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BETA-GAMMA DOSE RATES FROM U^{232} IN U^{233}

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INTRODUCTION

The gamma and beta dose rates encountered with U^{233} are created by the daughters of U^{232} which is invariably present as an impurity.

Large scale production of U^{233} with low concentrations of U^{232} (less than 10 ppm) will create a need for a simple method of predicting dose rates to which personnel could be exposed. This report defines in detail the source of the dose rate and describes a method by which they may be predicted.

It would be impossible to predict all significant dose rates because of the variety of shapes, sizes, and chemical compositions that U^{233} can assume during production and use. However, the method is based on a fully developed set of dose rates for a single finite mass of U^{233} that can be easily adjusted to an actual situation. Since the exposure received by personnel working with Pu^{239*} is familiar to many who may be concerned with U^{233} exposures, the Pu^{239*} dose rates for a comparable source are included to be used as a comparison for assistance in predicting total personnel exposures.

In contrast to Pu^{239*} , the other items of radiological concern are far less significant for U^{233} of low U^{232} concentration. Neutron dose rates do not become significant. Its hazard value⁽¹⁾ for contamination control and for internal emitters falls in the intermediate group whereas Pu^{239} is in the very hazardous group.

Information calculated from Arnold's⁽²⁾ work indicated that it would not be necessary to develop fully the neutron dose rates. The spontaneous fission neutron production in U^{233} contaminated with as much as 100 ppm U^{232} is insignificant compared to Pu^{239*} . In the presence of most light elements, the (α, n) reaction neutrons from U^{233} are less than 10% of the neutrons from Pu^{239*} . U^{232} contamination would have to exceed 10 ppm and its age would have to be several years before it and its daughters could

* Isotopic composition: 93.5% Pu^{239} , 6% Pu^{240} , and 0.5% Pu^{241} .

develop enough alpha activity to cause (α, n) neutrons equal to U^{233} . Under these conditions, the gamma dose rates would be intolerably high before the neutron dose rate is high enough to be significant. Only if the source is heavily shielded for gamma radiation are the neutrons likely to become significant.

SUMMARY

The significant external dose rate from U^{233} comes from the daughters of the U^{232} that is present as an impurity. For this reason, the dose rates increase with time as the daughter activity increases. The rate of increase is governed by the 1.9-year half-life of Th^{228} . The radiation consists primarily of very penetrating gamma (2.6 Mev) from Tl^{208} and energetic beta from both Bi^{212} (2.26 Mev) and Tl^{208} (1.8 Mev). At 1 ppm U^{232} , the dose rate starts well below that of Pu^{239*} but is equal to it within a month or two and reaches a level an order of magnitude higher within a year. The dose rates will be in direct proportion to the amount of U^{232} present, increased amounts of which will significantly reduce the age at which U^{233} can be handled at a reasonable dose rate. For example, at 10 ppm U^{232} , the U^{233} dose rate exceeds that of Pu^{239*} in 10 days and is 2 orders of magnitude higher in a year.

DISCUSSION OF CALCULATIONS

The calculations in this report are based on a thin disc of U^{233} metal whose physical characteristics are:

Weight	=	1.0 kg
Density	=	18.7 g/cm ³
Thickness	=	0.7 cm
Diameter	=	10 cm
Projected Area	=	78 cm ²
Impurity	=	1 ppm U^{232} = (1 mg per kg of U^{233})

If a Pu^{239*} source is used for comparison, it also is a 1.0-kg thin disc 10 cm in diameter.

* Isotopic composition: 93.5% Pu^{239} , 6% Pu^{240} , and 0.5% Pu^{241} .

Decay Activity

The U^{232} decays by alpha disintegrations with a 74-year half-life. (3)
One mg has an activity of 20.94 mc.

