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OPTIMIZATION OF COBALT-60 PRODUCTION
IN THE HANFORD TESTING FACILITIES

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INTRODUCTION AND PURPOSE

The longitudinal (axial) flux distribution in the Hanford production reactors quite closely approximates a "chopped" cosine. Consequently, any longitudinally uniform charge placed in a reactor will produce a daughter product with a specific activity distribution which also approximates a cosine. Such a distribution has an average-to-maximum specific activity of about 0.7 and is not desirable when product uniformity is required.

In order to optimize the production of cobalt-60 one must consider three important parameters, the thermal neutron flux, the irradiation time, and the charge shape. These three factors have been considered in an effort to determine the optimum charge for the production of cobalt-60 in the Hanford Testing facilities.

SUMMARY AND CONCLUSIONS

There is an optimum time for a specific flux value to produce a maximum specific activity (curies of Co-60 per gram of Co-59 irradiated) in the production of Co-60. If the average thermal flux in the Co-59 sample to be irradiated can be determined accurately, by computer calculations or experimentation, then the time to produce a desired specific activity can easily be determined.

A wide variation in the specific activity occurs when the Co-59 is irradiated in a cosine flux distribution. By varying the amount of Co-59 per piece we can vary the neutron absorption property of each piece. It is desirable to decrease the flux in the center of the column and maintain its base level in the ends of the column, to produce a more uniform specific activity. The addition of BNL strips to the central portion and the elimination of them in the end pieces produces a lower average specific activity, but there is less deviation from the center to the end pieces.

It is proposed that an experimental charge be authorized to substantiate the analytical conclusions reported herein.

DISCUSSION

A general solution to the differential equation of radioactive growth and decay was presented long ago by Bateman.^{/1/} The Bateman solution consists essentially of an equation for calculating the amount of a single daughter produced by a single parent (i.e. a single chain of n members). This single equation is applied repetitively until all combinations of parent and daughter are exhausted.

The classical equation can be considered as the product of two parts, the first being a product of finite constants, and the second being a function of the product and total removal constants and time. A form of the general expression is as follows, with $S(A_1 t)$ being the second or saturation term:

/1/ Bateman, H., "Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations," Proceedings of the Cambridge Philosophical Society, Vol. 15, pp. 423-427, 1910.

DISCUSSION (cont'd)

$$N_n = \left[N_1^0 \prod_{i=1}^{n-1} (A_i^* t) \right] S(A_i t) \quad (1)$$

$$\text{where } S(A_i t) = \sum_{i=1}^n \left[\frac{\exp(-A_i t)}{\prod_{j=1}^n (A_j t - A_i t)} \right] \quad (2)$$

and N_n = number of atoms of the n^{th} member of the decay chain at time t .

N_1^0 = initial number of atoms of the first parent of the chain.

A_i = total removal constant ($\lambda + \sigma\phi$) for the i^{th} member of the chain (this is the sum of the radioactive decay constants for all modes of radioactive decay and the product of cross section and flux for all reactions which result in the destruction of this nuclide).

A_i^* = partial removal constant which results in the production of the $(i+1)^{\text{th}}$ member of the chain. This may be equal to A_i or some component of A_i .

The first part of the expression is easily evaluated since it involves only the product of finite numbers. The second part is a series of positive and negative terms, which may be obtained by expanding the numerator in Maclaurin's series and factoring out all of the terms in the denominator. The resulting saturation term is an alternating series somewhat like an expansion of the exponential in Maclaurin's series.

$$S(A_i t) = \frac{1}{(n-1)!} + \sum_{m=1}^{\infty} \frac{(-1)^m}{(m+n-1)!} \prod_{i=1}^m \left(\sum_{j_i=1}^{j_i-1} A_{j_i} t \right) \quad (3)$$

where $j_0 = n$. The first four terms in the expression are

$$\frac{1}{(n-1)!} - \frac{t}{n!} \sum_{i=1}^n A_i + \frac{t^2}{(n+1)!} \sum_{i=1}^n \sum_{j=1}^i A_i A_j - \frac{t^3}{(n+2)!} \sum_{i=1}^n \sum_{j=1}^i \sum_{k=1}^j A_i A_j A_k \quad (4)$$

The above outlined method has been used to calculate the production of cobalt-60 from cobalt-59 assuming an 80 per cent operating efficiency. In Figure 1 it is noted that for a large flux and a long irradiation time, the burnout of the parent and of the daughter, as well as the decay of the daughter, becomes quite significant. This illustrates the point that for a large flux there is an optimum time to obtain a maximum amount of daughter product.

