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Reactivity Effects of Structural
Materials in the BEM-II B

K. V. Cooper

W. B. Henderson

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REACTIVITY EFFECTS OF STRUCTURAL MATERIALS
IN THE BEM-II B

K. V. Cooper and W. B. Henderson

UNITED STATES AIR FORCE

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ABSTRACT

Reactivity effects of 93.2% enriched or alloy, molybdenum, iron, niobium, 310 stainless steel, 304 stainless steel, Inconel X, FeCrAl, zirconium, nickel, nichrome V, and chromium clad with FeCrAl, in the form of foils in the center cell of the BEM-II B minimum void, beryllium moderated critical experiment are reported. Nineteen-energy-level diffusion calculations with cell corrections from both coarse and fine energy detail are correlated with the measurements. The fine energy detail improves the correlation, mainly because resonance self-shielding and flux depression are more adequately treated, and residual discrepancies for the most part can be attributed to inadequacies in the cross section data.

ACKNOWLEDGEMENT

The experimental data reported herein were gathered under the direction of D. H. Fraembs, Critical Experiments Unit.

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1.0 INTRODUCTION

The main purpose of this work was to determine the adequacy of ANPD diffusion analysis methods and data for predicting the reactivity effects of structural materials inhomogeneously distributed in a beryllium moderated reactor. There are many potential sources of error in this theory-experiment correlation, some of which are: the reactivity-displacement relation of a master and two auxiliary control rods by inter-calibration in terms of an arbitrary reactivity unit; the evaluation of the reactivity unit by inserting calculated kinetic constants and measured periods in the inhour equation; the assumptions of slowing-down-diffusion theory when applied to small sources and sinks; the assumptions contained in using mono-energetic cell corrections; the adequacy of the spectroscopic analysis for high absorption impurities; and the adequacy of the cross section data.

Although some error due to each of the above mentioned sources is no doubt present, by far the largest errors are concerned with the cross section data. Failure to use fine energy resonance detail, where it is available, in computing cell corrections can lead to gross overprediction of reactivity effects (74% overprediction in molybdenum was observed). Incomplete resonance data as evidenced by computed absorption integrals considerably smaller than measured (as in iron) leads to serious underprediction of reactivity effects. Absorption cross sections measured in broad spectrum resolution, which fails to resolve the resonance structure (as in molybdenum and niobium between 1 Kev and 100 Kev), while probably adequate for dilute homogeneously distributed poisons, lead to overprediction of reactivity effects when self-shielding must be applied.

2.0 EXPERIMENTAL RESULTS

Experiments performed in the BEM-II B critical assembly at GE-ANPD in January of 1959 yielded measurements of the reactivity effect of 93.2% enriched or alloy and structural materials including molybdenum, iron, niobium, 310 stainless steel, 304 stainless steel, Inconel X, FeCrAl, zirconium, nickel, nichrome V, and chromium clad with FeCrAl.

The BEM-II B critical assembly consists of hexagonal beryllium rods inserted in close packed array in an aluminum matrix. In the fueled region of the assembly the beryllium rods are split longitudinally and fuel in the form of thin foils is sandwiched between the halves. For the purpose of these measurements the fuel foil was removed from the center cell and the worth of this removal was measured. Foils of the various structural materials were then inserted in the vacated fuel space and the worths of these materials were measured. Measurements were made in terms of reactivity units (r.u.), where

$$1000 \text{ r.u.} = .773\% \frac{\Delta k^1}{k}$$

The conversion of the reactivity unit to reactivity is based on the inhour equation with six delayed groups. Kinetic constants were obtained from Program C_5^1 and the experimentally observed period.

The experimental results are given in Table 1. The accuracy is estimated to be $\pm 3\%$ or ± 5 r.u., whichever is larger, and is indicated accordingly in the table. The sign on the reactivity units corresponds to the change in reactivity when the foil is inserted into the void.

Table 1
MEASURED REACTIVITY OF FUEL AND STRUCTURAL MATERIALS
IN THE CENTER CELL OF THE BEM-II B

<u>Material</u>	<u>Foil Thickness (inches)</u>	<u>Weight (gm)</u>	<u>Reactivity (r.u.)</u>
Oralloy	.016	198.36	191 $\pm$ 6
Mo	.020	165.4	-165 $\pm$ 5
Fe	.020	120.3	-51 $\pm$ 5
Nb	.040	270.6	-151 $\pm$ 5
310 SS	.018	113.1	-62 $\pm$ 5
304 SS	.018	112.1	-62 $\pm$ 5
Inconel X	.0115	77.6	-52 $\pm$ 5
FeCrAl	.012	67.3	-26 $\pm$ 5
FeCrAl	.0245	137.9	-58 $\pm$ 5
Zr	.050	220.6	0 $\pm$ 5
Ni	.009	64.9	-40 $\pm$ 5
Nichrome V	.012	84.6	-52 $\pm$ 5
Cr clad with FeCrAl	total .020; cladding thickness .0055 on each side	110.8	-52 $\pm$ 5

3.0 METHODS OF ANALYSIS

3.1 Reactivity

The program used for the reactivity calculations was the one-dimensional, multi-region, multi-energy, slowing-down-diffusion Program G_2 (ANP Program 26). This program uses a nineteen-energy-level scheme and as many

¹P. G. Fischer, F. D. Wenstrup, and R. A. Pastore, "Program C_5 - Direct and Adjoint Bare Reactor Program -- Multi-group Constant Generator," XDC 59-6-220, May 13, 1959.

as 500 spatial lattice points in computing the flux, power density, and multiplication constant in the one-dimensional reactor.