The complete decay scheme for U^{232} and its daughters is shown in Figure 1. (3, 4) The activity during a 10-year period was calculated for each of the daughters from this decay scheme. For the first 380 days, the activity of each individual nuclide was computed at 0.5-day intervals for 20 days, and at 10-day intervals for 380 days through a computer program. After this, only the Th^{228} (1.9-year half-life) activity was computed. The rest of the daughters which have a relatively short half-life are in equilibrium with Th^{228} and were assumed to have equal activity. Tl^{208} and Po^{212} are exceptions, being on branch chains and having activities of 36% and 64% of Th^{228} , respectively. The Th^{228} activity was calculated as follows:

$$C_{Th} = \frac{(\lambda_{Th}) C_U}{(\lambda_{Th} - \lambda_U)} (e^{-\lambda_U t} - e^{-\lambda_{Th} t})$$

$$C_{Th} = Th^{228} \text{ activity (mc)}$$

$$C_U = \text{Initial } U^{232} \text{ activity (20.94 mc)}$$

$$\lambda_{Th} = \frac{0.693}{1.9 \text{ yr}} = 0.363$$

$$\lambda_U = \frac{0.693}{74 \text{ yr}} = 0.00942$$

$$t = \text{Total decay time for } Th^{228} \text{ in years}$$

$$\therefore C_{Th} = (21.5) (e^{-0.00942t} - e^{-0.363t})$$

Tl^{208} is on a 36% branch in the decay chain

$$\therefore C_{Tl} = (21.5) (0.36) (e^{-0.00942t} - e^{-0.363t})$$

FIGURE 1

Change in U²³³ Dose Rate Due to U²³² Daughters

The computed activity for each of the U^{232} daughters, which emit a significant amount of gamma radiation, is tabulated at representative time intervals in Table 1. The complete reference set of gamma photon values given in Figure 1, used to compute dose rates in Table 1, were consolidated for a single nuclide if the energies were about the same and omitted if the yield was insignificant.

The total gamma radiation emitted by U^{233} and its daughters amounts to 0.2 mr/hr at 1 ft at 1 year and 2 mr/hr at 1 ft at 10 years; this is insignificant compared to the gamma from even 1 ppm U^{232} . Therefore, it has been disregarded in the dose rate totals.

Gamma Dose Rates (Table 1)

The gamma dose rates were determined from each photon energy of each gamma-emitting U^{232} daughter at the same representative time intervals. The gamma activity (gamma curies) for each energy was determined by multiplying the gamma photon yield^(3, 4) in photons/disintegration by the decay rate activity (curies) of each radionuclide. The gamma activity is converted to dose rate at a finite distance (r/hr at 1 ft) by the dose rate factor⁽³⁾ for each particular gamma energy. Since all of the decay rate activities were determined and tabulated (Table 1), the gamma photon yield and the dose rate factor were combined into one multiplying factor, dose rate conversion, which converts the decay rate activity in curies directly to dose rate in r/hr at 1 ft.

Dose Rate Conversion (r/hr at 1 ft/curie)

$$\text{Dose Rate (r/hr at 1 ft)} = \overbrace{\text{Dose Rate Factor (r/hr at 1 ft/curie gamma)} \times \text{Gamma Photon Yield (Photon/disintegration)}}^{\text{Dose Rate Conversion}} \times \text{Decay Rate Activity (curie)}$$

In Table 1, this operation is shown for the daughters of 1 mg of U^{232} (1 mg U^{232} = 1 ppm U^{232} in 1 kg U^{233}) and the resulting individual dose rates are given in mr/hr from millicurie values of the decay rate activities. The total dose rate from 1 mg U^{232} and daughters is equal to the sum of the individual dose rates for the various energy levels of each of the radionuclides. In Table 1 the dose rates have been individually totaled and recorded in five energy groups to be available for use where shielding is introduced.

