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EFFECTIVE RESONANCE INTEGRALS OF TANTALUM

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16. Abstract

Effective resonance integrals of tantalum were measured for a range of thickness varying from 10^{-6} to 0.5 cm and were compared with resonance integrals calculated using the GAROL and the ZUT-TUZ codes. A value of 720±25 b was measured for the dilute resonance integral of tantalum, and it agrees with a calculated value of 730±35 b. The measured and calculated resonance integrals agree for most of the thickness range, with some evidence of discrepancy in the region of very thick samples. Resonance overlap effects were investigated and were calculated to be significant for very thick samples in both the unresolved and the resolved regions. When the overlap effect is taken into account, the agreement between measured and calculated resonance integrals is good for all values considered.

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SUMMARY

Tantalum is being considered for use in high-temperature reactors. Experiments have been performed to test the adequacy of published neutron resonance parameters. For this experiment the effective resonance absorption integrals of tantalum were obtained for sample thicknesses ranging from about 10^{-6} to 0.5 centimeter using both reactivity and activation methods. The very thin samples provide a measure of the dilute resonance integral. All measured values were obtained relative to the known resonance integral of gold.

The measured absorption integrals were compared with calculated resonance integrals (obtained using the ZUT-TUZ and the GAROL computer codes) to test the precision of resolved resonance parameters and of average resonance parameters that have been recommended for the unresolved resonance region. In addition, the ZUT-TUZ and the GAROL results were compared to determine whether there were any resonance overlap effects.

Good agreement was obtained between measured and calculated values of the dilute resonance integral with respective values of 720±25 and 730±35 barns. The measured and calculated effective resonance integrals agree for most values with some evidence of a 5-percent or 2-barn discrepancy for the thickest samples considered. Overlap between resonances in both the resolved and unresolved regions was found to account for this small discrepancy.

INTRODUCTION

The efficient generation of electrical power for space missions requires nuclear reactor heat sources that operate at high temperature. Refractory metals such as molybdenum, tungsten, rhenium, and tantalum are constituents of alloys that are considered for use in these reactors. Because these metals are relatively strong neutron absorbers, it is important to the reactor design that their resonance absorption parameters are

known accurately and completely. The resonance absorption integral is a quantity that can be measured experimentally and compared with analytical values evaluated from published resonance parameters. Measured and calculated results for tungsten and its isotopes and rhenium and its isotopes were measured at Lewis and were reported in references 1 to 3. The present report presents comparable results for tantalum.

Tantalum is composed essentially of tantalum-181, and its resonance parameters are known with precision for 75 resonances up to an energy of 330 electron volts (refs. 4 and 5). Contributions to capture above this resolved energy region are particularly important for thick samples where the resolved resonances are highly self-shielded. Therefore, measurements of resonance absorption integrals for a wide range of sample size and comparison with appropriate calculations serves as a test of the precision of known resolved resonance parameters and of the various statistically averaged resonance parameters that have been recommended for the unresolved energy region (ref. 6).

Resonance overlap effects were studied by comparing the integrals calculated with ZUT-TUZ (ref. 7) with those calculated with GAROL (ref. 8). In parts of the unresolved region, sets of resonances that satisfy measured statistical averages were generated by a random sampling technique (similar to that described in ref. 9) in order to check for possible overlap effects.

PRINCIPLES OF MEASUREMENT

The effective resonance integral I_{eff} for a sample in a neutron slowing-down medium is defined as the lethargy-integrated capture cross section that yields the correct capture rate when the sample is exposed to the unperturbed flux spectrum that would be present in the absence of the sample. For the case of a very thin sample, I_{eff} is the dilute resonance integral and is related to the energy-dependent microscopic capture cross section $\sigma_c(E)$ in the following way:

$$I_{eff} = \int_{E_{Cd}}^{\infty} \sigma_c(E) \frac{dE}{E} \tag{1}$$

where the slowing-down flux in the surrounding medium is standardized to vary inversely with neutron energy E and where E_{Cd} is an effective cadmium-filter cutoff energy.

For a thick sample or lump of material, the flux distribution changes so that I_{eff} depends on a volume integral of the product of the actual flux in the sample and the capture cross section.

$$NV\varphi_o I_{eff} = \int_{E_{Cd}}^{\infty} \int_r N\sigma_c(E)\varphi(E, r)dE\, dr \tag{2}$$

where N is the sample atom density, V the sample volume, and φ_o the total unperturbed flux. It is implicit in equation (2) that the flux per unit energy $\varphi(E)$ varies as 1/E when the thick sample is not present; therefore, equation (2) reduces to equation (1) for thin samples.

The upper and lower limits of the energy integrals in equations (1) and (2) represent a standardization of what is to be measured for a cadmium-filtered sample. The value of E_{Cd} used is 0.5 electron volt.