The cross sections of the principal elements in the foil materials of this study and the lethargies corresponding to the nineteen levels (lethargy zero = 10 Mev) are reproduced in section 4.0 directly from the nuclear data tape³ on which they are permanently recorded. For the purpose of reducing the calculations to one dimension the aluminum matrix and the foil materials, where present, were homogenized with the beryllium over the volume of each cell of the assembly. The center cell was treated as the inner region, the surrounding annulus of fueled cells as the second region (core), and the unfueled beryllium cells as the outer region (reflector). Since the assembly is unreflected on the ends, a one-dimensional radial calculation with perpendicular buckling computed from the bare height plus energy dependent extrapolation distance was considered to be an accurate portrayal of the assembly. The calculated multiplication constant of 0.997 bears out this contention. The regional and material data used in the G_2 calculations are given in Table II.

Table II

THE BEM-II B CONFIGURATION IN PROGRAM G_2

<u>Region</u>	<u>Center Cell</u>	<u>Core</u>	<u>Reflector</u>
Outer radius (cm)	2.3372	19.96	28.66
Number of Radial Space Intervals	10.0	60.0	40.0
Height (cm)	81.28	81.28	81.28
Material Volume Fractions			
Be ($\rho = 1.854$)	0.8472	0.8472	0.897
Al ($\rho = 2.70$)	0.0692	0.0692	0.0692
Oralloy ($\rho = 18.7$) or other foil	See Table I. The foil weight is homogenized over a cell volume of 1394.88 cm ³		

3.2 Cell Corrections

In an attempt to preserve the reaction rates in the homogenized cells, a cell correction, g , defined as the ratio of the average flux, ϕ , in the foil to the average flux in the moderator at a particular lethargy, u , was

³W. B. Henderson and M. J. Stanley, "Cross Sections for Reactor Analysis," APEX 515, May, 1957; Supplement 1, XDC 59-11-72, October 26, 1959; Supplement 2, XDC 60-6-148, June 30, 1960.

applied to all foil cross sections, σ , at that level. The cell corrections were computed by Program SLABG (ANP Program 209), which assumes monoenergetic slab diffusion theory in the moderator and determines the transmission and reflection coefficients of the foil in an infinite mass (monoenergetic) approximation to the integral transport equation by assuming cosine and cosine squared entrance current components and a spatially flat distribution of collided flux in computing the scatter collision density.

Two methods for determining the nineteen-level cell corrections for Program G₂ were used. The shorter method consisted of computing cell corrections from the nineteen-level foil cross sections given in section 4.0. Since it is important to preserve the foil reaction rate per atom integrated over lethargy,

$$\int_0^{\infty} \sigma \phi \, du,$$

it is unlikely that this method would be adequate when the cross section shows significant resonance structure which, if present, has already been averaged to obtain the nineteen-level cross sections.

To demonstrate how important the fine structure may be, the second method made use of the cross sections before averaging. These cross sections are contained on the C-Fine nuclear data tapes⁴, where each resonance for which resonance parameters were known has been portrayed by 23 points which preserve the absorption integral over the resonance to within 2% by trapezoidal integration. The flat flux averaging procedure of Program C-Fine (ANP Program 180)⁵ was used to generate nineteen-level cell-corrected cross sections, $g \sigma$. In this method a parameter table containing twenty entries of cell correction versus macroscopic absorption cross section, Σ_a , which spans the variation of absorption cross section with energy for a particular foil is provided as input to Program C-Fine. The program interpolates in the table to apply the appropriate g value to the cross sections at each fine energy level. The nineteen-level values of cell-corrected cross sections are computed in the program by averaging over groups with divisions at the mid-lethargy points between levels. This procedure preserves the reaction rates provided the flux is flat in lethargy ($1/E$ in energy).

⁴J. R. Cooper and W. B. Henderson, "Nuclear Data Tape Program with Fine Energy Detail," XDC 60-8-69, May 13, 1960.

⁵E. W. Klingenberg and W. B. Henderson, "Program C-Fine," XDC 59-12-230, December 22, 1959.

The correct utilization of the cell-corrected, digitalized cross sections from Program C-Fine would require the addition of these cross sections to the nineteen-level nuclear data tape.⁶ Since Program G₂ admits a single value of the cell correction at each level, it is possible to avoid adding cross sections to the tape by assuming that the cell corrections which would convert the nineteen-level absorption cross sections on the nineteen-level tape to the cell corrected values obtained from Program C-Fine could also be applied to all other cross sections. Actually the cell correction $g_x = \frac{g\bar{\Sigma}_x \text{ from C-Fine}}{\bar{\Sigma}_x \text{ from 19-level tape}}$ will be different for each type of cross section. Since the foils contribute very little to the homogenized cell scatter cross section and since the ratio of the absorption cross section, σ_a , to the fission cross section, σ_f , in or alloy is fairly constant on the average over a group, this assumption appears reasonably well justified. Consequently, the cell corrections at each level used in Program G₂ were defined as $g_a = \frac{g\bar{\Sigma}_a \text{ from C-Fine}}{\bar{\Sigma}_a \text{ from 19-level tape}}$. The value of $g_f = \frac{g\bar{\Sigma}_f \text{ from C-Fine}}{\bar{\Sigma}_f \text{ from 19-level tape}}$ was found to differ from g_a by less than 1% at every level.