Self-Shielding (Table 2)

The self-shielding of the gamma radiation created by the uranium is quite significant and was calculated by the following formula:

$$D_x = \frac{D_o (\rho/\mu) (1 - e^{-\mu x})}{x\rho} b$$

D_x = Self-shielded dose rate (mr/hr)

D_o = Calculated gamma dose rate of a finite energy with no self-shielding (mr/hr) (Values from Table 1)

μ/ρ = Mass attenuation coefficient for uranium (cm^2/g)

$x\rho$ = Mass thickness of uranium slab (g/cm^2)

b = Buildup factor

The contribution to the total dose rate from each successive layer of a homogeneous slab source is reduced by self-shielding at a rate proportional to $e^{-\mu/\rho}$ where μ/ρ is the mass attenuation coefficient (cm^2/g). Ultimately, the infinitely thick slab would have a dose rate equal to that from an amount of source material, not self-shielded, contained in a layer whose thickness is the reciprocal of the mass attenuation factor.

Although a buildup factor (b) is given in the equation, actually there will be little buildup since the major contribution to the total dose rate comes from the surface layers of the slab. An estimated buildup of 10% (factor = 1.1) was used for all cases.

TABLE 2
GAMMA DOSE RATE - SELF-SHIELDED
(at 1 ft from 1 mg U²³² Contained in
1.0-kg U²³³ Disc 0.7 cm Thick)

<u>Energy Group</u>	<u>Dose Rate at 1 ft</u>				
	II	III	IV	V	Total
<u>Self-Shielding Reduction Factor</u>	0.12	0.48	0.62	0.85	
<u>Age After Separation, Days</u>	<u>(mr/hr)</u>	<u>(mr/hr)</u>	<u>(mr/hr)</u>	<u>(mr/hr)</u>	<u>(mr/hr)</u>
4	<0.01	0.02	0.01	0.07	0.10
7	0.01	0.04	0.03	0.21	0.29
14	0.03	0.12	0.06	0.67	0.88
20	0.05	0.19	0.11	1.11	1.46
40	0.11	0.47	0.25	2.66	3.49
60	0.17	0.73	0.40	4.19	5.49
120	0.4	1.5	0.8	8.6	11.3
280	0.8	3.4	1.8	19.0	25.0
2 years	1.7	7.2	3.9	40.9	53.7
10 years	3.0	12.7	6.8	71.9	94.4

Example

From Table 1, Energy Group IV, at 10 years:

Dose rate $D_o = 10.9$ mr/hr

Gamma energy = 0.8 Mev

Mass absorption coefficient - uranium (μ/ρ) = $0.1 \text{ cm}^2/\text{g}$

Slab thickness (x) = (0.7 cm) (18.7 g/cm^3) = 13 g/cm^2

Dose buildup factor (b) = 1.1

$$D_x = \frac{(10.9)(1.1)}{(0.1)(13)} (1 - e^{-(0.1)(13)})$$

$$D_x = (10.9)(0.62) = 6.8 \text{ mr/hr}$$

The self-shielding factor for 0.8 Mev gamma from the 0.7-cm-thick uranium source is 0.62. The self-shielding dose rate reduction factors for each energy group are shown in Table 2. The dose rates given in Table 2 are the results of the Table 1 values reduced by the self-shielding factors. By totaling the resulting dose rates for the individual energy groups, the total dose rate from the 1.0-kg disc was determined.

Shielded Dose Rate, 1/4-in. Lead Filter (Table 3)

The low energy dose rates are significantly reduced when shielded by a 1/4 in. of lead. The amount of reduction was calculated for each shielding group. The reduction factor for each shielding group was calculated from the following equation:

$$\frac{D}{D_x} = b e^{-\mu x},$$

where

D_x = originating dose rate from Table 2,

b = dose buildup factor for lead,

μ/ρ = mass absorption coefficient for lead (cm^2/g),

$x\rho$ = mass thickness of the lead, $(1/4 \text{ in})(2.54)(11.34) = 7.2 \text{ g/cm}^2$, and

$$\text{RF} = \frac{D}{D_x} = b e^{-7.2 \mu/\rho}.$$

The reduction factor for each energy group is shown in Table 3. The dose rates given in Table 3 are the Table 2 self-shielded dose rate values reduced by the 1/4-in. lead shield reduction factors.