The reactivity and activation methods of measurement used here have been used previously and are discussed in detail in references 1 to 3. A uranyl fluoride solution reactor with centrally located cadmium covered samples is used to measure relative reactivities. The reactivity measurements yield effective resonance integrals using the following relation:

$$\frac{\Delta K}{NVK} = -cI_{eff}\left[\frac{\sum\left(I_{eff}^{calc}\right)_i \left(\varphi_c\right)_i \left(\varphi_c^*\right)_i}{I_{eff}^{calc}}\right] \tag{3}$$

where $\Delta K/NVK$ is the reactivity coefficient for the resonance absorber. The constant of proportionality c in mils per 10^{24} atom-barn (25.4 $\mu m/10^{24}$ at.-b), relating reactivity to absolute resonance integrals, is determined by reference to gold as a standard. Reactivity coefficients for gold have been obtained for a wide range of sample sizes, and these were used in reference 1 to obtain the constant $c = 10.0 \pm 0.5$ mils per 10^{24} atom-barn (254 ± 12.7 $\mu m/10^{24}$ at.-b). The bracketed term is the calculated multigroup importance correction factor for perturbations to the inverse energy neutron flux caused by the cadmium cover, I_{eff}^{calc} is the total calculated resonance integral to 0.5 electron volt, $\left(I_{eff}^{calc}\right)_i$ is the calculated contribution to the resonance integral from resonances in the i^{th} lethargy group, and $\left(\varphi_c\right)_i$ and $\left(\varphi_c^*\right)_i$ are the calculated flux and adjoint per unit lethargy. The lethargy groups (denoted by i) cover the energy range from 0 to 10^7 electron volts.

The reactivity effects due to inelastic scattering by the sample (ref. 1) are given by

$$\frac{\Delta K}{NVK} = \frac{\int_0^\infty \sigma(E \rightarrow E')\varphi(E)[\varphi^*(E') - \varphi^*(E)]dE'}{F_{tot}} \tag{4}$$

where $\sigma(E \rightarrow E')$ is the inelastic-scattering transfer cross section from E to E', where $\left[\varphi^*(E') - \varphi^*(E)\right]$ is the change in adjoint function from E to E', which for this experiment was positive and opposite in sign to the resonance capture reactivity, and where F_{tot} is the integrated total fission rate in the reactor. The inelastic-scattering

reactivity coefficient of equation (4) is difficult to calculate accurately because the transfer cross sections are generally unavailable. However, the reactivity coefficient may be measured for a highly inelastic-scattering but low-capturing material such as lead. When using this experimental inelastic-scattering reactivity coefficient for lead, the coefficients for other heavy elements may be estimated analytically. The resulting correction to the data is generally small and unimportant except for the largest samples of low-capture cross-section material.

For the activation measurements,

$$I_{eff}^{x} = \frac{(R - A)^{s}}{(R - A)^{x}} \frac{\sigma_{th}^{x}}{\sigma_{th}^{s}} I_{eff}^{s} \frac{\mu^{x}}{\mu^{s}} \tag{5}$$

where x represents the isotope under investigation, s represents the standard sample, σ_{th} is the radiative absorption cross section at 0.0253 electron volt, and R is the cadmium ratio.

$$R = \frac{\frac{B}{\epsilon_b}}{\frac{C}{\epsilon_c}} \tag{6}$$

where C is the saturated count rate for the cadmium shielded sample, B is the saturated count rate for the bare sample, and ϵ_c and ϵ_b are the respective counting efficiencies. Also,

$$\mu = \frac{I_{eff}^{calc}}{\sum_i \left(I_{eff}^{calc}\right)_i \left(\varphi_c\right)_i} \tag{7}$$

$$A = \frac{\sum_j \left(I_{eff}^{calc}\right)_j \left(\varphi_b\right)_j}{\sum_i \left(I_{eff}^{calc}\right)_i \left(\varphi_c\right)_i} \tag{8}$$

where $(\varphi_b)_j$ is the calculated flux without the cadmium shield and the index j covers the energy range from 10^7 to 0.41 electron volt (lethargy 0 to 17). A value of 21.0±0.7 barns (ref. 10) was used for the tantalum-181 capture cross section at

0.0253 electron volt. A corresponding cross section value of 98.8±0.3 barns is used for gold (ref. 4). For thick samples, the sample thickness is chosen so as to insure that the flux depression at 0.0253 electron volt produced by the gold standard is the same as that produced by the sample to be measured.

Natural tantalum metal samples were used throughout. Because of its low abundance (0.012 percent), the tantalum-180 isotope was not considered, and the resonance integral of natural tantalum is assumed to be equal to that of tantalum-181 within experimental error.

Effective resonance integrals for samples of various shapes are correlated by plotting against a thickness parameter $(S/M)^{1/2}$, which is the square root of the surface area-to-mass ratio of the sample. For reasons of accuracy, the reactivity method was used only for the thicker samples, those with $(S/M)^{1/2}$ values smaller than 4.5 centimeters per $gram^{1/2}$. The activation method was used for samples with size $(S/M)^{1/2}$ lying between 1.8 and 600 centimeters per $gram^{1/2}$.