4.0 CROSS SECTIONS

The principal cross sections which were evaluated by this study are reproduced on the following pages from the nineteen-level nuclear data tape. The other cross sections used in this study (U234, CFINE; U236, CFINE, RBE(N,ZN), AL CFINE, C CFINE, TI CFINE, Y CFINE, MN CFINE, and ZR CFINE) are listed in APEX 515⁷ and supplements thereto. The lethargy, $\ln \frac{E_0}{E}$, is based on $E_0 = 10$ Mev. All cross sections except those of beryllium have been digitalized by the flat flux averaging procedure in Program C-Fine and contain the same nuclear data from the C-Fine nuclear tapes as was used in obtaining the cell corrected digitalized cross sections as described in section 3.2.

The levels 3000 through 68 are thermal group cross sections, averaged over a Maxwellian flux for the Fahrenheit temperature indicated by the level number. Since this study was performed at room temperature, the 68°F cross sections were used as the thermal group.

Since all cross sections were supplied from Program C-Fine output, the use of ξ in $\xi\sigma_s$ and $(1-B)$ in $\sigma_{tr} = (1-B)\sigma_s$ was not necessary. For this reason, the values of XI and 1-B in the listings are not meaningful.

⁶K. Paine, "Nuclear Data Tape Program (704 Program NDTP)," XDC 58-2-204, December 20, 1957.

⁷Op. cit., APEX 515

The data which were used to determine cell homogenized macroscopic cross sections are given in Table III.

Table III
DATA FOR DETERMINING CELL HOMOGENIZED
MACROSCOPIC CROSS SECTIONS

<u>Material</u>	<u>Composition (wt. %)</u>	<u>Data</u>
Be	100% Be	Density and volume fractions given in Table II
Al	100% Al	"
Oralloy	93.18% U ²³⁵ , 5.42% U ²³⁸ 1.0% U ²³⁴ , 0.4% U ²³⁶	Density from foil weight in Table I and cell volume in Table II
Mo	100% Mo	"
Fe	100% Fe	"
Nb	100% Nb	"
Zr	100% Zr	"
Ni	100% Ni	"
310 SS	55.9% Fe, 25.0% Cr, 19.1% Ni	"
304 SS	71.42% Fe, 19% Cr, 9.5% Ni, 0.08% C	"
FeCrAl	65% Fe, 25% Cr, 5% Al, 3% Nb, 2% Y	"
Inconel X	73% Ni, 15% Cr, 7% Fe, 2.5% Ti, 1% Nb, 0.5% Mn	"
Nichrome V	80% Ni, 20% Cr	"
Cr clad with FeCrAl	35.94% Fe, 58.53% Cr, 2.76% Al, 1.66% Nb, 1.11% Y	Composition determined from volume fractions in Table I. Thus 11/20 is chromium, $\rho = 7.277$, and 9/20 is FeCrAl, $\rho = 7.19$. Density for this mixture from foil weight in Table I and cell volume in Table II.

5.0 RESULTS

The reactivity effect of the foils given in Table I were computed by Program G₂ as described in section 4.1. The calculated and measured reactivities are compared in Table IV. The reactivity was computed as $\Delta k/k$, largely because of precedent, where Δk is the change in multiplication constant when the foil is inserted into the void and k is the multiplication constant with foil inserted. It is fortunate that k is so close to unity (Δk and $\Delta k/k$ do not differ by more than about $\frac{1}{2}\%$), since there is no valid reason to assume that the error in k also appears in Δk in the same proportion and since the experimental k was made unity both before and after foil insertion by means of the calibrated reflector controls.

APRIL 18, 61

DESIGNATION	FORMULA	CODE	DENSITY
CF 235 URAN	U235 CFINE	-1.0820	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	I-B
92.00000	235.11750	1.00000	0.00000

CROSS SECTIONS

LETHARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	3.4374614	0.6763955	0.6910081	2.5352148
1 0.500	5.1834738	3.2801998	2.3465369	1.7129494
2 1.000	6.2512301	4.0615421	3.4982190	1.4451706
3 1.500	5.7645340	2.6008012	3.3766386	1.5123018
4 2.000	5.1522307	1.7468553	3.2729288	1.4681921
5 2.500	5.3590515	1.6220368	3.7601081	1.3968770
6 3.000	6.1992431	1.3476928	4.6034080	1.4404724
7 3.500	7.4234471	1.0129796	5.8534204	1.6239860
8 4.000	9.2629858	0.8042408	8.1910087	2.1108953
9 6.000	10.352577	0.0985557	10.245376	3.7301160
10 8.000	10.199984	0.0872915	10.170812	7.3692298
11 10.000	13.149161	0.1125305	13.111553	21.010643
12 12.000	21.319517	0.1824524	21.258541	54.873752
13 14.000	10.675002	0.0913567	10.644471	79.567306
14 15.500	11.171581	0.0956064	11.139630	35.867774
15 16.500	12.644239	0.1082094	12.608076	85.865986
16 17.500	13.656149	0.1168693	13.617092	221.39245
17 18.500	14.209185	0.1216022	14.168546	326.47052
18 19.795	14.427859	0.1234730	14.386597	520.62417
3000 17.675	14.000000	0.1198000	13.960000	214.20000
2500 17.831	14.000000	0.1198000	13.960000	234.80000
2000 18.016	14.000000	0.1198000	13.960000	260.70000
1500 18.243	14.000000	0.1198000	13.960000	294.60000
1000 18.537	14.000000	0.1198000	13.960000	343.40000
500 18.957	14.000000	0.1198000	13.960000	429.40000
68 19.555	14.000000	0.1198000	13.960000	600.39998

14.