TABLE 3

GAMMA DOSE RATE AT 1 ft THROUGH 1/4-in. LEAD FILTER

(for 1 mg U^{233} in 1.0 kg U^{233} 0.7 cm thick)

<u>Energy Group</u>	<u>Dose Rate at 1</u>				
	II	III	IV	V	Total
<u>1/4-in. Lead Shield</u> <u>Reduction Factor</u>	0.025	0.5	0.6	0.8	
<u>Age After</u> <u>Separation, Days</u>	<u>mr/hr</u>	<u>mr/hr</u>	<u>mr/hr</u>	<u>mr/hr</u>	<u>mr/hr</u>
4	<0.01	0.01	0.01	0.06	0.08
7	<0.01	0.02	0.02	0.17	0.21
14	<0.01	0.06	0.04	0.54	0.65
20	<0.01	0.10	0.07	0.89	1.07
40	<0.01	0.24	0.15	2.13	2.53
60	<0.1	0.37	0.24	3.35	3.97
120	<0.1	0.8	0.5	6.9	8.3
280	<0.1	1.7	1.1	15.2	18.1
2 years	0.1	3.6	2.4	32.7	38.8
10 years	0.1	6.4	4.1	57.5	68.1

Beta Dose Rates and Total Dose Rates

In 1958, Heid and Keck⁽⁵⁾ measured dose rates from a thin metal disc of U^{233} about 2 months after separation:

Weight = 500 to 600 g
 Density = 18.7 g/cm³ (assumed)
 Diameter = 7 cm
 Area = 39 cm²
 Thickness = 0.7 cm
 Impurity U^{232} = 60 ppm (~30 mg)

They used a HAPO extended CP (TCP), which has a chamber 3 in. in diameter and 5-11/16 in. long with 7 mg/cm² end window and 440 mg/cm² walls, to make the measurements. Their measurements are shown in Table 4.

TABLE 4
ABSORPTION STUDY⁽⁵⁾

Mat. Identification U ²³³ CBM-8 MPM-215 256				By A. H. Keck Date 7-14-58		
				Dimensions 2-3/4-in. -Diameter Button		
				Weight 500-600 g		
Chamb. Distance	Metal 1	TCP Meter mr/hr	D ^{-1/2}	Aluminum 0.02536 g/cm ² Per Layer		
				Layers	mr/hr	% Penetration
0		4100	0.0157	0	4100	100.6
0.5		3150	0.0178	1	3800	92.6
1.0		2600	0.0196	2	3550	86.6
1.5		2150	0.0216	3	3350	81.8
2.0		1850	0.0232	4	3200	78.1
2.5		1550	0.0254	5	3000	73.2
3.0		1350	0.0274	6	2850	69.5
3.5		1200	0.0289	7	2700	65.9
				8	2550	62.2
				9	2550	62.2
				10	2300	56.2
				15	1900	46.3
				20	1600	39.1
				30	1450	35.4
				40	1400	34.2
				50	1400	34.2
				60	1400	34.2
Thick Lead 2.041 g/cm ² Per Layer				Cellulose Acetate 0.00976 g/cm ² Per Layer		
Layers		mr/hr	% Penetration	Layers	mr/hr	% Penetration
0		4100	100	0	4100	100
0-Lead + Acetate		3900	95.2	1	3900	95.2
1-Lead + Acetate		1200	29.3	2	3800	92.7
2-Lead + Acetate		1050	25.6	3	3700	90.3
3-Lead + Acetate		950	23.2	4	3600	87.8
4-Lead + Acetate		900	22.0	5	3500	85.4
5-Lead + Acetate		800	19.5	6	3450	84.0
Thin Lead 0.136 g/cm ² Per Layer				7	3400	82.9
Layers		mr/hr	% Penetration	8	3300	80.5
0		4100	100	9	3200	78.2
0-Lead + Acetate		3900	95.2	10	3150	76.8
1-Lead + Acetate		2200	53.6	15	2850	69.5
2-Lead + Acetate		1650	40.2	20	2600	63.4
3-Lead + Acetate		1400	34.2	30	2150	52.5
4-Lead + Acetate		1350	33	40	1800	43.9
5-Lead + Acetate		1300	31.7	50	1700	41.5
Thick Brass 0.1057 g/cm ² Per Layer				60	1600	39.0
Layers		mr/hr	% Penetration	Thin Brass 0.023 g/cm ² Per Layer		
0		4100	100	Layers	mr/hr	% Penetration
1		3000	73.2	0	4100	100
2		2250	55	1	3750	91.5
3		1800	43.9	2	3500	85.5
4		1550	37.8	3	3300	80.5
5		1400	34.2	4	3100	75.6
Thin Brass 0.023 g/cm ² Per Layer				5	2900	70.8
Layers		mr/hr	% Penetration	6	2700	65.9
0		4100	100			
1		3750	91.5			
2		3500	85.5			
3		3300	80.5			
4		3100	75.6			
5		2900	70.8			
6		2700	65.9			

