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Ac^{227} AND Th^{228} PRODUCTION AS A FUNCTION
OF TIME FOR VARIOUS VALUES OF NEUTRON
FLUX

Information Report

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Miamisburg, Ohio
Operated by
Monsanto Chemical Company

August 28, 1952

Prepared By: G. R. Grove

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INTRODUCTION

Actinium-227 can be produced by the reaction:

The amount of actinium-227 that can be produced per curie of radium-226 is dependent upon (1) the total neutron exposure, (2) the neutron-capture cross section for radium-226, (3) the rate of decay of actinium-227, and (4) the amount of actinium-227 which is converted to thorium-228 by the reaction:

Recent measurements of the thermal-neutron-absorption cross section for actinium-227 gave a value, $\sigma_a = 493$ barns.¹ With this value of σ_a , the amount of actinium-227 per curie of radium-226 was calculated for various values of neutron flux and various irradiation times. For this calculation a neutron-capture cross section for radium-226 of 12 barns² was used.

The amount of thorium-228 produced per curie of radium-226 was also calculated for various flux intensities and irradiation times. Finally, the percentage of actinium-227 converted to thorium-228 relative to the total amount of actinium-227 produced was calculated.

These calculations should be of value in estimating the optimum irradiation conditions for the actinium program. They also indicate that the shielding in the cave area will need to be increased because of the high gamma-ray dosage-rate from thorium-228 and its daughters.

DETAILED REPORT

The following quantities were used in the calculation of the production of actinium-227 and thorium-228:

$$N_0 = \text{number of atoms of radium-226 per curie} = 2.7 \times 10^{21}$$

$$N_1 = \text{number of atoms of actinium-227}$$

$$N_2 = \text{number of atoms of thorium-228}$$

$$\lambda_1 = \text{decay constant of actinium-227} = 1. \times 10^{-9} \text{ sec}^{-1(3)}$$

$$\lambda_2 = \text{decay constant of thorium-228} = 1.16 \times 10^{-8} \text{ sec}^{-1(4)}$$

$$\sigma_0 = \text{neutron-capture cross section of radium-226} = 12 \text{ barns}^{(2)}$$

$$\sigma_1 = \text{neutron-capture cross section of actinium-227} = 493 \text{ barns}^{(1)}$$

The reactions prevailing when pure radium-226 is irradiated in a pile are:

The half life of radium-227 and the neutron-capture cross section of thorium-228 are assumed to be small enough so that their effect on the calculations can be neglected.

The number of atoms of actinium-227 produced per second in a flux intensity nv is

$$\frac{dN_1}{dt} = nvN_0 \sigma_0 - \lambda_1 N_1 - nvN_1 \sigma_1 \quad (1)$$

where N_0 is considered constant, i.e., both the burn-up and decay of radium-226 are negligible.

The solution of Equation (1) is

$$N_1 = \frac{nvN_0 \sigma_0}{\lambda_1 + nv \sigma_1} \left[1 - e^{-(\lambda_1 + nv \sigma_1)t} \right] \quad (2)$$

Expressed in units of curies of actinium-227 Equation (2) becomes

$$C_1 = \frac{nv\lambda_1 N_0 \sigma_0}{3.7 \times 10^{10} (\lambda_1 + nv \sigma_1)} \left[1 - e^{-(\lambda_1 + nv \sigma_1)t} \right] \quad (3)$$

For the case of no burn-up (σ_1 negligible) the solution reduces to

$$C_1^0 = \frac{nvN_0 \sigma_0}{3.7 \times 10^{10}} (1 - e^{-\lambda_1 t}) \quad (3a)$$

Values of C_1^0 for various times and neutron-flux intensities are given in Table I.

The number of atoms of actinium-228, and consequently thorium-228, produced per second in the same flux, nv , is

$$\frac{dN_2}{dt} = nvN_1 \sigma_1 - \lambda_2 N_2 \quad (4)$$

The solution of which, expressed in curies, is

$$C_2 = \frac{(nv)^2 \sigma_1 \sigma_0 N_0}{3.7 \times 10^{10}} \left[\frac{1}{(\lambda_1 + nv \sigma_1)} - \frac{e^{-\lambda_2 t}}{(\lambda_1 - \lambda_2 + nv \sigma_1)} + \frac{\lambda_2 e^{-(\lambda_1 + nv \sigma_1)t}}{(\lambda_1 + nv \sigma_1) (\lambda_1 - \lambda_2 + nv \sigma_1)} \right] \quad (5)$$

Equations (3) and (5) can be represented in the form

$$C_1 = C_1(nv) [1 - f_1(nv, t)]$$

$$= C_1(nv) F_1(nv, t)$$

$$\text{and } C_2 = C_2(nv) [f_2(nv) + f_3(nv, t) + f_4(nv, t)]$$

$$= C_2(nv) F_2(nv, t)$$

Calculated values of the functions C_1 , C_2 , C_1 , C_2 , F_1 , and F_2 are given in Tables II, III, IV, and V and are shown graphically in Figures 1 and 2.

