUOUS SPECTRUM FROM SPONTANEOUS FISSION.
α-n NEUTRONS	SPECTRUM VARIABLE WITH COMPONENTS. MOST IMPORTANT FOR ENERGETIC ALPHAS INTERACTING WITH LIGHT ELEMENTS.
PHOTONEUTRONS	FROM GAMMA-NEUTRON REACTION. REQUIRES GAMMA ENERGY GREATER THAN 7 MEV EXCEPT FOR D, Be, C, Li.
n-2n NEUTRONS	MOST IMPORTANT FOR NEUTRON INTERACTION WITH Be.
SCATTERED NEUTRONS	ELASTIC OR INELASTIC SCATTERING.
INELASTIC GAMMAS	FROM INELASTIC NEUTRON SCATTERING.
NEUTRON CAPTURE GAMMAS	FROM NEUTRON CAPTURE IN MOST ELEMENTS.

Figure 1

the atomic electrons, ejecting it from the atom. It is the dominant process with low-energy photons and elements of high atomic number. In pair production the photon creates a position-electron pair; the position subsequently is annihilated nearby giving two photons of energy 0.51 Mev. It is the dominant effect for high-energy photons and elements of high atomic number. The Compton effect, scattering of photons by electrons, decreases the energy and changes the direction of a photon. The probability of scattering through any angle varies with primary photon energy, the scattering being more forward for high photon energies. This effect causes buildup of low-energy photons in shields and is most important for shielding materials of low atomic number. Compton scattering must be considered in the design of shadow shields for space applications, since photons would be scattered around the shield by components surrounding the isotope package. As a general rule of thumb, shadow shields are not effective for gamma attenuation of more than a factor of 10 because of scattering around the shadow shield.

Bremsstrahlung

Characteristic x-rays are produced following photoelectric interaction of gamma rays, or other processes in which the atomic electrons are disturbed. These x-rays are, in general, very soft and are of negligible consequence in shield design. Continuous x-rays, or bremsstrahlung, are produced when high-energy charged particles are decelerated in the atomic electric field. The order of 1 to 50% of the energy of electrons may be emitted as photons by this process. The gamma energy and differential spectrum increases approximately directly as the product of the electron energy and the average atomic number of the absorber. A few of the photons approach the energy of the incident electron with the majority having lower energy. The energy release and yield of photons in a given energy range for an alpha particle incident on a target is of the order of a million less than for a beta particle of comparable energy. For this reason, bremsstrahlung from alpha particles ordinarily is not significant. For the isotopes of interest, bremsstrahlung is most abundant and energetic when energetic beta particles, such as those accompanying decay of $Sr\text{-}Y^{90}$, interact with heavy elements.

Prompt Gamma From Spontaneous Fission

A continuous spectrum of gamma rays, varying in energy from approximately 0.1 to 8 Mev, is promptly emitted in the process of spontaneous fission. Approximately 7.5 Mev is emitted in this fashion in each fission.

Decay Gamma From Fission Products Formed by Spontaneous Fission

Fission products formed in spontaneous fission ultimately emit approximately 5.5 Mev of total gamma rays per each fission. These gamma rays generally have lower energy than the prompt gammas from spontaneous fission. The fission-product gammas approach a steady state decay rate within a few hours after a spontaneously fissioning nuclide is isolated.

Neutrons From Spontaneous Fission

A continuous spectrum of neutrons varying in energy from approximately 0.1 to 18 Mev are emitted from the spontaneous fission process. An average of 2 to 4 neutrons are emitted per fission, depending on the fissioning isotope.

α-n Neutrons

Neutrons are produced from mixtures of alpha emitters and certain elements, including most of the light elements. The energy spectrum of the neutrons is a continuous distribution extending from very low energies up to a maximum energy that is slightly less than the sum of the alpha energy and the energy liberated in the reaction. The yield of neutrons varies with the target elements and the composition of the mixture. Be produces the most neutrons per alpha. Al, C, and O produce progressively fewer neutrons.

Photoneutrons

A photon can eject a neutron when its energy exceeds the neutron binding energy. A photon of energy greater than 7 Mev is required for all isotopes except deuterium, Be^9, C^{14}, and Li^6. Cross sections for the reaction are of the order of 1 mb and the neutrons generally have energy of 0.1 to 1 Mev.

n-2n Neutrons

If the bombarding neutron has sufficient energy, it is possible for the compound nucleus to emit two neutrons. The threshold energy is relatively high for all isotopes except deuterium and Be^9. Thus, Be, which may be used as a heat shield in space, may serve to multiply the neutron flux though, usually, only to a slight degree.

Scattered Neutrons

Most materials elastically and inelastically scatter neutrons through relatively large angles. In general, neutrons scatter more readily than gamma rays. Scattering at large angles is most predominant with heavier elements.

Inelastic Gammas

Inelastic scattering of neutrons, the predominant process of slowing down in the heavier elements, is accompanied by the emission of photons. The total photon energy is less than the incident neutron energy. Ordinarily the energy absorbed from the neutron is emitted as several photons.

Neutron Capture Gammas

Essentially all isotopes, with the exception of Li^6 and B^{10}, emit energetic gamma rays upon the capture of a neutron. The gamma source is especially important for those elements with high neutron capture cross sections.

METHODS OF CALCULATION AND SOURCES OF DATA

While it is not within the scope of this paper to present a detailed discussion of methods of performing shielding calculations, some of the applicable methods are outlined and references to sources of data and techniques are given (Fig. 2).