Reactivity Measurements

The NASA ZPR-1, an unreflected solution reactor, was used for both the reactivity and activation experiments. The reactor is shown in figure 1 and is described in detail in reference 1. The fuel solution consisted of 93.3-percent enriched uranium-235 as uranyl fluoride in water. The fuel solution concentration was 7 percent by weight of uranyl fluoride with a hydrogen to uranium-235 atom ratio of about 500. Criticality was achieved by increasing the height of the fuel solution in the reactor vessel by small increments. The reactor was controlled entirely by variation of the solution height.

Reactivity measurements and activations were made by suspending the samples at the center of the reactor vessel in the wire sample holder shown in figure 1. The samples were separated from the fuel solution by a cylindrical methacrylate plastic box with a 0.25-centimeter wall thickness. For the reactivity measurements and the epithermal activations, the samples were within a 0.89-millimeter-wall cadmium cover in the methyl methacrylate box. The maximum container size used was 6.3 centimeters in diameter and 1.6 centimeters high. With the largest cadmium cover in place, the critical solution height was about 52 centimeters; without the cadmium cover, the height was about 46 centimeters. Solution height changes could be measured to ±0.2 mil (±5 μm) using the micrometer lead screw height measuring device shown in figure 1.

The reactivity of a sample at the center of the core was determined as the difference between critical height ΔH for sample-in and sample-out conditions. After several experiments were performed with different samples, the critical height with the sample holder and empty cadmium cover was redetermined to assure that reference reactor

