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 Thermal Neutron Flux Monitor
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Abstract

Inconel can be used for thermal neutron flux measurements by means of its cobalt impurity or its chromium constituent where conventional monitors are unsuitable. The use of cobalt should also be applicable to other nickel alloys. Discriminatory counting is required.

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Introduction

The measurement of the thermal neutron flux in an in-pile experiment is often complicated by experimental conditions which are inappropriate for the use of monitors, such as cobalt or cobalt aluminum alloys. In a series of capsule experiments in the MTR, high operation temperature, high velocity air cooling, and space limitations, prevented the use of conventional monitors, and, as a consequence, the flux monitoring potential of the container material, Inconel, was studied. It was found that either the cobalt impurity, by means of the $\text{Co}^{59} (n, \gamma) \text{Co}^{60}$ reaction, or the chromium constituent, through the $\text{Cr}^{50} (n, \gamma) \text{Cr}^{51}$ reaction, could be used to obtain a measure of the thermal neutron dose received. The method using the cobalt impurity could also be extended to other nickel alloys, since the cobalt appears as an impurity in the nickel used in the alloy. Either of the methods, does, however, require gamma spectrometry, since irradiated Inconel contains several radioactive species, and a determination of the disintegration rate of a particular species is needed.

Discussion

Inconel is nominally an 80% Ni, 14% Cr, 6% Fe alloy with traces of other elements, and containing about 0.15% cobalt as an impurity. The radioactive nuclides present in Inconel three months after neutron irradiation are presented in Table I, and a typical gamma spectrum is shown in Figure 1. A determination of the specific disintegration rate of either the Cr^{51} or Co^{60} will permit the calculation of the neutron dose to which the specimen has been subjected.

The determination of the disintegration rate of Cr^{51} in the Inconel is accomplished by the method of area integration. The area under the Cr^{51} peak from a gamma spectrum run on the irradiated Inconel is compared with the area under the peak from a gamma spectrum of a standard Cr^{51} source, run under the

same conditions. The disintegration rate of the Cr^{51} in the irradiated Inconel can then be determined from a knowledge of the disintegration rate of the standard.

A basic disadvantage of Cr^{51} is its relatively short half-life. This seriously limits its use as a flux integrator for periods of irradiation exceeding one or two months and requires that the counting be done within two or three months after irradiation. A second disadvantage results because Compton scattering of the higher energy gamma rays in the irradiated Inconel increases the background count at the 300 Kev level, and hence introduces a difficulty in the background correction necessary for the area integration technique.

The determination of the specific disintegration rate of the Co^{60} in irradiated Inconel is made somewhat more difficult than in the case of Cr^{51} because of the interference from the Fe^{59} gamma rays. One way of circumventing this difficulty is to chemically separate the cobalt from the other constituents of the Inconel, followed by subsequent discriminatory counting.

A method for determining the Co^{60} disintegration rate without prior chemical separation involves counting the sum peak of the Co^{60} gamma rays. Because the two gamma rays of Co^{60} occur in cascade (2), a gamma spectrum made on Co^{60} in the proper geometry will show a prominent sum peak at 2.5 Mev. This peak results from the two gamma rays exciting the scintillation crystal simultaneously. The gamma rays from Fe^{59} on the other hand do not occur in cascade, but occur singly (2). Hence a gamma spectrum of Fe^{59} does not show a sum peak. Figure 2 shows a gamma spectrum measurement of a source of pure Co^{60} and one of an Fe^{59} source of comparable strength. As can be seen the counting rate in the case of the Co^{60} remains significant beyond the 1.33 Mev peak

because of the existence of the sum peak at 2.5 Mev, whereas in the case of Fe^{59} the counting rate falls off very rapidly. It has been found that all of the counts above 1.6 Mev in irradiated Inconel can be attributed to Co^{60} without introducing a significant error. The disintegration rate of the Co^{60} in Inconel can be determined, then, by integral counting above 1.6 Mev.

Another method for determining the Co^{60} disintegration rate in Inconel without the necessity for chemical separation would be to use discriminatory counting to count the Fe^{59} - Co^{60} peaks in irradiated Inconel and in a standard Fe^{59} - Co^{60} mixture twice, separated by a period of about two months. From the data obtained a pair of simultaneous equations may be solved to yield the Co^{60} disintegration rate.

There are, then, several methods available for determining the disintegration rate of Co^{60} in irradiated Inconel despite the interference of the Fe^{59} . The long half-life of Co^{60} makes it an excellent flux integrator. Also the fact that Co^{60} is used so extensively for flux monitoring is advantageous because comparisons can be made with other flux measurements.