Questions about the techniques described should be directed to the Radiation Shielding Information Center (RSIC), which is located at ORNL.

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METHODS OF CALCULATION AND SOURCES OF DATA

TYPE OF CALCULATION	REFERENCES
FP GAMMA SOURCES DECAY GAMMA SOURCES	(DATA) GOLDSTEIN, (PHOEBE CODE) RSIC (FROM SF) MND-P-2801. STROMINGER, REVS. MOD. PHYSICS, 30, 585 (1958).
BREMSSTRAHLUNG	(DATA) PRICE, HORTON, AND SPINNEY, HW-69533, MND-P-2529. (OGRE CODE) RSIC, (M-1 CODE) MND-P-2726.
GAMMA ATTENUATION	(DATA) GOLDSTEIN, (SDC CODE) RSIC, (OGRE CODE) RSIC, (M-1 CODE) MND-P-2726.
SCATTERED GAMMA	(DATA) STEPHENSON, (OGRE CODE) RSIC.
SF NEUTRON AND GAMMA SOURCES	(DATA) UCRL-9036.
ALPHA NEUTRON SOURCES	(DATA) MND-P-2801.
NEUTRON ATTENUATION	(DATA) GOLDSTEIN, (RENUPAK, NIOBE CODES) RSIC.
NEUTRON CAPTURE AND INELASTIC GAMMA	(DATA) GOLDSTEIN, MND-P-2801. (DSN CODE) LAMS-2346, (RENUPAK, NIOBE) RSIC.
PHOTONEUTRONS	(DATA) GOLDSTEIN.
n-2n	(DATA) PRICE, HORTON, AND SPINNEY. (DSN CODE) LAMS-2346.

Figure 2

This center compiles, evaluates, and disseminates information on all facets of radiation shielding.

Fission Product Gamma Sources

Data on the gamma spectrum from U^{235} fission products as a function of irradiation and cooling time are given by Goldstein in his book, Fundamental Aspects of Reactor Shielding. The yield of fission products from many other actinide elements is tabulated in UCRL-9036. The ORNL PHOEBE code is used to calculate the properties of fission products given the rate and time of fission and cooling time. A. M. Spamer in MND-P-2801 treats the fission products present in conjunction with a spontaneously fissioning source.

Decay Gamma Sources

Decay schemes of most radioisotopes of interest are summarized by Strominger et al. in Volume 30 of Revs. Mod. Physics and B. S. Dzhelepov and L. K. Peker in Decay Schemes of Radioactive Nuclei.

Bremsstrahlung

Good references for methods of bremsstrahlung calculations are Radiation Shielding by Price, Horton, and Spinney, and HW-69533. Bremsstrahlung from Sr^{90} is discussed in MND-P-2529. Precise Monte Carlo gamma transport codes for calculating bremsstrahlung and shielding requirements with an IBM-7090 computer include the ORNL OGRE code and the Martin M-1 code. A wide variety of source and shield configurations are possible with OGRE. M-1 utilizes a cylindrical source.

Gamma Attenuation

Gamma attenuation data including attenuation coefficients and buildup factors are included in Goldstein's book. Similar data, including shielding equations, are given in the Handbook of Nuclear Engineering. Very rapid gamma shielding calculations for a variety of source geometries and shields may be made with the SDC IBM-7090 code. SDC utilizes up to 12 source gamma energy groups. OGRE and M-1 may be used for more precise, but more time-consuming, calculation.

Scattered Gamma

Data and methods of hand calculation of scattered gamma radiation are given by Stephenson in his book, Introduction to Nuclear Engineering. More precise calculations may be done with the OGRE code.

Spontaneous Fission Neutron and Gamma Sources

Yields and spectra of prompt neutrons and gammas from spontaneous fission are given by Hyde in UCRL-9036.

Alpha-Neutron Sources

Experimental data on α-n sources and methods of extension of these data are given in MND-P-2801.

Neutron Attenuation

The calculation of dose and spectra from fast neutrons in thick shields has become precise only in the last few years with the development of special transport codes for handling very fast neutrons. While the reactor transport and diffusion codes, which have been in use for many years, may adequately calculate the behavior of intermediate- to low-energy neutrons, they are not set up to handle the high-energy penetrating neutrons that are important in thick neutron shields.

The two new transport codes are Renupak and NIOBE. They are both coded for an IBM-7090 and calculate neutron current, flux, spectrum, and dose rate as a function of shield thickness. Correlated data from calculations with these codes for some neutron shields are presented by Goldstein. The Radiation Shielding Information Center can furnish references to other calculations including those for LiH and concretes.

Neutron Capture and Inelastic Gamma

Knowledge of the neutron flux and spectrum in a shield is required to calculate inelastic and capture gammas. Approximate answers for the ordinarily small sources and shields used for space applications may be obtained by use of the DSN reactor transport code or other reactor codes. Renupak, NIOBE, and TRANSFORM (a combination of Renupak and MODRIC, a reactor diffusion code) are available for more precise calculation. Goldstein, MND-P-2801, and Price, Horton, and Spinney present data for calculating sources of capture and inelastic gamma; but, in general, it is not practical to perform the calculations by hand, especially for those cases in which fast and intermediate neutrons are important.

Photoneutrons

Data for photoneutron calculations are given in the books of Goldstein and Price, Horton, and Spinney.

n-2n Reactions

Price, Horton, and Spinney give data for n-2n calculations. The DSN code calculates n-2n reactions.