DESIGNATION	FORMULA	CODE	DENSITY
CF 235 URAN	U235 CFINE	-1.0820	0.00000

LEVEL	LETHARGY	NU	SIGMA	FISSION
			FISSION	SPECTRUM
0	0.000	6.9925210		0.0000000
1	0.500	4.5403728		0.0000000
2	1.000	3.6345988		0.0000000
3	1.500	3.6462461		0.0000000
4	2.000	3.4146576		0.0000000
5	2.500	3.1485105		0.0000000
6	3.000	3.1571243		0.0000000
7	3.500	3.4727327		0.0000000
8	4.000	4.3411736		0.0000000
9	4.000	7.2096283		0.0000000
10	8.000	13.321375		0.0000000
11	10.000	35.433343		0.0000000
12	12.000	88.213590		0.0000000
13	14.000	116.75076		0.0000000
14	15.500	67.543470		0.0000000
15	16.500	180.91095		0.0000000
16	17.500	454.13146		0.0000000
17	18.500	684.54809		0.0000000
18	19.795	1085.1309		0.0000000
3000	17.675	436.80000		0.0000000
2500	17.831	478.80000		0.0000000
2000	18.016	532.10000		0.0000000
1500	18.243	602.60000		0.0000000
1000	18.537	705.60000		0.0000000
500	18.957	886.89999		0.0000000
68	19.555	1242.0000		0.0000000

APRIL 18.6J

DESIGNATION	FORMULA	CODE	DENSITY
CF 238 URAN	U238 CFINE	-1.0840	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	I-B
92.00000	238.12520	1.00000	0.00000

CROSS SECTIONS

LETHARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	4.8740267	6.6944607	3.0368882	1.0150000
1 0.500	6.2302029	5.8982034	3.1788638	0.7200939
2 1.000	7.1895432	4.5505559	3.3670933	0.5822751
3 1.500	6.6943703	3.2884843	3.7677715	0.5990790
4 2.000	6.5530605	2.3073481	4.4849035	0.2665853
5 2.500	6.9065034	1.3932751	5.0202868	0.1523061
6 3.000	8.0344107	0.7122479	6.1540152	0.1270516
7 3.500	9.3166157	0.3632919	7.5274119	0.1369370
8 4.000	11.472360	0.1656840	10.174524	0.2397217
9 6.000	13.264913	0.1138595	13.129704	0.4704326
10 8.000	14.298487	0.1201073	14.258450	1.1110579
11 10.000	23.668785	0.1988178	23.602509	6.0971205
12 12.000	56.919174	0.4781211	56.759800	37.908871
13 14.000	24.137062	0.2027513	24.069479	111.31363
14 15.500	7.9855257	0.0670784	7.9631663	0.5335789
15 16.500	8.2824273	0.0695724	8.2592366	0.5906141
16 17.500	8.3449018	0.0700972	8.3215362	0.8863046
17 18.500	8.3663111	0.0702770	8.3428853	1.4152286
18 19.795	8.3502400	0.0701420	8.3268591	2.0570701
3000 17.675	8.6575999	0.0727238	8.6333586	0.9525000
2500 17.831	8.6163000	0.0723769	8.5921743	1.0298000
2000 18.016	8.5649999	0.0719460	8.5410179	1.1296000
1500 18.243	8.4957999	0.0713647	8.4720116	1.2656000
1000 18.537	8.3967999	0.0705331	8.3732888	1.4664000
500 18.957	8.2340000	0.0691656	8.2109447	1.8085000
68 19.555	7.9182000	0.0665129	7.8960289	2.4389000

16.

DESIGNATION	FORMULA	CODE	DENSITY
CF 238 URAN	U238 CFINE	-1.0840	0.00000

LEVEL	LETHARGY	NU SIGMA FISSION	FISSION SPECTRUM
0	0.000	3.7597239	0.0000000
1	0.500	2.4032950	0.0000000
2	1.000	1.6843074	0.0000000
3	1.500	1.5529864	0.0000000
4	2.000	0.4584836	0.0000000
5	2.500	0.0190008	0.0000000
6	3.000	0.0004298	0.0000000
7	3.500	0.0000000	0.0000000
8	4.000	0.0000000	0.0000000
9	6.000	0.0000000	0.0000000
10	8.000	0.0000000	0.0000000
11	10.000	0.0000000	0.0000000
12	12.000	0.0000000	0.0000000
13	14.000	0.0000000	0.0000000
14	15.500	0.0000000	0.0000000
15	16.500	0.0000000	0.0000000
16	17.500	0.0000000	0.0000000
17	18.500	0.0000000	0.0000000
18	19.795	0.0000000	0.0000000
3000	17.675	0.0000000	0.0000000
2500	17.831	0.0000000	0.0000000
2000	18.016	0.0000000	0.0000000
1500	18.243	0.0000000	0.0000000
1000	18.537	0.0000000	0.0000000
500	18.957	0.0000000	0.0000000
68	19.555	0.0000000	0.0000000