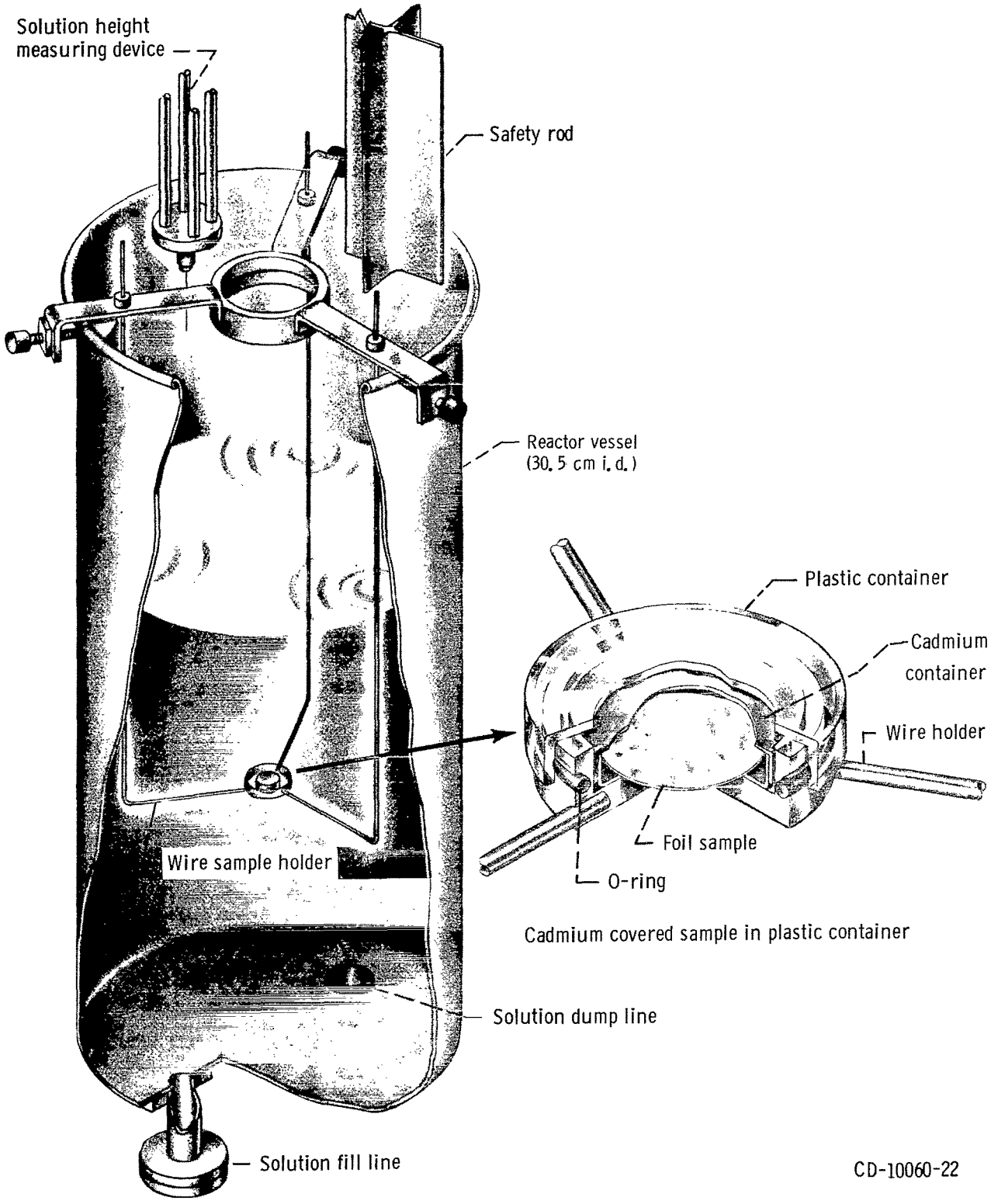


Figure 1. - Samples in reactor vessel.

conditions were maintained. A reference critical solution height of 45.720 centimeters at a reference solution temperature of 21.1° C was maintained.

Sample Preparation and Activation Techniques

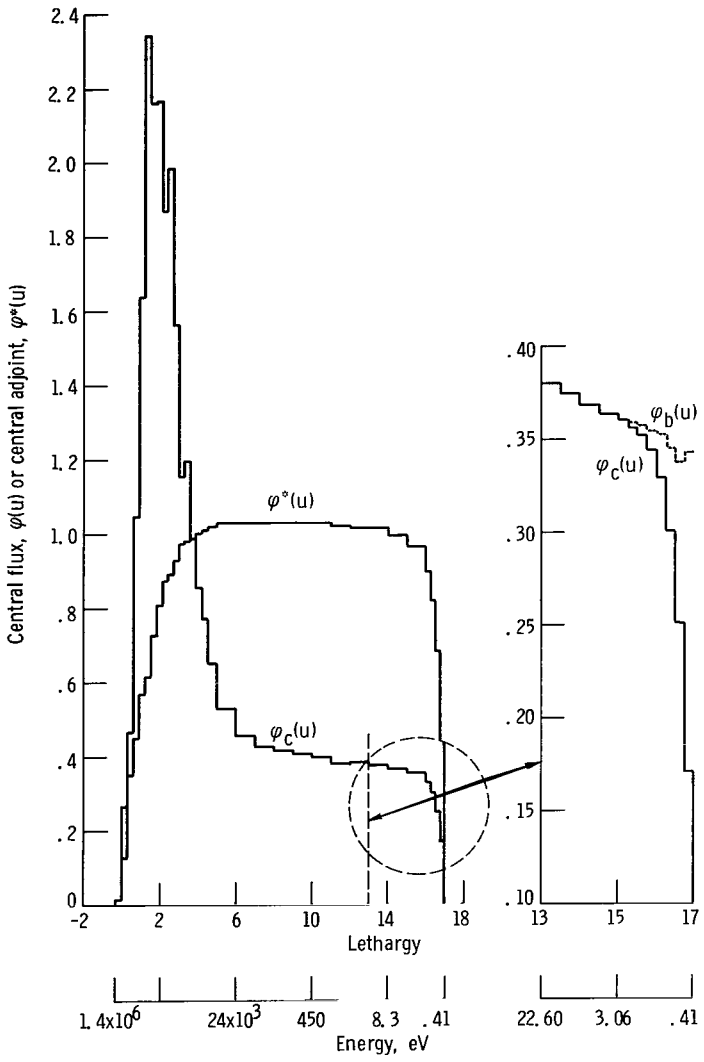
The thin samples were prepared by vacuum depositing the metal on 2.5×10^{-3} centimeter thick aluminum. Five tantalum and two gold foils were prepared this way. The amount deposited was determined by weighing the aluminum foil before and after deposition. Errors in weights are estimated to be less than 10 percent. Since the same samples were used for the cadmium shield as for the bare activations, errors in weight for these thin samples are not very important. The thick samples were 5.08-centimeter-diameter disks cut from tantalum sheet metal and from gold sheet metal.

Both β and γ counting was done. Because γ-rays are emitted with much lower intensity than β-rays for the thinnest samples, these samples were beta counted. A windowless 2π proportional gas-flow counter was used. The plateau was checked at regular intervals, and count rates were monitored using a depleted uranium sample. Beta detection efficiency can be a problem for thicker samples because ϵ_c will not be equal to ϵ_b (eq. (6)), although the same sample is used for both bare and cadmium shielded activations. This efficiency difference is the result of neutron self-absorption in the sample (ref. 2). For this reason, the thicker samples were gamma counted, using a NaI(Tl) scintillation crystal and a single-channel analyzer. The tantalum samples were counted over the energy range from 1.06 to 1.50 million electron volt. The gold samples were counted over the energy range 0.3 to 0.9 million electron volt.