The α-n emission rate and maximum neutron energy of mixtures of Po^{210}, Pu^{238}, Cm^{242}, and Cm^{244} with various light elements are shown in Fig. 3. It is conservative to use the maximum neutron energy to calculate shielding and radiation levels if the spectrum is not known. Approximately 5×10^{6} neutrons/sec-α curie with neutron energy up to 11 Mev are emitted from mixtures of Be and alpha emitters. The yields and energy increase with alpha energy. Yields and maximum neutron energies are lower for Al, C, and O.

ALLOWABLE RADIATION LEVELS

Typical values of the allowable radiation levels that would determine the required shield or separation distance for isotopic sources are summarized in Fig. 4.

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ALPHA–NEUTRON EMISSION RATE FROM TYPICAL MIXTURES OF ALPHA EMITTING RADIOISOTOPES AND LIGHT ELEMENTS

TARGET ELEMENT	RADIOISOTOPE			
	Po^{210}	Pu^{238}	Cm^{242}	Cm^{244}
Be (n/sec/a curie)	3×10^6	4×10^6	7×10^6	6×10^6
MAX. NEUT. ENERGY (mev)	10.8	10.9	11.5	11.2
C (n/sec/a curie)	4×10^3	5×10^3	1×10^4	8×10^3
MAX. NEUT. ENERGY (mev)	7.2	7.4	8.0	7.6
O (n/sec/a curie)	2.4×10^3	3×10^3	6×10^3	5×10^3
MAX. NEUT. ENERGY (mev)	5.6	5.8	6.3	6.1
Al (n/sec/a curie)	3×10^4	4×10^4	7×10^4	5×10^4
MAX. NEUT. ENERGY (mev)	2.3	2.5	3.1	2.7
REFERENCE: MND-P-2801				

Figure 3.

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MAXIMUM ALLOWABLE RADIATION DOSES AND DOSE RATES

	TYPE OF RADIATION		
	β, γ	FAST NEUTRONS	SOLAR PROTONS
MAN, TOTAL BODY HANDS, ARMS	3 RAD/13 WEEKS 25 RAD/13 WEEKS	0.3 RAD/13 WEEKS 2.5 RAD/13 WEEKS	
TRANSISTORIZED INSTRUMENT SYSTEMS	10^7 RAD	10^4 RAD $\sim 10^{12}$ N/cm^2	$\sim 10^4$ RAD $\sim 10^{11}$ P/cm^2
NUCLEAR INSTRUMENTATION	0.00001 TO 1 RAD/HR	0.00001 TO 1 RAD/HR	

Figure 4.

Man

The National Committee on Radiation Protection has established maximum permissible radiation dose rates for occupational personnel exposure. It is assumed that these dose rates would apply to personnel working around isotopic sources and preparing them for a launch. The recommended maximum allowable doses, integrated over a 13-week period, without reference to instantaneous dose rate, are 3 rad of gamma and 0.3 rad of fast neutrons for whole body exposure and 25 rad of gamma and 2.5 rad of neutrons for exposure of hands and arms.

Transistorized Instruments Systems

Data on the effects of radiation on instrument systems are available in reports of the REIC series from the BMI Radiation Effects Information Center and TID-7652, the proceedings of a recent symposium on Protection Against Radiation Hazards in Space. Allowable radiation doses vary widely with the type of radiation and type of instrument system. The doses in Fig. 4, 10^7 rad of gamma, 10^4 rad of fast neutrons, and 10^4 rad of solar protons, were chosen on the basis that they probably would not cause significant radiation damage in typical transistorized instrument systems. Damage has been observed for doses an order of magnitude greater, and there is significant damage at two orders of magnitude greater dose.

Nuclear Instrumentation

Nuclear instrumentation (including scintillation counters, GM counters, and ionization chambers) is used to measure the radiation background in space, on or near the moon or planets, or physical properties such as density and composition. Thus, power sources emitting radiation of type and energy similar to that being measured must be shielded or maintained remote from the instrumentation to prevent interference with the measurement. For some measurements it may be desired that the radiation level at the instrument from the power source be as low as 0.01 mrad/hr.

SPACE RADIATION LEVELS

The primary types of penetrating radiation in space are from trapped electrons and protons in the Van Allen belts, solar-flare protons, and galactic cosmic rays (Fig. 5). These are described in TID-7652.

Outer Van Allen Belt

The radiation environment in the outer Van Allen belt is dominated by electrons with energy predominantly less than 1 Mev. When there is little shielding, the electron dose rate may be greater than 1000 rad/hr; but the electron dose rate is reduced to negligible levels by a shield equivalent to 4 cm of Al or 10 g/cm^2. The dose rate from bremsstrahlung even through a 10 g/cm^2 shield is 1-30 rad/hr.

Inner Van Allen Belt

Protons with energy from 10-100 Mev predominate in the inner Van Allen belt. Dose rates from the protons and secondaries may vary from 10 to 100 rad/hr through a thin shield, with approximately an order of magnitude less dose rate through a shield of 10 g/cm^2.