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DESIGNATION	FORMULA	CODE	DENSITY
CF IRON	FE CFINE	4.0020	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	I-B
26.00000	55.86000	0.00000	0.00000

CROSS SECTIONS

LETHARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	3.2668091	3.3578186	1.6488002	0.0164391
1 0.500	3.6355741	3.0707483	1.8401255	0.0182947
2 1.000	3.4717118	2.4740702	2.2951270	0.0174884
3 1.500	2.9818451	1.6409864	2.3346322	0.0150021
4 2.000	2.7414634	0.9058794	2.3297191	0.0138006
5 2.500	2.7234236	0.4649042	2.3175361	0.0135700
6 3.000	3.2507674	0.2678747	2.9480067	0.0163422
7 3.500	3.0187835	0.1057665	2.5602092	0.0151644
8 4.000	5.4278527	0.1915952	5.2773098	0.0236071
9 6.000	9.3143156	0.3325211	9.2025439	0.0464360
10 8.000	7.7772703	0.2776485	7.6839429	0.0187645
11 10.000	10.359464	0.3698329	10.235150	0.0197468
12 12.000	11.344484	0.4049981	11.208349	0.0555143
13 14.000	11.262078	0.4020562	11.126934	0.1389542
14 15.500	11.154130	0.3982024	11.020280	0.2996990
15 16.500	11.041319	0.3941751	10.908823	0.5006877
16 17.500	10.929120	0.3901696	10.797970	0.8134154
17 18.500	10.730514	0.3830794	10.601748	1.3400252
18 19.795	10.658135	0.3804954	10.530237	1.9612291
3000 17.675	10.819700	0.3824800	10.690690	0.8707700
2500 17.831	10.810400	0.3821500	10.681500	0.9416800
2000 18.016	10.800200	0.3817900	10.671420	1.0334000
1500 18.243	10.785200	0.3812600	10.656600	1.1584800
1000 18.537	10.767200	0.3806200	10.638810	1.3441900
500 18.957	10.758200	0.3803100	10.629920	1.6637600
68 19.555	10.753300	0.3801300	10.625080	2.2562900

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DESIGNATION	FORMULA	CODE	DENSITY
CF NICKEL	NI CFINE	4.1020	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	I-B
28.00000	58.72000	0.00000	0.00000

CROSS SECTIONS

LETHARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	3.3467951	3.5433666	1.7268272	0.0168435
1 0.500	3.6106460	3.3697305	1.9391465	0.0181705
2 1.000	3.4104429	2.6464084	2.3021460	0.0171498
3 1.500	3.2226481	1.3145346	2.4006504	0.0162025
4 2.000	3.2580239	0.3185074	2.5197566	0.0163931
5 2.500	3.3981577	0.1013509	2.7793608	0.0170762
6 3.000	3.9376129	0.1247899	3.4082149	0.0200036
7 3.500	4.9264286	0.1633481	4.4679337	0.0247619
8 4.000	6.5151590	0.2290968	6.3131599	0.0327442
9 6.000	20.780728	0.7418720	20.531359	0.1044946
10 8.000	31.864722	1.1375705	31.482344	0.2536577
11 10.000	16.141457	0.5762498	15.947760	0.0378443
12 12.000	17.116147	0.6110462	16.910752	0.1055136
13 14.000	17.284612	0.6170607	17.077197	0.2616449
14 15.500	17.316241	0.6181898	17.108447	0.5480808
15 16.500	17.292099	0.6173279	17.084594	0.9650265
16 17.500	17.394561	0.6209858	17.185827	1.5801446
17 18.500	17.254060	0.6159699	17.047012	2.5603869
18 19.795	16.790386	0.5979874	16.589321	3.7134250
3000 17.675	17.464200	0.5876500	17.266090	1.6601900
2500 17.831	17.474000	0.5879800	17.275780	1.7953200
2000 18.016	17.478300	0.5881300	17.280040	1.9702200
1500 18.243	17.466800	0.5877400	17.268670	2.2083800
1000 18.537	17.432800	0.5865900	17.235050	2.5605200
500 18.957	17.371800	0.5845400	17.174740	3.1620400
68 19.555	17.274300	0.5812600	17.078350	4.2713500

APRIL 1961

DESIGNATION	FORMULA	CODE	DENSITY
CF CHROMIUM	CR CFINE	4.2020	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	I-B
24.00000	52.01000	0.00000	0.00000

CROSS SECTIONS

LETHARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	3.2178816	3.0633729	1.5261893	0.0161928
1 0.500	3.5840297	2.7681056	1.7260361	0.0180391
2 1.000	3.7598234	2.3515140	2.3779259	0.0189127
3 1.500	3.5299555	1.6051876	2.7004586	0.0177587
4 2.000	2.7905689	0.3171438	2.1645828	0.0140386
5 2.500	2.7979819	0.0833736	2.2868485	0.0140824
6 3.000	3.4030884	0.1080407	2.9509341	0.0171269
7 3.500	2.7909778	0.0924796	2.5286199	0.0142303
8 4.000	5.0243890	0.1770850	4.8680766	0.0199706
9 6.000	4.9355990	0.1762009	4.8763716	0.0237137
10 8.000	30.482520	1.0882259	30.116729	0.1206360
11 10.000	4.2649546	0.1522588	4.2137746	0.0452746
12 12.000	4.2541134	0.1518718	4.2030638	0.0794952
13 14.000	4.2166491	0.1505344	4.1660492	0.1697196
14 15.500	4.1944404	0.1497415	4.1441070	0.3501848
15 16.500	4.0918819	0.1460802	4.0427793	0.6061325
16 17.500	4.1193823	0.1470619	4.0699496	1.0037585
17 18.500	4.1629310	0.1486166	4.1129758	1.6468054
18 19.795	4.1294872	0.1479776	4.0797412	2.3971002
3000 17.675	4.0495900	0.1537800	3.9976700	1.0482700
2500 17.831	4.0951200	0.1555100	4.0426199	1.1387900
2000 18.016	4.1201100	0.1564600	4.0672899	1.2525800
1500 18.243	4.1295200	0.1568200	4.0765800	1.4058500
1000 18.537	4.1282800	0.1567700	4.0753500	1.6328500
500 18.957	4.1133900	0.1562100	4.0606500	2.0241300
68 19.555	4.0633399	0.1543000	4.0112500	2.7581200