For the thick sample activation measurement, the resonance integral for $(S/M)^{1/2}$ equal to 3.14 centimeters per gram$^{1/2}$ was determined by cadmium ratio using equation (5); the resonance integrals for two other samples with $(S/M)^{1/2}$ between 1 and 10 were determined by measuring count rates taken in constant geometry, relative to this sample. Stacked samples were used for the thicker case, where γ-ray attenuation could be a problem.

Importance Correction Factor

The calculated scalar and adjoint flux per unit lethargy within the cadmium cover at the center of the reactor are shown in figure 2. The calculations were made using the method described in reference 11. The flux per unit lethargy $\varphi(u)$, varies slowly with lethargy over the resolved resonance region. Although $\varphi^*(u)$, the adjoint function, is constant over much of the resonance region, it declines rapidly to zero from about 3 to



(a) Flux and adjoint flux with cadmium cover.

(b) Magnification of flux below 22.60 electron volts.

Figure 2. - NASA ZPR-1 central flux and central adjoint flux.

0.41 electron volt because of the cadmium cover. The details of calculating the importance correction factor of equation (3) have been discussed in reference 1. As will be shown presently, the maximum value of this importance correction factor for tantalum is 1.10.

Inelastic Scattering Effect

The observed negative reactivity data for absorptive samples included an inelastic scattering effect that is opposite in sign to the resonance capture effect. Therefore, the observed negative reactivity data must be made more negative by correcting for the inelastic reactivity effect.

The inelastic scattering effect was determined relative to a reactivity coefficient of 14.7 mils per 10^{24} atoms (373 μm/10^{24} at.) that was measured for lead (ref. 1). This resulted in a 4-barn correction to the data, which is significant for the thickest samples.

Activation Flux Correction Factors

The flux correction factors A and μ (eq. (5)) for the activation experiment are obtained by the same method as that used for calculating the importance correction factor. The calculated flux $\varphi_b(u)$ for the bare sample irradiation is shown in figure 2(b). The flux is significantly different from the flux within the cadmium cover $\varphi_c(u)$ between about 3 and 0.41 electron volt. Above 3 electron volts, there is no significant difference between $\varphi_c(u)$ and $\varphi_b(u)$.

CALCULATIONS FROM RESONANCE PARAMETERS

Methods for calculating I_{eff} from measured resonance parameters and statistical distributions of these parameters are available (refs. 7 and 8). The analytical methods used herein are digital computer techniques that employ direct numerical integration of the integral equations representing neutron captures and scattering processes for a sample surrounded by a hydrogenous moderator. The methods make use of the flat-source assumption for computing escape probabilities that account for scattering in the sample. This source distribution is a good approximation for predominantly capturing resonances present in tantalum.

TABLE I. - CALCULATED EFFECTIVE RESONANCE INTEGRALS FOR TANTALUM

USING THE ZUT-TUZ and the GAROL CODES

Sample thickness, τ, cm	Sample size $(S/M)^{1/2}$, $cm/g^{1/2}$	Energy range, eV				
		0.5 - 1.83	1.83 - 330	330 - 10 560	10 560 - 10^6	0.5 - 10^6
		Effective resonance integral, I_{eff}, b				
10^{-6}	347	4.5	698.3	24.8	3.6	731.2
10^{-5}	109.8	4.5	692.4	24.8	3.6	725.3
10^{-4}	34.7	4.5	656.1	24.7	3.6	688.9
10^{-3}	10.98	4.5	499.0	24.5	3.6	531.6
10^{-2}	3.47	4.5	229.6	23.2	3.6	260.9
10^{-1}	1.098	4.3	77.9	17.3	3.6	103.1
10^{0}	.347	3.4	24.0	9.1	3.4	39.0

Effective Resonance Integrals

Calculated effective resonance integrals for tantalum using the ZUT-TUZ (ref. 7) and the GAROL (ref. 8) computer codes are presented in table I. A range of sample thicknesses from dilute to very thick are considered. The first resonance integral column lists the contributions to the resonance integral from cadmium cutoff of 0.50 electron volt to $3E_0^1/7$, where E_0^1 is the resonance neutron energy for the first resolved energy resonance at 4.28 electron volt, calculated using a thermal capture cross section of 21.0 barns (ref. 10) and the GAROL code (ref. 8). The second column lists the contributions for the resolved region to 330 electron volts calculated using the ZUT code. Neutron resonance parameters used in this calculation were obtained from reference 4. The third column lists contributions for the unresolved region to 10 000 electron volts obtained using the TUZ code. The average parameters are listed as follows:

Average capture width, $\langle\Gamma_\gamma\rangle$, mV	56
Average reduced neutron width, $\langle\Gamma_n^o\rangle$, mV	1.60
Average level spacing, $\langle D\rangle$, eV	4.35
Statistical factor, g	0.5

The values for $\langle\Gamma_n^o\rangle$ were obtained from references 5 and 6. The values for $\langle\Gamma_\gamma\rangle$ and $\langle D\rangle$ were obtained from the resolved resonances. The fourth column of table I lists contributions for energies above 10 000 electron volts where the absorption of neutrons of higher angular momentum becomes important; the recommended curve of average cross sections of reference 4 were used with the GAROL code. The last column lists the total

epi-cadmium effective resonance integrals with a dilute integral calculated as 731.2±35 barns. The uncertainty has been estimated from the uncertainties in the parameters of the larger resolved resonances.