Solar Flares

Solar flares occur sporadically and have relatively short duration. The most significant source of radiation from these flares is protons ranging in energy from approximately 50 to 500 Mev. Dose rates may be of the order of 10 to 100 rad/hr through a thin shield and 1 to 10 rad/hr through 10 g/cm^2. The largest flares would be expected to cause total doses of approximately 400 rads through a thin shield and approximately 40 rads through 10 g/cm^2. In general, through a few g/cm^2 of shield, the total dose from flares integrated over a period of years is less than that from galactic cosmic rays.

Galactic Cosmic Rays

Galactic cosmic radiation, radiation from outside our solar system, is composed primarily of protons of energy considerably greater than 100 Mev.

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SPACE RADIATION LEVELS (RAD/HR)

	SHIELD THICKNESS	
	0	10g/cm^2
VAN ALLEN OUTER BELT, ELECTRONS	10^3-10^5	~ 0
BREMSSTRAHLUNG	1-100	1-30
VAN ALLEN INNER BELT, PROTONS	10-100	1-10
SOLAR FLARE PROTONS (TYPICAL)	10-100	1-10
GALACTIC COSMIC RAYS	~ 10^{-3}	~ 10^{-3}

Figure 5.

It forms a relatively constant background of 10^{-3} to 10^{-4} rad/hr in interplanetary space and is so penetrating that reasonable shielding has no effect on the intensity of the radiation.

During periods of little solar activity, the radiation level on the moon would be primarily that from galactic cosmic rays and secondary neutrons and protons and would be expected to be approximately 10^{-3} rad/hr.

RADIATION LEVELS AND SHIELDING REQUIREMENTS OF ISOTOPES OF CURRENT INTEREST

Calculations are being made of the radiation level and shielding requirements of the eight isotopes that are currently envisioned for space applications. Preliminary results of these calculations will be presented.

Assumed Properties of Isotopic Power Sources

Some of the properties of the isotopic power sources that are assumed in the ORNL calculations are given in Fig. 6. The isotopes are arranged with respect to decreasing half life. It is assumed that Cs^{137} is in the form of glass; Sr^{90}, Pu^{238}, Cm^{242}, Pm^{147}, Ce^{144}, and Cm^{242} are assumed to be in the form of oxides; and Po^{210} is assumed to be in the form of polonium metal.

Power densities, in watts/cc, are assumed to be 0.21 for Cs^{137}, 1.4 for Sr^{90}, 3.5 for Pu^{238}, 26.4 for Cm^{244}, 2.0 for Pm^{147}, 20 for Ce^{144}, and 75 for Cm^{242} and Po^{210}. For Cm^{242} and Po^{210}, which rapidly generate helium from alpha decay, it is assumed that the fuel is in the form of a pellet at a power density of 150 watts/cc and that there is an equal volume of void space for gas collection.

Radiation from Lightly Shielded Sources

The radiation dose rates (rad/hr) at 50 cm from lightly shielded, right cylinder sources, with length equal to diameter, are summarized in Fig. 7. Levels of gamma and neutron radiation are given for sources of 200, 2000, and 20,000 thermal watts. The sources are unshielded except

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ASSUMED FORM AND POWER DENSITY OF ISOTOPIC POWER SOURCES

ISOTOPE	HALF LIFE	FORM	POWER DENSITY (WATTS/cc)
Cs^{137}	30y	GLASS	0.21
Sr^{90}	28y	SrO	1.4
Pu^{238}	89.6y	PuO_2	3.5
Cm^{244}	18.4y	Cm_2O_3	26.4
Pm^{147}	2.52y	Pm_2O_3	2.0
Ce^{144}	290d	CeO_2	20
Cm^{242}	162.5d	Cm_2O_3	75[a]
Po^{210}	138.4d	Po METAL	75[a]

[a] 150 WATTS/cc IN PELLET WITH EQUAL VOLUME OF VOID SPACE.

Figure 6

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GAMMA AND NEUTRON DOSE RATE (RAD/HR) AT 50 cm FROM UNSHIELDED[a] EQUILATERAL RIGHT CYLINDER ISOTOPIC POWER SOURCES

ISOTOPE	SOURCE SIZE (THERMAL WATTS)					
	200		2000		20,000	
	GAMMA	NEUTRONS	GAMMA	NEUTRONS	GAMMA	NEUTRONS
Cs^{137}	3900	-	18,000	-	84,000	-
Sr^{90}	130	-	660	-	3400	-
Pu^{238}	0.005	0.0083	0.015	0.076	0.030	0.63
Cm^{244}	0.11	0.24	0.73	2.3	3.3	21
Pm^{147}	0.033	-	0.13	-	0.59	-
Ce^{144}	770	-	5700	-	26,000	-
Cm^{242}	0.022	0.020	0.18	0.19	1.2	1.8
Po^{210}	0.044	0.0003	0.40	0.0028	3.2	0.026

[a] EQUIVALENT OF 1 cm Pb ASSUMED FOR ATTENUATION OF VERY SOFT GAMMAS.

Figure 7

that the equivalent of 1 cm Pb is assumed for attenuation of very soft gamma and x-rays.

The gamma attenuation calculations, including self-attenuation in the source, were made using the SDC code. The source strengths of gammas and neutrons were calculated by hand essentially using the methods described in the references that have been presented.

The penetrating radiation from Cs^{137} is predominantly from gammas accompanying beta decay. Because of the relatively low energy, the effect of self-shielding as the source becomes larger is significant.

Penetrating radiation from Sr^{90} is predominately from bremsstrahlung caused by the high energy beta rays from the Y^{90} daughter.

