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PRODUCTION OF COBALT-60

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PRODUCTION OF COBALT-60

February 29, 1960

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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PRODUCTION OF COBALT-60

INTRODUCTION

Cobalt samples frequently are irradiated in nuclear reactors to produce gamma sources and can be irradiated as integral flux monitors because of the long half-life of the isotope produced. At the present time a small cobalt sample is being irradiated within the KW Reactor Snout facility for future use as a radiographic source for inspection of finished product in the Chemical Processing Department. The following analysis was made to estimate the buildup of activity in this sample; the general equation may be of interest and value for other cobalt sample irradiations.

SUMMARY

The number of curies of cobalt-60 produced in a sample is related to the neutron flux and length of the irradiation by the equation:

$$C_{60} = \frac{4.17 \times 10^{-20} \phi W_{59}^0}{4.159 \times 10^{-9} - 30.3 \times 10^{-24} \phi} e^{-(4.159 \times 10^{-9} + 6 \times 10^{-24} \phi)t} \left[\frac{(4.159 \times 10^{-9} - 30.3 \times 10^{-24} \phi)t}{e} - 1 \right]$$

where ϕ is the conventional thermal neutron flux in neutron/cm² second, t is the exposure time in seconds, and W_{59}^0 is the weight of the unirradiated cobalt-59 sample in grams. The attached figure presents buildup curves as a function of time for various fluxes.

DISCUSSION

A. Derivation of Equation

Cobalt-60 is produced from cobalt-59 in isomeric states. The short half-life (10.4 minutes) isomer decays primarily by gamma emission to the long half-life (5.28 year) isomer which subsequently beta decays to an excited state of nickel 60. Photons of energy 1.17 and 1.33 Mev are emitted to stabilize the nickel 60 nucleus. For long irradiations the existence of the short half-life isomer can be neglected and the differential equation describing the formation of cobalt-60 is:

$$\frac{dN_{60}}{dt} = \phi \sigma_{59} N_{59}^0 e^{-\phi \sigma_{59} t} - \phi \sigma_{60} N_{60} - \lambda_{60} N_{60}$$

where N = number of atoms of cobalt (the subscripts refer to the isotopes),

ϕ = conventional neutron flux, n/cm² sec,

σ = absorption cross section for 2200 m/sec neutrons,

λ = decay constant (= 0.693/ T) in sec⁻¹,

t = exposure time in sec,

and the superscript refers to the original number of atoms present. This is a linear, first order differential equation whose general solution is:

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$$N_{60} = \frac{\phi \sigma_{59} N_{59}^0 e^{-(\phi \sigma_{60} + \lambda_{60})t}}{\phi \sigma_{60} + \lambda_{60} - \phi \sigma_{59}} \left[e^{\frac{(\phi \sigma_{60} + \lambda_{60} - \phi \sigma_{59})t}{\lambda_{60}}} - 1 + \frac{N_{60}^0}{\frac{\phi \sigma_{59} N_{59}^0}{\phi \sigma_{60} + \lambda_{60} - \phi \sigma_{59}}} \right]$$

where the constant of integration has been evaluated by assuming N_{60}^0 atoms of cobalt-60 to be present initially (if none are present the last term within the brackets will be zero). The number of curies of cobalt-60 as a function of time can be obtained from the relation:

$$C_{60} = \frac{N_{60} \lambda_{60}}{3.7 \times 10^{10}}$$

disintegrations/sec (not photons/sec)

B. Numerical Evaluation

It is convenient to express sample size in weight rather than number of atoms. The conversion relation is:

$$N_{59}^0 = \frac{W_{59} N_0}{M}$$

where W_{59}^0 = weight of cobalt 59 sample in grams

N_0 = Avogadro's number, 6.023×10^{23} atoms per gram atomic weight

M = atomic weight of cobalt, 58.94 grams per gram atomic weight

Cross section and decay constants used are those found in BNL-325, Second Edition:

$$\sigma_{59} = 36.3 \pm 1.5 \text{ barns}$$

$$\sigma_{60} = 6 \pm 2 \text{ barns}$$

$$\lambda_{60} = 4.159 \times 10^{-9} \text{ sec}^{-1}$$

The relation for the number of curies of cobalt-60 produced as a function of time and conventional thermal neutron flux level becomes:

$$C_{60} = \frac{4.17 \times 10^{-20} \phi W_{59}^0}{4.159 \times 10^{-9} - 30.3 \times 10^{-24} \phi} e^{-(4.159 \times 10^{-9} + 6 \times 10^{-24} \phi)t} \left[e^{\frac{(4.159 \times 10^{-9} - 30.3 \times 10^{-24} \phi)t}{-1}} - 1 \right]$$

The buildup curves in the attached figure were obtained using this equation for unit weight samples at various flux levels. The uncertainty associated with the cross sections does not affect the calculations significantly over the range plotted; the estimated uncertainty in the curves is less than ± 2 per cent.

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$0.915 = 1.83$

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$48.5 = 0.53$

$\frac{53}{48.5} = 1.093$

C. Experimental Results

A cobalt sample was irradiated in a C Reactor process tube to an exposure of 2800 MWD/AT during 1956 and 1957 for use in the Chemical Processing Department as a radiography source. The gamma strength of the source was measured in air about a month after the sample was discharged and the activity was estimated to be 48.5 curies per gram. Using the relation derived above, it is calculated that the sample activity should have been 53 curies per gram. The error which should be associated with the calculation is unknown. No experimental determination of the rise factor was made for that particular sample; the estimated rise factor of 2.0 could have an uncertainty of as much as 20 per cent. The assumption of a cosine front-to-rear distribution could introduce an error of 10 per cent. The use of a constant flux and continuous irradiation followed by an extended outage to account for the irradiation would introduce a small error. It is concluded that the uncertainty associated with estimating the flux in a sample will limit the accuracy of calculating the buildup of activity.

D. Present Sample

The sample which is currently being irradiated within the Snout facility at the KW Reactor has a goal exposure of 100 curies per gram. A rise factor of approximately 2.0 has been measured for this facility. For K III N elements operating at 1400 kw per tube adjacent to the sample location, it is calculated that 3.25×10^7 seconds of exposure will produce the desired activity. This exposure (equivalent to 525 MWD/adjacent tube) would require between sixteen and seventeen months if the time operated efficiency is 75 per cent. Accuracy of this calculation is limited by the uncertainty in the rise factor and the front-to-rear flux distribution. As in the previous sample, it is anticipated that the activity should be within about 10 per cent of that calculated.

48.5 curies per gram *13 g. of Co for 100 kw tube (near tube 2)*
cal. dist. assumed 1 inch

$4.22 \times 10^{13} \text{ n/cm}^2\text{-sec}$

W. L. Bunch

W. L. Bunch:bmr

curies are in d/s here

Irradiation Testing

"real" curies (photons/sec) will be twice as many.

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Cobalt-60 activity as a function of
conventional neutron flux level and
exposure time

Curies per gram

K&E
10 X 10 TO THE 1/2 INCH
KEUFFEL & ESSER CO.
MADE IN U.S.A.

2.0

0

116 days

252 days

Seconds ($\times 10^{-4}$)

305 days

464 days

 $\phi = 1 \times 10^{19}$

0

116 days

252 days

Seconds ($\times 10^{-4}$)

305 days

464 days

 $\phi = 1 \times 10^{19}$

0

116 days

252 days

Seconds ($\times 10^{-4}$)

305 days

464 days

 $\phi = 1 \times 10^{19}$

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