The efficiency factors for the production of actinium-227 are shown in Table VI and Figure 3. The efficiency factor is defined as the percentage of the actinium which suffers neutron capture relative to the total amount of actinium which was produced or $100(C_1^0 - C_1)/C_1^0$.

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TABLE I

CURIES OF Ac^{227} PRODUCED PER CURIE OF Ra^{226} WITH NO BURN-UP

IRRADIATION TIME (10^8 SEC)	CURIES OF Ac^{227} (C_1^0)					
	NEUTRON-FLUX INTENSITY					
	10^{13}	2×10^{13}	5×10^{13}	10^{14}	2×10^{14}	5×10^{14}
2.5	0.0219	0.0438	0.1095	0.2190	0.4380	1.0950
5.0	0.0437	0.0874	0.2185	0.4370	0.8740	2.1850
7.5	0.0653	0.1306	0.3265	0.6530	1.3060	3.2650
10	0.0871	0.1742	0.4355	0.8710	1.7420	4.3550
12.5	0.1088	0.2176	0.5440	1.0880	2.1760	5.4400
15	0.1304	0.2608	0.6520	1.3040	2.6080	6.5200
17.5	0.1519	0.3038	0.7595	1.5190	3.0380	7.5950
20	0.1734	0.3468	0.8670	1.7340	3.4680	8.6700
25	0.2162	0.4324	1.0810	2.1620	4.3240	10.810
30	0.2588	0.5176	1.2940	2.5880	5.1760	12.9400

TABLE II

CALCULATED VALUES OF C_i^* AND F_1^{**}

IRRADIATION TIME (10^8 SEC)	NEUTRON-FLUX INTENSITY [$F_1(nv)$]					
	10^{13}	2×10^{13}	5×10^{13}	10^{14}	2×10^{14}	5×10^{14}
2.5	0.0147	0.0268	0.0621	0.1181	0.2204	0.4614
5.0	0.0293	0.0529	0.1204	0.2224	0.3923	0.7099
7.5	0.0435	0.0783	0.1750	0.3142	0.5262	0.8437
10	0.0576	0.1029	0.2262	0.3953	0.6306	0.9159
12.5	0.0713	0.1270	0.2744	0.4667	0.7121	0.9547
15	0.0852	0.1503	0.3194	0.5298	0.7755	0.9756
17.5	0.0986	0.1731	0.3617	0.5853	0.8250	0.9869
20	0.1118	0.1952	0.4013	0.6343	0.8636	0.9929
25	0.1378	0.2378	0.4734	0.7156	0.9171	0.9979
30	0.1630	0.2781	0.5368	0.7492	0.9496	0.9994
$C_i(nv)$	1.477	1.613	1.707	1.741	1.758	1.769

$$*C_i = \frac{nv\lambda_1 N_0 \sigma_0}{3.7 \times 10^{10} (\lambda_1 + nv \sigma_1)}$$

$$**F_1 = 1 - e^{-(\lambda_1 + nv \sigma_1)t}$$

TABLE III
CALCULATED VALUES OF C_j^* AND F_2^{**}

IRRADIATION TIME (10^8 SEC)	NEUTRON-FLUX INTENSITY [$F_2(nv_1 t)$]					
	10^{13}	2×10^{13}	5×10^{13}	10^{14}	2×10^{14}	5×10^{14}
2.5	0.00002646	0.00004184	0.00003644	0.000035	0.000034	0.0000290
5.0	0.0001595	0.0001542	0.000138	0.0001318	0.000123	0.0000972
7.5	0.0003134	0.0004721	0.000296	0.0002798	0.000252	0.0001844
10	0.0005562	0.0005811	0.000513	0.0004735	0.000412	0.000281
12.5	0.0008190	0.0009141	0.000777	0.0007069	0.000594	0.000381
15	0.001223	0.001173	0.00109	0.000969	0.000791	0.000482
17.5	0.001612	0.001657	0.00144	0.001258	0.000998	0.000582
20	0.002039	0.001940	0.00183	0.001571	0.001213	0.000670
25	0.003141	0.003170	0.00268	0.002239	0.00165	0.000868
30	0.004391	0.004323	0.00364	0.003129	0.00209	0.00105
$C_j(nv)$	43.17	172.68	1079	4317	17,268	107,900