The distance was measured nominally from the surface of the disc to the chamber end window, the maximum being 3.5 in.

Figure 2 shows the calculation of the surface dose rate from their measurements with a resulting dose rate of 72 rad/hr. The surface dose rate of U^{233} metal depends on the thickness of the metal and the concentration of beta-gamma emitters (ppm U^{232} and age of the metal). The basic 1.0-kg thin disc of U^{233} was purposely established to have the same thickness as the one measured by Keck and Heid, so at the same age (60 days), the dose will be in direct proportion to the ppm of U^{232} and have a dose rate of $\frac{(72 \text{ rad/hr})(1 \text{ ppm})}{(60 \text{ ppm})} = 1.2 \text{ rad/hr}$ at the surface, which is the dose rate of a thin metal disc of U^{233} containing 1 ppm U^{232} .

Using the values from Table 4, Heid calculated the total dose rate (beta plus gamma) at 1 ft to be 475 mrad/hr by the DR^2 method.⁽⁴⁾ Converting this to a dose rate for the basic 1.0-kg U^{233} thin disc with 1 ppm U^{232} yields $(475) \frac{(1)}{(60)} \frac{(78)}{(39)} = 15.8 \text{ mrad/hr}$ at 1 ft. In this calculation, the dose rate was reduced by the ratio of U^{232} and increased by the ratio of the projected areas. The thickness of both discs is the same. At 60 days, the difference between this total dose rate 15.8 mrad/hr, and the calculated gamma dose rate, 5.5 mr/hr (Table 2), amounts to 10.3 mrad/hr. This is assumed to be the beta contribution and it amounts to 65% of the total. This is in close agreement with the value determined by Heid and Keck, which is slightly in excess of 60%.

Heid calculated a spectrum of effective energies from the measured data in Table 4 by a method Helgeson documented.⁽⁶⁾ The energy distribution measured and calculated by Heid for 60-day-old material compared favorably with the theoretical distribution.

FIGURE 2

Surface Dose Rate Determination by DR^2 Method⁽⁴⁾

Beta and Gamma Energy Distribution
A Comparison Between Measured and Calculated Values

<u>Energy Range, Mev</u>	<u>From Heid-Keck⁽⁵⁾ Measurements, %</u>	<u>From Table III Theoretical Calculations, %</u>
1.5 to 2.6 Gamma	30	26.1
0.5 to 1.5 Gamma	<5	7
0.15 to 0.5 Gamma	6	1
<0.15 Gamma	2	<0.1
2.0 - 3.0 Mev Beta	60+	65

Bi^{212} is a primary beta emitter in the decay chain and it is in equilibrium with the other beta emitters, so it was assumed that the beta dose rate remains in proportion to the Bi^{212} activity. The calculated beta dose rate of 10.3 mrad/hr at 1 ft and the total surface dose rate of 1.2 rad/hr at 60 days were used to determine the dose rates at the other decay ages, by proportioning them to the Bi^{212} activity (millicuries) in Table 5.