APRIL 18.6J

DESIGNATION	FORMULA	CODE	DENSITY
CF MOLY	CF MO	5.3010	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	I-B
42.00000	95.95000	0.00000	0.00000

CROSS SECTIONS

LEI HARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	4.1145629	4.0614702	2.0729810	0.0101873
1 0.500	3.9309739	3.6809570	2.3676553	0.0097240
2 1.000	4.0119643	2.8513760	2.7384047	0.0093526
3 1.500	4.8111932	1.8033503	3.3664055	0.0101672
4 2.000	6.0404713	0.8149107	4.0444641	0.0130483
5 2.500	7.2144279	0.2025328	4.8756320	0.0180254
6 3.000	8.1624894	0.1705960	6.1620224	0.0268281
7 3.500	8.8475430	0.1849136	7.5890534	0.0318350
8 4.000	8.8373113	0.1846998	8.1798148	0.0331014
9 4.500	7.4466990	0.1556360	7.3209292	0.0343434
10 8.000	6.6579910	0.1391520	6.6113852	0.0361932
11 10.000	8.9527906	0.1871133	8.8901192	1.0139718
12 12.000	13.944747	0.2914450	13.847131	10.405035
13 14.000	5.4459644	0.1138206	5.4078425	0.1481155
14 15.500	5.6629026	0.1183547	5.6232620	0.3042829
15 16.500	5.8432196	0.1221233	5.8023171	0.5266286
16 17.500	5.8494244	0.1222530	5.8084783	0.8742346
17 18.500	5.6253734	0.1175703	5.5859958	1.4343696
18 19.795	5.2435262	0.1095897	5.2068214	2.0898113
3000 17.675	5.8322000	0.1218930	5.7913744	0.8659000
2500 17.831	5.8153999	0.1215419	5.7746921	0.9362000
2000 18.016	5.7871000	0.1209504	5.7465902	1.0270000
1500 18.243	5.7426000	0.1200203	5.7024017	1.1506000
1000 18.537	5.6661000	0.1184215	5.6264372	1.3331000
500 18.957	5.5207000	0.1153826	5.4820549	1.6441000
68 19.555	5.2359999	0.1094324	5.1993479	2.2172000

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DESIGNATION	FORMULA	CODE	DENSITY
CF NIOBIUM	NB CFINE	5.3610	0.00000
ATOMIC NUMBER	ATOMIC WEIGHT	XI	1-B
41.00000	92.91000	0.00000	0.00000

CROSS SECTIONS

LETHARGY LEVEL	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION
0 0.000	3.6945826	3.6477123	1.8607851	0.0087212
1 0.500	3.6196267	3.4078799	2.1868624	0.0102447
2 1.000	3.9391291	2.8656733	2.7055483	0.0125370
3 1.500	4.8758274	1.8434880	3.4155000	0.0162722
4 2.000	6.2400107	0.8271599	4.1761113	0.0281819
5 2.500	7.6708843	0.2195359	5.1657922	0.0533588
6 3.000	8.5918541	0.1890208	6.3761260	0.0687497
7 3.500	8.9061438	0.1959352	7.3479165	0.0801769
8 4.000	9.0741383	0.1996310	8.3140248	0.0969965
9 4.500	7.5648870	0.1664275	7.3986710	0.2887870
10 8.000	6.7061837	0.1475360	6.6565562	0.5036091
11 10.000	7.0812193	0.1557868	7.0288184	2.1766568
12 12.000	6.4455495	0.1418021	6.3978518	0.5245239
13 14.000	6.3457920	0.1396074	6.2988333	0.0618535
14 15.500	6.2881203	0.1383386	6.2415882	0.1313110
15 16.500	6.1699415	0.1357387	6.1242841	0.2243530
16 17.500	6.0076407	0.1321681	5.9631840	0.3723592
17 18.500	5.7711880	0.1269661	5.7284812	0.6109352
18 19.795	5.5007449	0.1209075	5.4600939	0.8907046
3000 17.675	6.0190000	0.1285600	5.9758000	0.3810000
2500 17.831	5.9881000	0.1279000	5.9452000	0.4119300
2000 18.016	5.9481000	0.1270500	5.9054000	0.4518600
1500 18.243	5.8938000	0.1258900	5.8515000	0.5062300
1000 18.537	5.8134000	0.1241700	5.7717000	0.5865500
500 18.957	5.6766000	0.1212500	5.6359000	0.7233700
68 19.555	5.4245000	0.1158700	5.3856000	0.9755100