Gammas from Pu^{238} include those from decay, fission products, and spontaneous fission. Most of the neutrons are generated by α-n reactions with oxygen, but approximately 5% come from spontaneous fission. These calculations do not include gammas from neutron reactions in the shield.

The gammas from Cm^{244} also are those accompanying alpha decay, from fission products, and from spontaneous fission. Most of the neutrons are from spontaneous fission but approximately 4% originate in α-n reactions with oxygen.

Gammas from Pm^{147} are low in energy and abundance. They include bremsstrahlung from the low-energy betas and gammas from Pm^{146}.

Penetrating radiation from Ce^{144} is predominantly that from the Pr^{144} daughter. This includes bremsstrahlung from energetic beta decay and gammas accompanying beta decay with energy up to 2.2 Mev.

Gammas from Cm^{242} are those from decay, fission products, and spontaneous fission. Neutrons are emitted at approximately equal rates from spontaneous fission and α-n reactions with oxygen.

Gammas with energy of 0.8 Mev accompany the alpha decay of Po^{210}. The neutrons, approximately 100 neutrons/sec/α curie, are from α-n reactions with the oxygen impurity in the polonium metal.

Penetrating radiation dose rates at 50 cm from lightly shielded 2000-watt sources of Cs^{137}, Ce^{144}, and Sr^{90} are of the order of 1000 to

10,000 rad/hr and are of the order of 1 rad/hr for Cm^{244}, Cm^{242}, Po^{210}, Pm^{147}, and Pu^{238}.

The Effect of Uranium Shield Thickness

The effect of thickness of uranium on the primary gamma dose rate at 50 cm from 2000 thermal watt isotopic power sources is shown in Fig. 8. The gammas from Cs^{137} are attenuated readily, while the harder gammas from Ce^{144} or Sr^{90} are attenuated to a lesser extent. The gamma from Pm^{147} is not shown, since it falls below the minimum value of the ordinate. While the gamma radiation from Cm^{244}, Cm^{242}, and Po^{210} is comparable through a thin shield, the gammas from Cm^{244} and Cm^{242} are more penetrating than those of Po^{210}. The dose rate from shielded Pu^{238} is very low, and the gammas are attenuated readily.

In general, a few cm of uranium shield will have very little effect on the neutron dose rate at 50 cm from the source.

The Effect of LiH Shield Thickness

The effect of LiH shield thickness on the neutron dose rate at 50 cm from 2000-watt sources (Fig. 9) was calculated using attenuation data for a fission source and theoretical adjustments of the water data from Goldstein's book for α-n neutrons. For 40 cm of LiH shield thickness, the neutron dose rate at 50 cm decreases by over two orders of magnitude for the predominantly spontaneous fission neutrons from Cm^{244} but only about one order of magnitude from the oxygen α-n neutrons from Po^{210}.

Lithium hydride is probably the best neutron shield material for space applications. A single collision with a hydrogen atom reduces fast neutrons to near thermal energy; the Li^6 content of natural Li serves to suppress capture gamma rays. The density of LiH is 0.82 g/cc at 20°C, and the melting point is 680°C.

Shield Weight for Five-Year Mission Life

Estimates of shield weight for a 5-year mission life for the isotopic sources adaptable to such a mission are shown in Fig. 10. It is assumed

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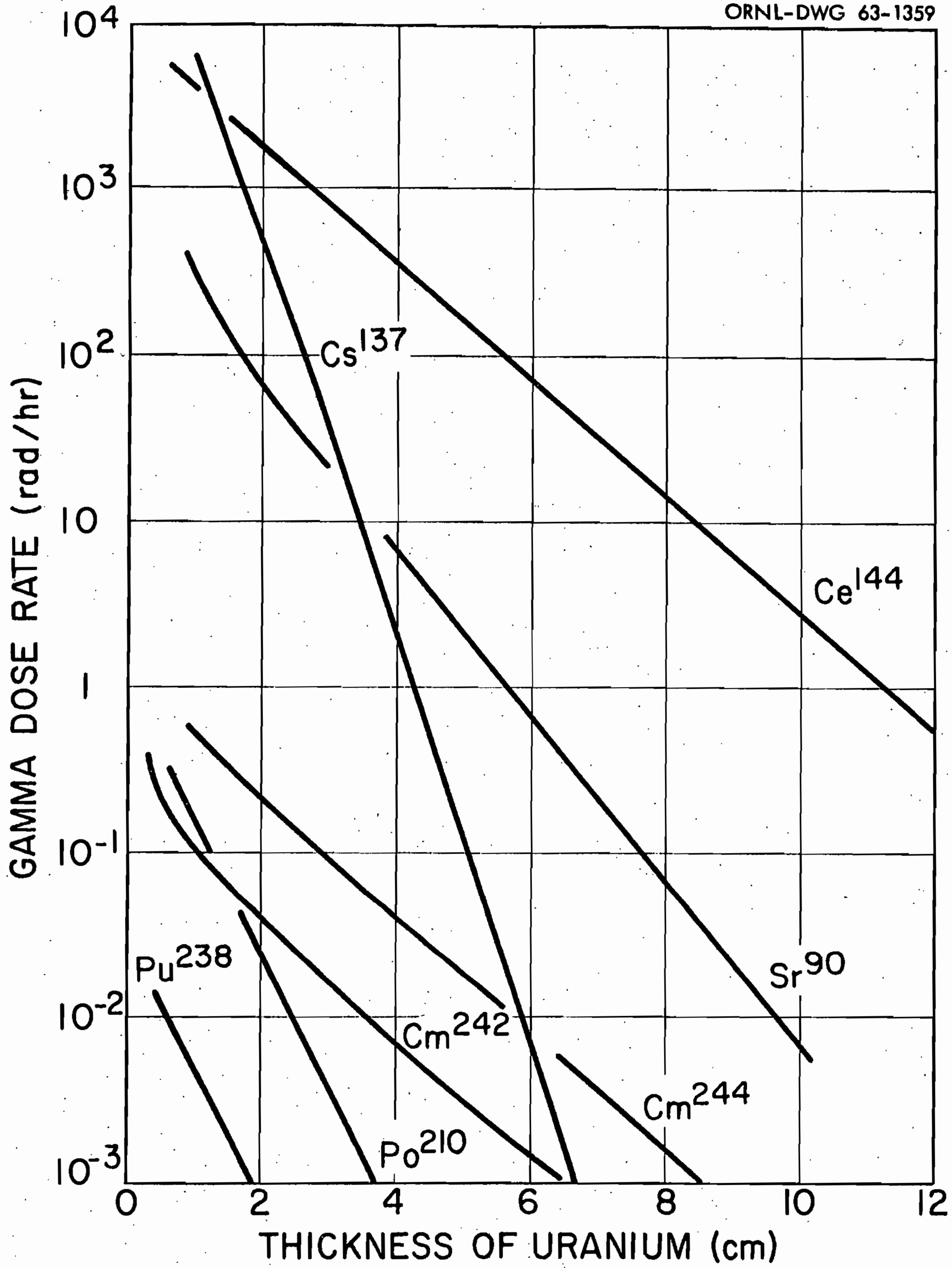