The value used for $\langle \Gamma_n^o \rangle$ in the TUZ calculation has small effect on the total resonance integral for tantalum although tantalum has considerable resonance structure in this energy range. This is because the resolved resonances make a substantial contribution to the resonance integral, even for the thicker samples considered herein. A value for $\langle \Gamma_n^o \rangle$ of 1.84×10^{-3} electron volt, obtained from the recommended value of 2.1×10^{-4} for the s-wave strength function (ref. 6) results in a TUZ code value of 26.17 barns for the contribution to the dilute integral and 9.26 barns for the contribution to the resonance integral for the thickest samples. These values are higher than the corresponding values given in table I by only 1.41 and 0.12 barns, respectively.

Importance Correction Factors

The importance weighted effective resonance integrals are shown in table II for three moderate to thick tantalum samples. The sample size is expressed in terms of $(S/M)^{1/2}$ (surface area/(sample mass)$^{1/2}$, cm/g$^{1/2}$). Six neutron energy groups in the resolved region below 330 electron volts and three groups in the unresolved region to 10 500 electron volts are considered separately. All higher energies are combined into a single group. The importance parameter (see eq. (3)) which is the product of the group flux and group adjoint for the NASA solution reactor and which corrects for departures from the standardized inverse energy flux variation, is shown in the second column. The rapid self-shielding of the lower group resonances as sample thickness increases (smaller $(S/M)^{1/2}$) is apparent. The more gradual fall-off of contribution to the calculated effective resonance integral for the unresolved region is also apparent. The results of the calculations illustrated in table II also indicate the magnitude of the importance correction factor applied to the present experimental reactivity measurements to vary from 1.05 to 1.10.

Resonance Overlap Effect

The existence of possible resonance overlap effects in the resolved region were evaluated by separate calculations using the GAROL computer code. The resolved region was divided into energy groups, and the calculation was done separately for each group to insure adequate mesh coverage of the resonances. Two, and for some groups three, sets of resonances were formed from the resolved resonances of tantalum and were

TABLE II. - IMPORTANCE WEIGHTED EFFECTIVE RESONANCE INTEGRAL

FOR TANTALUM-181

Neutron energy range, eV	Product of flux and adjoint, $\varphi\varphi^*$	Sample size, $(S/M)^{1/2}$, $cm/g^{1/2}$					
		3.47		1.098		0.347	
		Effective resonance integral, I_{eff}^{calc}	Flux-weighted resonance integral, $I_{eff}^{calc}\varphi_c\varphi_c^*$	Effective resonance integral, I_{eff}^{calc}	Flux-weighted resonance integral, $I_{eff}^{calc}\varphi_c\varphi_c^*$	Effective resonance integral, I_{eff}^{calc}	Flux-weighted resonance integral, $I_{eff}^{calc}\varphi_c\varphi_c^*$
0.41 to 1.83	0.56	5.5	3.1	5.3	3.0	4.1	2.4
0.50 to 1.83	----	4.5	---	4.3	---	3.4	---
1.83 to 7.3	1.00	101.7	101.7	30.4	30.4	8.2	8.2
7.3 to 37.6	1.05	68.0	71.1	23.7	24.7	7.4	7.7
37.6 to 102	1.07	29.3	31.4	11.6	12.4	4.5	4.8
102 to 198	1.10	14.8	16.3	6.1	6.7	2.3	2.5
198 to 330	1.13	14.5	16.3	6.5	7.3	2.5	2.8
330 to 1300	1.15	16.1	18.5	11.0	12.7	5.0	5.8
1300 to 5300	1.19	5.9	7.0	5.1	6.1	3.2	3.8
5300 to 10 500	1.23	1.2	1.5	1.2	1.5	.9	1.1
Higher energy	1.92	3.6	6.9	3.6	6.9	3.4	6.5
Total	----	[a]259.6	273.8	[a]103.4	111.7	[a]40.8	45.6
Importance correction factor, $I_{eff}^{calc}\varphi(u)\varphi^*(u) / I_{eff}^{calc}$		1.05		1.08		1.12	

[a]Total for a cadmium cutoff of 0.5 eV.

run separately using GAROL. The sets were made up such that no resonance energy spacing was less than 5 electron volts. The resonances were then combined in their natural order to obtain the resonance integral contributions with overlap. Resonance overlap shows only a 2-percent reduction in the contribution from the important resonance at 4.21 electron volts for an $(S/M)^{1/2}$ of 0.347 centimeter per $gram^{1/2}$, but more significant reductions due to overlap occur for other resolved resonances. The reduction for this sample size for the 32- to 42-electron-volt energy region is 31 percent or 0.8 barn. The total reduction in the resolved resonance contribution was 9 percent (or 2.2 b) for a $(S/M)^{1/2}$ of 0.347 centimeter per $gram^{1/2}$ and 2 percent (or 1.6 b) for an $(S/M)^{1/2}$ of 1.098 centimeter per $gram^{1/2}$. The resonance overlap effect is insignificant for a thinner sample with an $(S/M)^{1/2}$ of 3.47 centimeters per $gram^{1/2}$.