The percent error in the calculated $\Delta k/k$ is based on the experimental value containing the assigned error estimates. The calculated results are given for cell corrections obtained from the standard nineteen-level cross sections and from the cross sections in fine energy detail using Program C-Fine as described in section 3.2

Table IV

COMPARISON OF COMPUTED AND MEASURED REACTIVITY FOR FOIL MATERIALS

<u>Material</u>	<u>k</u>	<u>Δk (for foil insertion)</u>	<u>% $\Delta k/k$ (calculated)</u>	<u>% $\Delta k/k$ (measured)</u>	<u>% error</u>
STD Void	.9862009				
CF Void	.9954579				
STD Fuel	.987442	.0012433	.12591	.1476 $\pm$.0046	+2.7 -14.7
CF Fuel	.9969345	.0014766	.14811	.1476 $\pm$.0046	+3.2 -3.0
STD Mo	.9933939	-.0020640	-.20734	-.1275 $\pm$.0039	+5.1 -4.8
CF Mo	.9943285	-.0011294	-.113455	-.1275 $\pm$.0039	+2.8 -2.6
STD Fe	.9952171	-.0002408	-.024190	-.0394 $\pm$.0039	+6.7 -5.5
CF Fe	.9952178	-.0002401	-.024120	-.0394 $\pm$.0039	+6.7 -5.5
STD Nb	.9942070	-.0012509	-.125661	-.1167 $\pm$.0039	+3.7 -3.5
CF Nb	.9945536	-.0009043	-.09084	-.1167 $\pm$.0039	+2.7 -2.5
STD Zr	.9954224	-.0000355	-.003566	0 $\pm$.0039	+4.63 $\pm$ 5 r.u.
CF Zr	.9954372	-.0000207	-.002079	0 $\pm$.0039	+2.69 $\pm$ 5 r.u.
STD Ni	.9951466	-.0003113	-.031272	-.0309 $\pm$.0039	+14.6 -11.3
CF Ni	.9951517	-.0003062	-.030760	-.0309 $\pm$.0039	+14.4 -11.2
STD Inc-X	.9951124	-.0003455	-.034708	-.0402 $\pm$.0039	+9.3 -7.6
CF Inc-X	.9951176	-.0003403	-.034185	-.0402 $\pm$.0039	+9.1 -7.5
STD 304SS	.9951779	-.0002800	-.0281278	-.0479 $\pm$.0039	+5.2 -4.4
CF 304SS	.9951806	-.0002773	-.0278565	-.0479 $\pm$.0039	+5.2 -4.4
STD 316SS	.9951363	-.0003216	-.032307	-.0479 $\pm$.0039	+6.0 -5.1

(Cont'd.)

Table IV (Cont'd.)

CF 3LOSS	.9951403	-.0003176	-.031905	-.0479±.0039	-33.4	+5.9 -5.0
STD TN-FeCrAl	.9953047	-.0001532	-.0153899	-.0201±.0039	-23.4	+18.4 -12.5
CF TN-FeCrAl	.9953065	-.0001514	-.0152091	-.0201±.0039	-24.3	+17.2 -12.3
STD TK-FeCrAl	.9951468	-.000311	-.0312519	-.0448±.0039	-30.2	+6.7 -5.6
CF TK-FeCrAl	.9951504	-.0003075	-.0308903	-.0448±.0039	-31.1	+6.6 -5.5
STD Cr-FeCrAl	.9951580	-.0002999	-.0301268	-.0402±.0039	-25.1	+8.0 -6.6
CF Cr-FeCrAl	.9951635	-.0002944	-.0295743	-.0402±.0039	-26.4	+7.9 -6.5
STD Nichrome V	.9950786	-.0003793	-.0381031	-.0402±.0039	-5.2	+10.2 -8.4
CF Nichrome V	.9950856	-.0003723	-.0373999	-.0402±.0039	-7.0	+10.0 -8.2

STD indicates cell corrections obtained from 19-level cross sections,
 CF indicates cell corrections obtained from cell corrected C-Fine cross
 sections as described in section 3.2,
 TN-FeCrAl = FeCrAl of .012" thickness,
 TK-FeCrAl = FeCrAl of .0245" thickness,
 Cr-FeCrAl = chromium clad with FeCrAl.

6.0 DISCUSSION

6.1 General

The increased shielding of the foils from neutrons, obtained when cell corrections are computed using the fine energy lattice and Program C-Fine, shows up to some extent in the oralloy foil calculations and markedly for the molybdenum and niobium foils. A greater effect would be observed in the oralloy foil were it not for the fact that the ratio of fission to absorption is fairly constant with energy. Except for the competition of leakage and moderator absorption, the neutrons which are shielded from the oralloy resonances are absorbed in fuel at lower (primarily non-resonant) energies. For the most part, Σ_f/Σ_a is smaller than average in resonances, and for this reason the positive reactivity of the oralloy foil is greater when the shielding of the resonances is applied in Program C-Fine. The excellent agreement with experiment (0.3%) is somewhat beclouded by discrepancies in the absorption and fission integrals of U^{235} discussed in section 6.3; however, the 15%

increase in reactivity obtained with cell-corrected cross sections from Program C-Fine indicates that failure to properly account for shielding of the resonance structure in detail will lead to considerable overprediction of the resonance absorption. The core average fraction of fissions due to thermal neutrons is 15.1% using or alloy cell corrected by C-Fine and is 13.7% using nineteen-level cell corrections.