Since the cobalt in Inconel is present as an impurity and in such a small quantity, it is necessary to prove its homogeneity and abundance in the particular batch to be used. This was done by selecting several 50 mgm samples of Inconel from various portions of the stock used in the fabrication of the capsules and submitting them for cobalt analysis. The samples were analyzed by a chemical potentiometric method and also by activation analysis. The results of the analysis showed that the Inconel was homogeneous in its cobalt content and that it contained $1.57 \pm 0.04 \times 10^{-3}$ gm of cobalt per gram of Inconel.

In general, other batches of Inconel which were studied showed themselves to be homogeneous in their cobalt content to within the accuracy of the analysis. However, results of samples from a piece of Inconel welding rod varied from 1.24×10^{-3} to 4.0×10^{-3} grams of cobalt per gram of Inconel, so the homogeneity of the cobalt in Inconel cannot be pre-assumed.

Another question which arose was whether or not the $\text{Ni}^{60} (n, p) \text{Co}^{60}$ reaction contributed significantly to the Co^{60} in irradiated Inconel. To obtain a measure of this contribution samples of high purity cobalt-free nickel were irradiated in the lattice (Hole C-46) of the LITR. The subsequent analysis showed that the $\text{Ni}^{60} (n, p) \text{Co}^{60}$ reaction would contribute less than 0.5% to the Co^{60} disintegration rate in irradiated Inconel containing 0.15% cobalt.

Results

Table II shows the results which have been obtained using the Co^{60} and Cr^{51} disintegration rates to determine the average fluxes to which three different capsules were submitted. The disintegration rates for cobalt were obtained in this case by discriminatory counting of the samples after the cobalt had been chemically separated from the other Inconel constituents. The disintegration rates for the chromium were determined by area integration on the Cr^{51} gamma peak.

Table III shows the results which have been obtained on capsules using the sum peak to determine the Co^{60} disintegration rate. These results are compared with values determined from the yields of Zr^{95} and Cs^{137} in simultaneous irradiation of U^{235} .

In the calculation to obtain thermal flux from the measured disintegration rates the following constants were used: for Co^{60} , $t_{1/2} = 5.3 \text{ yr. (1)}$,

$\sigma_{th} = 37$ barns (3); for Cr^{51} , $t_{1/2} = 27.8$ d (1), $\sigma_{th} = 16.3$ b (3); for Zr^{95} , $t_{1/2} = 63.3$ d (1), fission yield = 6.64×10^{-2} (4); for Cs^{137} , $t_{1/2} = 33$ yrs. (1), fission yield = 5.9×10^{-2} (5). The fission cross section of U^{235} was taken to be 580 barns (3). No attempt was made to correct the Co^{60} for cadmium ratio.

The experimental error in the use of Co^{60} to measure the thermal dose is within 10%. The error in using Cr^{51} is probably somewhat greater because of the difficulty of the area integration and more basically because of its poorer integrating properties. The experimental errors in the determination of the flux from Zr^{95} and Cs^{137} are also 10% and the errors overlap in most cases.

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Table I

Radioactive Nuclides in Inconel Three Months After Neutron Irradiation

Nuclide	Half-Life ^a	Gamma Ray ^a Energies, Mev	Source
Cr ⁵¹	27.8 days	0.323	Cr ⁵⁰ (n, γ)
Co ⁵⁸	72 days	0.805, 0.511	Ni ⁵⁸ (n, p)
Fe ⁵⁹	45.1 days	1.10, 1.29	Fe ⁵⁸ (n, γ)
Co ⁶⁰	5.3 years	1.17, 1.33	Co ⁵⁹ (n, γ)

^aValues taken from Reference (1).

Table II

Comparison of Average Flux Obtained from Co^{60} and Cr^{51} in Irradiated Inconel

Capsule Number	Irradiation Time (Megawatt Days)	Average Flux ($n, \text{cm}^2 \text{ sec}$) $\times 10^{-24}$	
		By Co^{60}	By Cr^{51}
245	802	0.83	0.77
274	802	0.69	0.67
275	802	1.01	1.05

Table III

Comparison of Average Flux Obtained from Co^{60} in Irradiated Inconel and Zr^{95}
and Cs^{137} Yield from U^{235} Fission

Capsule Number	Irradiation Time (Megawatt Days)	Average Flux ($n, \text{cm}^2/\text{sec}$) $\times 10^{-14}$		
		By Co^{60}	By Zr^{95}	By Cs^{137}
231	1046	0.77	0.75	0.61
247	1000	1.38	1.13	1.16
276	534	0.98	0.85	0.70
316	1980	1.77	1.50	1.97
317	1980	1.12	-	1.19
333	510	0.78	-	0.76
345	510	0.59	-	0.67

Fig. 2. Comparison of Gamma Spectra of Co^{60} and Fe^{59} , Multi-Channel Analyzer; 3- x 3-in. NaI(Tl) Crystal. 0 - 1000 = 4 Mev.

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