For the unresolved region the overlap effect was checked by generating a set of specific resonances that satisfy measured statistical averages using a random sampling technique like that described in reference 9. This set of resonances in the 330- to 2640-

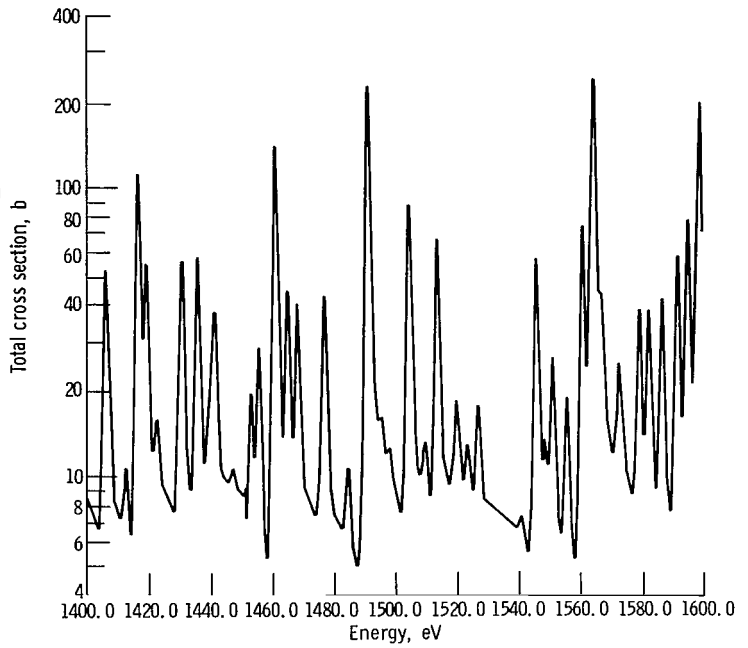


Figure 3. - A plot of cross sections over small portion of unresolved resonance region. Parameters for these generated resonances were used in ZUT and GAROL codes to test for resonance overlap effects.

electron-volt region were compared by calculation using ZUT and GAROL. A plot of cross sections in a portion of this region is shown in figure 3. The cross sections in the region shown vary from 5 to 250 barns. Comparison of calculated results shows a 10-percent (0.7 b) reduction due to overlap in the resonance integral for the energy region considered and for an $(S/M)^{1/2}$ of 0.347 centimeter per gram$^{1/2}$. For an $(S/M)^{1/2}$ of 1.098, the reduction is 2 percent (0.3 b). These percentile reductions were assumed to hold for the total unresolved s-wave contribution to the resonance integral, making the contributions from 330 to 10 500 electron volts 8.2 and 16.9 barns for sample sizes of $(S/M)^{1/2}$ equal to 0.347 and 1.098 centimeters per gram$^{1/2}$, respectively. For a relatively thin sample with $(S/M)^{1/2}$ of 3.47 centimeters per gram$^{1/2}$ there was no significant difference in the two results. Therefore, the resonance overlap effect in the unresolved region is important only for thick samples. Applying these corrections, the calculated resonance integrals for the two thickest sample sizes shown in table I reduce to 36.8±1.8 and 101.8±4.8 barns, where the uncertainties have been estimated from the resonance parameters.

TABLE III. - MEASURED RESONANCE INTEGRALS

FOR TANTALUM

Sample thickness, mg/cm^2	Sample size, $(S/M)^{1/2}$, $cm/g^{1/2}$	Resonance integral, b
0.04	Dilute	[a]720±25
.30	82	[a]685±40
43.1	7.0	[a]416±20
102.0	4.43	[b]292±20
204.0	3.13	[b]222±10
218.0	3.13	[a]241±10
648.0	1.81	[a]157±10
1825.0	1.05	[b]93±5
3650.0	.74	[b]74±5
8160.0	.50	[b]51±3

[a]Values obtained by activation.

[b]Values obtained by reactivity.

RESULTS AND DISCUSSION

Effective Resonance Integrals

The measured activation and reactivity resonance integral values for tantalum-181 are shown in table III. For the thicker samples measured by reactivity, the correction that is required due to inelastic scattering in the sample (see eq. (4)), has been estimated to be 4 barns, and this value has been included in the data shown in table III. The dilute value shown in the table is the average of the values obtained for the very thin samples with $(S/M)^{1/2}$ values greater than 100 centimeters per $gram^{1/2}$. The measurements throughout this range of values of $(S/M)^{1/2}$ show no change in the resonance integral beyond the error limits.