$$*C_j = \frac{(nv)^2 \sigma_1 \sigma_0 N_0}{3.7 \times 10^{10}}; **F_2 = \left[\frac{1}{(\lambda_1 + nv \sigma_1)} - \frac{e^{-\lambda_2 t}}{(\lambda_1 - \lambda_2 + nv \sigma_1)} + \frac{\lambda_2 e^{-(\lambda_1 + nv \sigma_1)t}}{(\lambda_1 + nv \sigma_1)(\lambda_1 - \lambda_2 + nv \sigma_1)} \right]$$

TABLE IV
CURIES OF Ac^{227} PRODUCED PER CURIE OF Ra^{226}

IRRADIATION TIME (10^8 SEC)	CURIES OF Ac^{227} (C_1) NEUTRON-FLUX INTENSITY					
	10^{13}	2×10^{13}	5×10^{13}	10^{14}	2×10^{14}	5×10^{14}
2.5	0.0217	0.0432	0.1060	0.2056	0.3875	0.8162
5.0	0.0433	0.0853	0.2055	0.3872	0.6897	1.2558
7.5	0.0642	0.1263	0.2987	0.5470	0.9251	1.4925
10	0.0851	0.1660	0.3861	0.6882	1.1086	1.6202
12.5	0.1053	0.2049	0.4684	0.8125	1.2519	1.6889
15	0.1258	0.2424	0.5452	0.9224	1.3633	1.7258
17.5	0.1456	0.2792	0.6174	1.0190	1.4504	1.7458
20	0.1651	0.3149	0.6850	1.1043	1.5182	1.7564
25	0.2035	0.3836	0.8081	1.2459	1.6123	1.7653
30	0.2408	0.4486	0.9163	1.3044	1.6694	1.7679

TABLE V
CURIES OF Th^{228} PRODUCED PER CURIE OF Ra^{226}

IRRADIATION TIME (10^8 SEC)	CURIES OF Th^{228} (C_2) NEUTRON-FLUX INTENSITY					
	10^{13}	2×10^{13}	5×10^{13}	10^{14}	2×10^{14}	5×10^{14}
2.5	0.0011	0.0072	0.0395	0.151	0.588	3.13
5.0	0.0069	0.0266	0.1490	0.569	2.124	10.49
7.5	0.0135	0.0500	0.3195	1.208	4.352	19.90
10	0.0240	0.1004	0.5535	2.044	7.114	30.38
12.5	0.0354	0.1578	0.8385	3.052	10.258	41.12
15	0.0528	0.2026	1.1765	4.183	13.658	52.02
17.5	0.0696	0.2862	1.5540	5.431	17.234	62.81
20	0.0880	0.3350	1.9750	6.782	20.946	73.39
25	0.1356	0.5474	2.8925	9.666	28.492	93.68
30	0.1896	0.7464	3.9305	13.508	36.090	113.32

TABLE VI
PERCENTAGE BURN-UP OF Ac^{227} RELATIVE TO TOTAL AMOUNT OF Ac^{227} PRODUCED

IRRADIATION TIME (10^8 SEC)	PER CENT BURN-UP RELATIVE TO TOTAL Ac^{227} PRODUCED NEUTRON-FLUX INTENSITY					
	10^{13}	2×10^{13}	5×10^{13}	10^{14}	2×10^{14}	5×10^{14}
2.5	0.91	1.37	3.20	6.12	11.72	25.46
5.0	0.92	2.40	5.95	11.40	21.09	42.53
7.5	1.68	3.29	8.51	16.23	29.17	54.29
10	2.30	4.71	11.34	20.99	36.36	62.80
12.5	3.22	5.84	13.90	25.32	42.47	68.95
15	3.53	7.06	16.38	29.26	47.73	73.53
17.5	4.15	8.10	18.71	32.92	52.26	77.01
20	4.79	9.20	20.99	36.31	56.22	79.74
25	5.87	11.29	25.25	42.37	62.71	83.67
30	6.96	13.33	29.19	49.60	67.75	86.34

CURIES OF Ac 227 PER CURIE OF Ra 226

FIGURE 1

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FIGURE 2

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PERCENTAGE BURN-UP OF Ac227
RELATIVE TO TOTAL Ac227 PRODUCED

FIGURE 3