Pu^{239*} Dose Rates

The dose rates for Pu^{239} given in this document are from measurements of production metal and represent not a single measurement but the long term average. The measurements were adjusted to the 1.0-kg thin metal disc. These are 1.2 r/hr at the surface, 13 mr/hr at 1 ft from the bare metal, and, when the metal is shielded by 1/4 in. of lead, 2 mr/hr at 1 ft. Although the bare metal dose rate will build up with time as the Am^{241} activity increases,⁽⁷⁾ this has not been considered in the dose rates given here and shown in Figures 3 and 4. The main contributors to the Pu^{239*} dose rate are Pu^{239} and U^{237} and fission products. The plutonium isotopes and daughters all have energies less than 0.4 Mev and because so much of it is below 0.04 Mev, the 1/4-in. lead shield reduces total dose rate to insignificance.

* Isotopic composition: 93.5% Pu^{239} , 6% Pu^{240} , and 0.5% Pu^{241} .

TABLE 5TOTAL DOSE RATE FOR BARE U²³³ METAL

<u>Age, Days</u>	<u>Activity</u> Bi ²¹² , mc	<u>Dose Rates*</u>		
		<u>Beta</u>	<u>Total Beta and Gamma</u>	
		<u>at 1 ft,</u> <u>mrad/hr</u>	<u>at 1.0 ft,</u> <u>mrad/hr</u>	<u>Surface,</u> <u>rad/hr</u>
4	0.018	0.2	0.3	0.02
7	0.055	0.5	0.8	0.06
14	0.175	1.7	2.6	0.19
20	0.293	2.8	4.3	0.32
40	0.697	6.6	10.1	0.78
60*	1.09	10.3*	15.8	1.2*
120	2.25	21.2	32.5	2.45
280	5.0	47	72	5.5
2 years	10.7	110	154	11.8
10 years	18.8	117	271	20.6

* Basis: Calculated beta dose rate at 60 days. Other dose rates are in proportion to the Bi²¹² activity.

FIGURE 3

U^{233} Dose Rate at 1 ft Due to U^{232} Daughters

FIGURE 4

U^{233} Surface Dose Rate Due to U^{232} Daughters

Fission Product Contribution

All of the gamma radiation greater than 0.4 Mev comes from fission products that have carried over from the irradiated fuel separations process. The 2 mr/hr at 1 ft dose rate (1/4-in. lead filtered) shown in Figure 3 can be attributed entirely to fission product carryover. This dose rate will reduce with time as the fission products decay away.

In U^{233} production, some fission product carryover can be expected. On the basis of Pu^{239*} production experience, it might be expected to contribute as much as the 2 mr/hr at 1 ft and 0.1 to 0.2 r/hr at surface. Since there is no sound basis for this judgment, it has been depicted in Figures 3 and 4 as gray zones marked "F. P. Carryover."

DISCUSSION OF RESULTS

U^{233} metal increases in radioactivity with time because of the U^{232} impurity whose daughters emit both gamma and beta radiations in significant quantity. The dose rate increases as the U^{232} daughters are produced as decay products after chemical separation has taken place. The activity buildup is determined by the 1.9-year half-life Th^{228} , the first daughter of U^{232} . The remaining daughters come into equilibrium with the Th^{228} very quickly, because their total half-life amounts to only 4 days. By the end of 10 years, a maximum is reached as the Th^{228} reaches equilibrium with the 74-year half-life U^{232} .

Figure 1

The dose rate buildup calculated in Table 2 was converted to percent buildup versus time growth and is presented in Figure 1. This is based on 100% for the maximum dose rate which will be reached at about 10 years, when the Th^{228} comes into equilibrium with the U^{232} . Time of growth starts with the chemical separation step in the U^{233} production process. The daughters of U^{232} are elementally different from uranium, so although U^{232} remains with the U^{233} , the daughters can be removed by a chemical separation process.