The measured and calculated resonance integrals are shown in figure 4, plotted against sample size. Resonance integrals calculated using the ZUT-TUZ code for the resolved and unresolved s-wave contributions (table I) are shown as the solid line. The dashed line shows the result of correcting for the overlap effect. The agreement between measured and calculated values is very good when the overlap effect is taken into account.

The experiment does not provide conclusive evidence for the overlap effect because of the uncertainties in the calculated and measured values. There is an indication, however, that for thick samples the overlap effect can be of significance in determining the neutron capture rate for the sample.

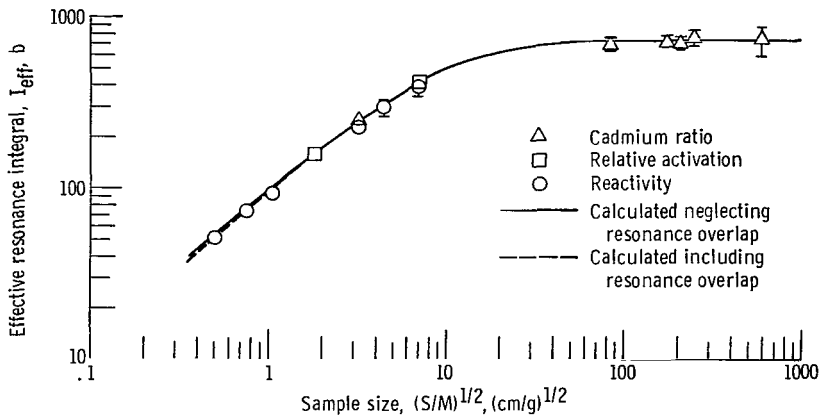


Figure 4. - Effective resonance integrals for tantalum.

TABLE IV. - SUMMARY OF EXPERIMENTAL VALUES OF TANTALUM RESONANCE INTEGRALS

Resonance integral, b	Source	Method of measurement	Resonance integral of gold	Thermal absorption cross sections		Corrected[a] resonance integral
				σ_{th}^{Ta}	σ_{th}^{Au}	
517±80	Ref. 14	Cadmium ratio	1337	20.6	93	659±80
474±62	Ref. 13	Reactivity	----	----	--	474±62
1100±400[b]	Ref. 12	Reactivity	1558	----	--	[b]1110±400
$720\pm^{50}_{80}$	Ref. 10	Cadmium ratio	1558	21.0	98.7	[b]$728\pm^{50}_{80}$
720±25	This report	Cadmium ratio	1575	21.0	98.8	720±25

[a]Corrected for resonance integral and thermal cross section used in this work.
[b]About 6 b should be added to these values to extend the integral to 0.5 eV.

Dilute Resonance Integrals

The dilute resonance integrals measured were compared with dilute values obtained by others in table IV. The various measured results have been corrected for reference gold dilute resonance integrals and thermal absorption cross sections used herein. The large discrepancy in the Tattersall et al. result (ref. 12) may be due to an error in extrapolating to the dilute sample region from measurements made on thick samples. The lower value in reference 13 could be due to a deviation of the spectrum from a 1/E variation.

Estimation of Uncertainties

For the reactivity results, the errors were determined (ref. 1) by the uncertainty of the reactivity coefficient measurement plus an estimated uncertainty of 10 mils per 10^{24} atoms (254 m/10^{24} at.) for the inelastic scattering correction, which corresponds to 1 barn in the I_{eff} scale. For the activation results, the errors are determined by the counting statistics and the uncertainties in the thermal cross sections and in the gold resonance integral. The uncertainties are standard deviations. The uncertainty in the measured dilute resonance integral was obtained from the standard deviation of the values for samples with $(S/M)^{1/2} > 100$, using the formula for data pooling.

CONCLUSIONS

Effective resonance integrals of tantalum were measured for a range of thicknesses varying from 10^{-6} to 0.5 centimeter and were found to be in agreement with resonance integral values calculated using the GAROL and the ZUT-TUZ codes. The measurements resulted in a dilute resonance integral of 720±25 barns which is in agreement with a calculated value of 730±35 barns.

For thick samples, a comparison of calculated and measured resonance integrals indicated a slight discrepancy for the thickest samples measured. Comparison of calculated resonance integrals using the ZUT-TUZ and the GAROL codes for the same energy region produced a test for resonance overlap effects. Resonance overlap effects for thick tantalum samples were present for contributions in both the unresolved and the resolved energy regions. When the calculated values are corrected for resonance overlap, the agreement between measurement and calculation is good for all values considered.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 27, 1969,
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