THE EFFECT OF THICKNESS OF U ON THE PRIMARY GAMMA DOSE RATE AT 50 CM FROM 2000 THERMAL WATT ISOTOPIC POWER SOURCES

Figure 8

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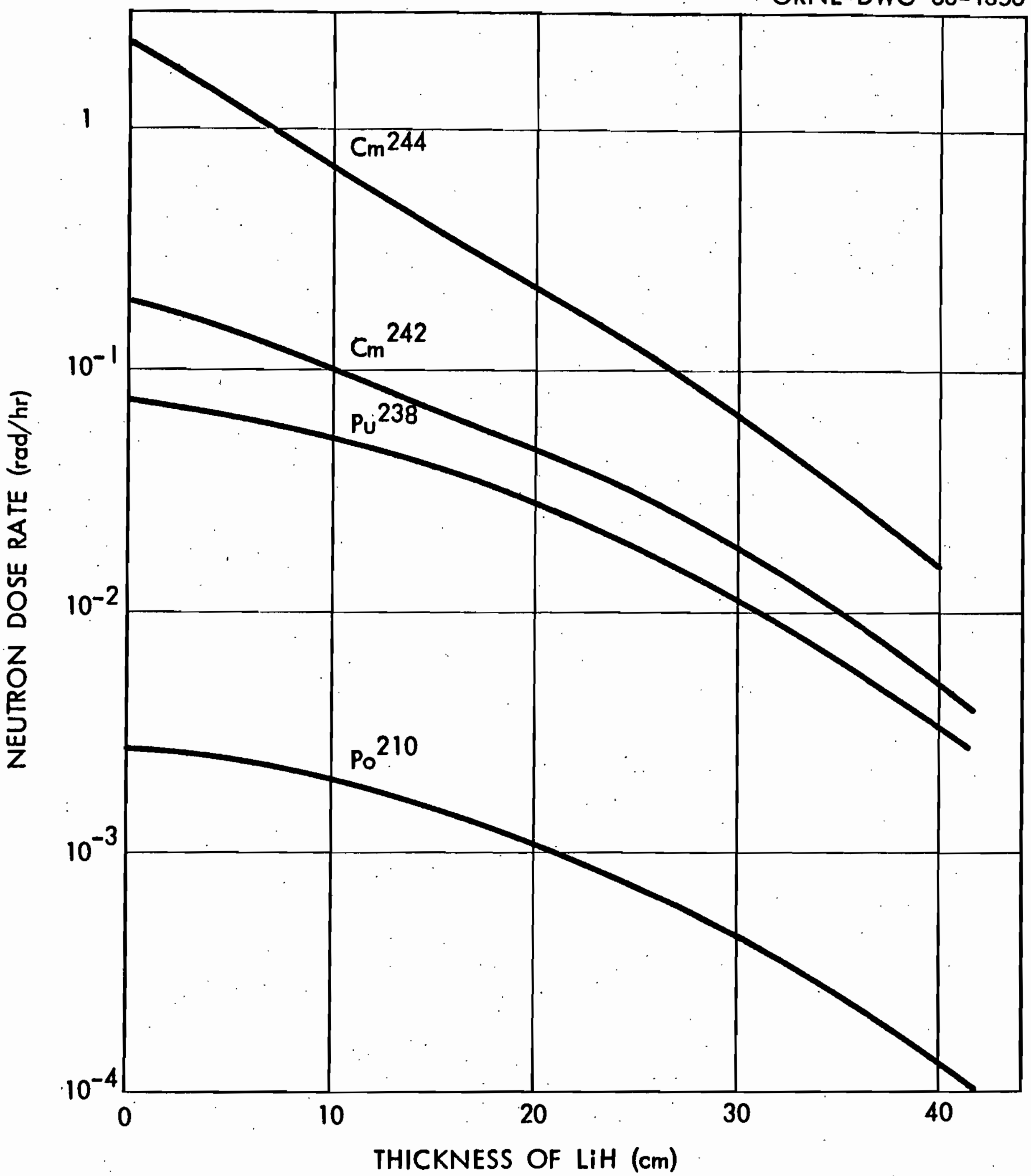
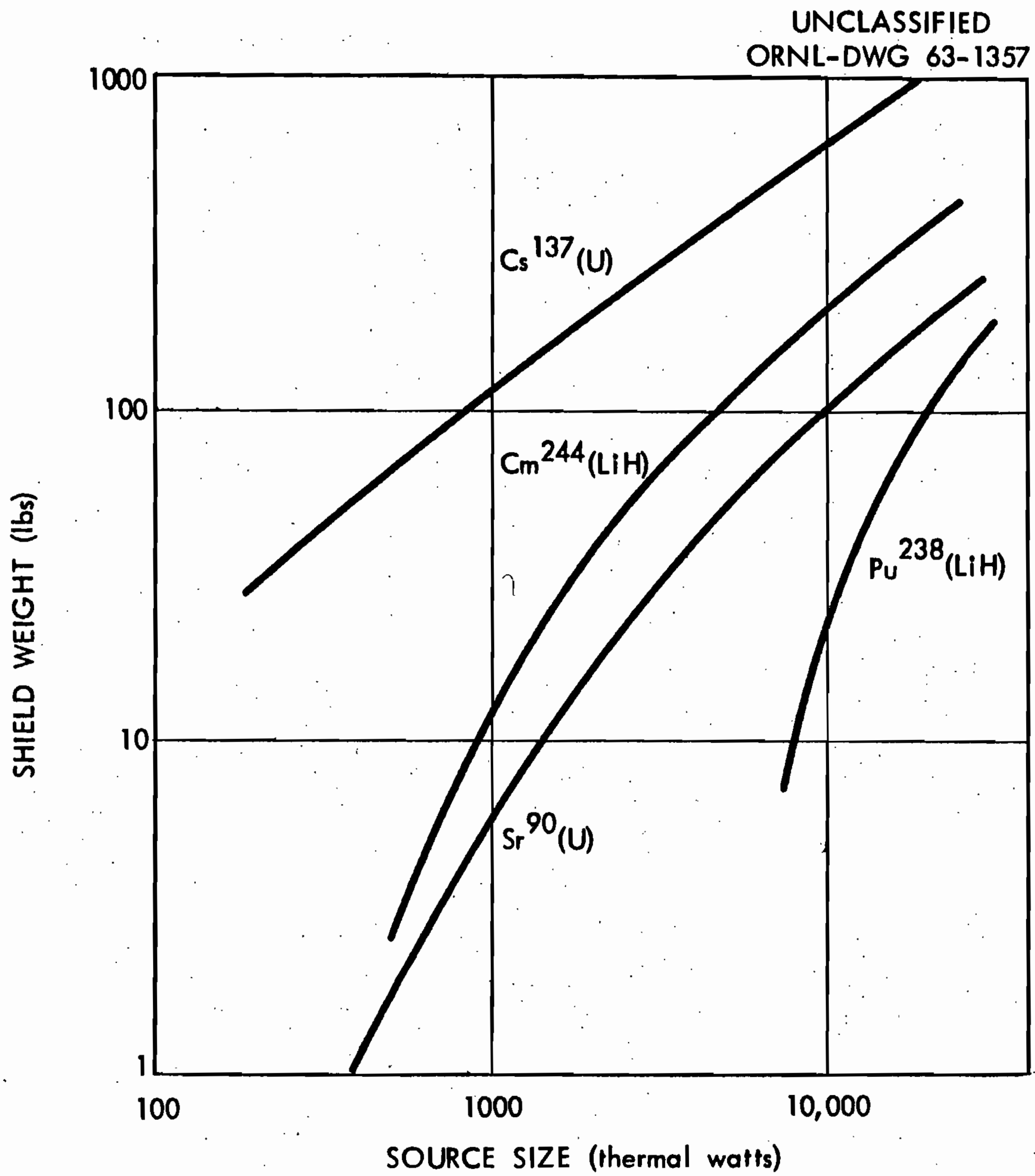


THE EFFECT OF THICKNESS OF LiH ON THE NEUTRON DOSE RATE AT 50 cm FROM 2000 THERMAL WATT ISOTOPIC POWER SOURCES.

Figure 9



THE EFFECT OF SOURCE SIZE ON LiH-U SHIELD WEIGHT FOR 5 YR MISSION LIFE. SOURCE–RECEPTOR SEPARATION DISTANCE 50 cm. ALLOWABLE DOSE AT RECEPTOR 10^4 RAD (NEUTRONS) AND 10^7 RAD (GAMMA).

Figure 10

that the sensitive elements of a transistorized instrument system are located 50 cm from the edge of the source and the allowable dose from neutrons and gammas is 10^4 and 10^7 rad, respectively. The sources are equilateral right cylinders. One third of the source is covered by a shield of such thickness as to cause the desired dose, and the remaining 2/3 of the source is covered with a shield of thickness such as to cause 10 times the desired dose. This technique allows approximate determination of the weight of a contoured shield assuming that the sensitive instruments would be intercepted by only a small fraction of the total solid angle from the source.