* Isotopic composition. 93.5% Pu^{239} , 6% Pu^{240} , and 0.5% Pu^{241} .

Figure 3

The dose rates which build up 1 ft from the basic 1.0 kg thin metal disc are shown in Figure 3, both from the bare metal and from metal shielded with 1/4 in. of lead. This is a graphical display of values obtained from Tables 3 and 5.

Since there is a sizeable amount of beta and some lower energy gamma radiations present as well as the very penetrating 2.6 Mev gamma from Tl^{208} , a 1/4-in. lead filter was used as a method for showing and comparing the penetrating radiations with those more readily shielded. Average dose rates encountered in handling Pu^{239*} metal of the same size and shape are included for comparison.

The shaded area in Figure 3 indicates the increased dose rate that might result from fission product carryover from the separation process. If anything, this estimate is high. With Pu^{239*} , for example, the shielded dose rate of 2 mr/hr at 1 ft comes entirely from fission products carried over. It will be noted that the dose rate from bare metal U^{233} aged about 60 days equals that of Pu^{239*} . The penetrating dose rates, however, are equal when the U^{233} is less than a month old because of the predominately high energy gamma from U^{233} and low energy gammas from Pu^{239*} .

Figure 4

The U^{233} surface dose rate which builds up with time is shown in Figure 4. These values are taken from Table 5. As a comparison, the average surface dose rate found on Pu^{239*} metal is shown on the chart. It will be noted that the dose rates are about equal when the U^{233} has aged about 60 days.

CONCLUSIONS

The information presented here may be used to determine or predict the dose rates when U^{232} is present or whenever the $Th^{228} \rightarrow Tl^{208} \rightarrow Pb^{208}$ chain occurs in a wide variety of situations for U^{233} processing and handling. The information is also adaptable to situations other than those of U^{233} material.

* Isotopic composition: 93.5% Pu^{239} , 6% Pu^{240} , and 0.5% Pu^{241} .

1. ppm of U^{232}

All beta and gamma dose rates from U^{233} are directly proportional to the ppm of U^{232} .

2. Dose Rate Buildup

The change in dose rate for a U^{232} created source can be determined over any time period from the curve in Figure 1.

3. Shielding

In Table 1, the dose rate from each energy of gamma radiation has been determined at significant time intervals so the effect of shielding can be accurately calculated.

4. Uranium Self-Shielding

An equation for determining the self-shielding for a homogeneous source is given in the Calculations and values for the 1.0-kg U^{233} disc are given in Table 3.

5. Beta Dose Rates

- a. Beta radiation is a surface phenomenon so that changes in a field beta dose rate are directly proportional to the projected area of the source. Table 5 gives the field beta dose rates from an area of 78 cm^2 .
- b. The beta radiations are so energetic (1.8 to 2.26 Mev) that the beta-to-gamma ratio remains constant out to distances of a foot or more from the source.
- c. The surface beta dose rate is independent of the area and mass and depends only on the concentration of U^{232} .

6. Approximations

- a. If the mass of metal is larger or smaller than 1 kg, the field dose rates from the higher energy gammas, those filtered by 1/4 in. of lead (Table 3 and Figure 3), can be assumed to change in direct proportion to the mass.

- b. If the area (78 cm^2) of the disc is changed, the total dose rate 1 ft from bare metal (Table 5 and Figure 3) will change in direct proportion to the area.
- c. The beta-to-gamma ratio is about 2:1 for the 1.0-kg thin disc considered; this will reduce to about 1:1 for a 1-kg sphere.

7. Th²²⁸

If Th²²⁸ is present in other materials, the dose rates can be estimated by comparison of the Th²²⁸ curies/kg of material to the corresponding dose rates given in this report.

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