In addition to optimizing the irradiation time to the flux, the target loading along the length of the irradiation facility, in a cosine flux distribution, should

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0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 Years

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Figure 1

Figure 2

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DISCUSSION (cont'd)

be optimized to produce a more uniform product (i.e., minimize the variation in the specific activity of the daughter product). Previous calculations^{/2/} have shown that a uniform target loading of 250 grams of cobalt-59 per foot of tube can adequately be supported by seven columns of enrichment per column of cobalt-59. It is desirable to maintain the maximum of cobalt-59 that may be supported while reducing the amount in the upstream and downstream portions of the column and increasing the amount in the central portion of the column.

A two dimensional diffusion theory approximation^{/3/} was used to determine the effect of varying the target loading, along the column, on the flux and on the reactivity effect of the column. The problem was run in an rZ cylindrical geometric configuration for a K-Reactor General Purpose test facility. (See Figure 6.) The same results should be applicable to the other K Reactor central zone test facilities as well as those in the old reactors, since the same relative changes should occur.

The base case was a column of solid aluminum pieces which gave a cosine flux distribution. The next case was a uniform loading of fifteen 13-inch cobalt-59 pieces, each containing four standard BNL strips with 62.25 grams of cobalt-59 per strip. The cobalt density was varied along the charge by the addition or subtraction of varying numbers of BNL strips from the aluminum cans. The results given in Table I are for the most favorable charges. It was noted that the effective reactivity does not change appreciably by flattening the central portion of the cosine flux distribution with a somewhat more dense cobalt-59 charge in that region. Figures 3, 4, and 5 compare the specific activity achieved by each piece and by each BNL strip in a piece for the various loadings. Case two appears to give the most desirable uniformity for the specific activity per BNL strip, and indicates the feasibility for producing a uniform product in a cosine flux distribution.

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/2/ RL-REA-N-1, Engineering Notes, M. H. Montgomery (Secret).

/3/ ORNL-TM-842, Exterminator - A Multigroup Code for Solving Neutron Diffusion Equations In One and Two Dimensions, T. B. Fawler, M. L. Tabias, D. R. Vondy.

TABLE I

<u>Case</u>	<u>Piece Number*</u>	<u>No. Strips To Add Per Piece</u>	<u>No. Strips To Subtract Per Piece</u>	<u>Effectivity Reac- tivity Change From Uniform Charge**</u>	<u>Ave.(Integrated) Specific Activity Normalized to 1.0</u>
1	Uniform Charge**	0	0	0	0.86
2	1, 2	0	2	+ 6 cmk	0.80
	3, 4	0	1		
	5, 6	0	0		
	7, 8, 9	1	0		
	10, 11	0	0		
	12, 13	0	1		
	14, 15	0	2		
3	1, 2, 3	0	2	+ 2 cmk	0.83
	4	0	1		
	5, 6, 7	0	0		
	8	1	0		
	9, 10, 11	0	0		
	12	0	1		
	13, 14, 15	0	2		

* Pieces are numbered from the downstream piece to the upstream piece.

** "Uniform Charge" has four strips/piece.

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Figure 3

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CASE I

CASE 2

Figure 4

TWO-DIMENSIONAL DIFFUSION THEORY MODEL

Z

Upstream Aluminum Train	15 Cobalt Pieces	Downstream Aluminum Train
Water		
Aluminum		
Graphite		
KVE-Homogenized Cell		
KVN-Homogenized Cell		

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