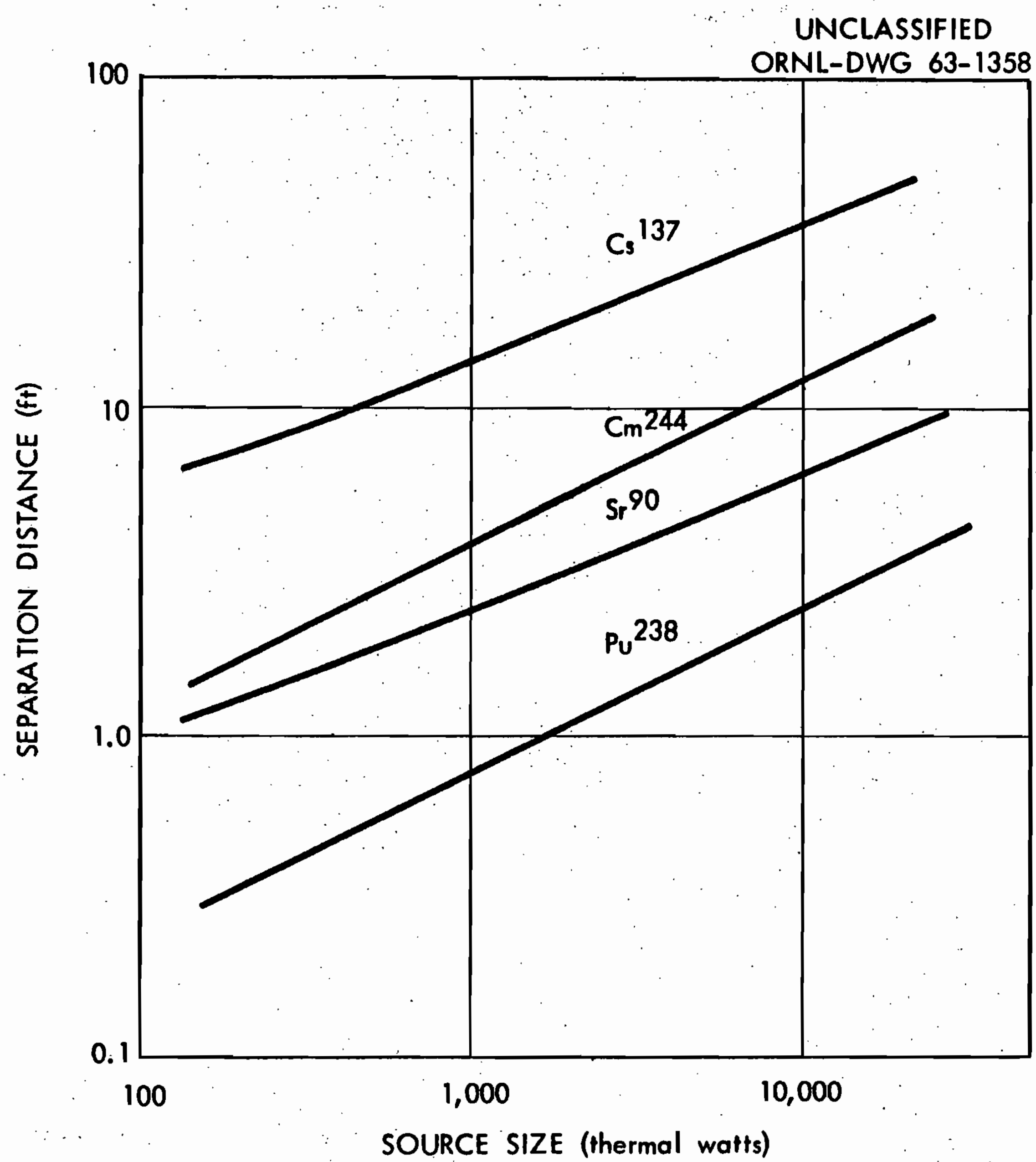
Shield weights are largest for Cs^{137} and are progressively lower for Cm^{244}, Sr^{90}, and Pu^{238}.

Separation Distance for Five-Year Mission Life

A very effective method for decreasing the radiation dose rate from radioisotope sources is to provide a minimum shield for soft gamma radiation and to separate the sensitive instrumentation and the power source by placing one or the other at the end of a boom. A boom can have low weight; and, generally, attaining the required length is within established technology.

Perhaps the most serious disadvantage of this technique is that of radiation exposure to personnel from unshielded sources during the period of preparation for launch. This exposure probably can be controlled within allowable levels by use of portable shadow shields and careful programming of operations.

The effect of source size on separation distance for a 5-year mission life is shown in Fig. 11. A shield equivalent to 1 cm of lead is assumed for attenuation of very soft gammas, and the allowable radiation doses are taken to be 10^4 rad of neutrons and 10^7 rad of gamma. The separation distances for 2000 thermal watt sources are 18 ft for Cs^{137}, 5 ft for Cm^{244}, 3 ft for Sr^{90}, and 1 ft for Pu^{238}.



THE EFFECT OF SOURCE SIZE ON SOURCE–RECEPTOR SEPARATION DISTANCE FOR 5 YR MISSION LIFE. SHIELD EQUIVALENT TO 1 Cm Pb. ALLOWABLE DOSE AT RECEPTOR 10^4 RAD (NEUTRONS) AND 10^7 RAD (GAMMA).

Figure 11

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