When the contribution to absorption by the resonance structure is small or when the cell corrections are not far from unity (or both) the effect of using fine energy detail in computing cell corrections is not appreciably different from that of nineteen-level cell corrections. The resonance structure portrayed in the nickel and chromium cross sections contributes only about 15% to the total absorption integral, and resonances supplied for iron contribute even less (see section 6.3). The cell corrections in structural materials containing these elements, even in the resonance peaks, did not fall below 0.95 (except in FeCrAl, where the niobium content requires cell corrections as small as 0.8). It is not surprising that in those structural materials, and in zirconium, the combination of low resonance absorption integrals and cell corrections near unity show little difference between the two methods of cell correcting cross sections. Thicker samples of these materials would show a bigger difference in the two methods.

Although inadequacies in the nuclear data discussed in section 6.3 tend to obscure the correlation of analysis methods themselves with the measured reactivities, the results can be interpreted to show that when the computed absorption integrals agree with measured values and when important resonance structure is portrayed in fine energy detail, the methods used herein produce excellent agreement with the measured reactivities.

6.2 Impurities

The large underprediction of reactivity in structural materials containing iron suggests that either the absorption integral for iron is too small (and it is, see section 6.3), or that there are perhaps some impurities associated with iron which are not included in the compositions given in Table III but which contribute appreciably to the absorption integral. A spectrographic analysis was therefore requested for iron-containing materials, and the results⁸ are given in Table V. The maximum increases in absorption integral were computed assuming the upper limit in the quantities of boron, cobalt, and cadmium. Rather than recompute the

⁸D. H. Fraembs, private communication.

reactivity effect of all iron-bearing materials based on the maximum poison content, the reactivity of 310 stainless steel was recomputed, and the reactivities of Fe, Inconel X, 304SS, and FeCrAl were adjusted in proportion. The revisions are shown in Table V. There is a definite, although not precise, correlation of the error in predicted reactivity and the contribution of iron to the absorption integral.

Table V

RESULTS OF SPECTROGRAPHIC ANALYSIS OF IRON-BEARING MATERIALS
FOR HIGH ABSORPTION IMPURITIES

<u>Material</u>	<u>Elements</u>	<u>Wt. %</u>	<u>Max. Increase in Absorption Integral</u>	<u>Max. Change in Computed Reactivity</u>	<u>Revised Error in Theory-Experiment Correl. of Reac.</u>
Fe	Cr	<.01	6.79%	6.22% (estimated)	-35.0 ^{+7.2} -5.8 %
	B	<.01			
	Co	<.01			
	Cd	0±.01			
Inconel X	Cr	15.36 (15.0 assumed)	2.39%	2.19% (estimated)	-13.1 ^{+9.3} -7.7 %
	B	<.001			
	Co	0.06			
	Cd	0±.01			
310 SS	Cr	25.57 (25.0 assumed)	14.51%	13.30%	-24.5 ^{+6.7} -5.7 %
	B	<.01			
	Co	0.19			
	Cd	0±.01			
304 SS	Cr	18.71 (19.0 assumed)	10.90%	9.99% (estimated)	-36.0 ^{+5.7} -4.8 %
	B	<.01			
	Co	0.10			
	Cd	0±.01			
FeCrAl	Cr	24.71 (25.0 assumed)	6.49%	5.95% (estimated)	-19.6 ^{+19.6} -13.2 % (thin sample)
	B	<.01			
	Co	<.01			-26.6 ^{+7.0} -5.9 % (thick sample)
	Cd	0±.01			

6.3 Evaluation of Cross Section Data

The excellent agreement between predicted and measured reactivities for or alloy, zirconium, and nickel foils, using cell corrected cross sections from Program C-Fine, tends to indicate that the theory and the nuclear data are good. The computed absorption integral of nickel is 3.2 barns compared with 4 barns measured absorption⁹, 3.2 barns measured activation¹⁰,

⁹R.L. Macklin and H.S. Pomerance, "Resonance Capture Integrals," Progress in Nuclear Energy, Series I: Physics and Mathematics, Vol. 1, p. 179, New York: McGraw-Hill Co.

¹⁰V.B. Klimentov and V.M. Griazev, "Some Neutron Absorption Integrals," Journal of Nuclear Energy 9, Part II, p. 20, 1959.

and less than 3.2 barns measured resonance plus $1/v$ contribution.¹¹ The computed absorption integral of zirconium is 0.9 barns compared with 3 barns measured absorption¹² and 0.7 barns measured resonance plus $1/v$ contribution.¹¹ The computed absorption integral of U^{238} is 289 barns compared with 282 barns measured absorption¹² and 286 barns measured resonance plus $1/v$ contribution.¹¹ The computed absorption integral of U^{235} is 460 barns compared with 370 barns quoted by Westcott.¹³ The computed fission integral of U^{235} is 325 barns compared with measured values of 271 barns¹² and 274 barns.¹⁴ As indicated in section 6.1, it is possible to be in error in both absorption and fission integrals of or alloy, as is evidently the case here, and still produce good theory-experiment correlation as long as the absorption and fission cross sections are in the right ratio.

There is obviously an error in the iron absorption cross sections since there is a consistent underprediction of reactivity in the iron-bearing materials, as shown in Table V. The computed absorption integral is 1.5 barns compared with 2.1 barns measured absorption¹² and 1.8 barns measured resonance plus $1/v$ contribution.¹¹ If one postulates the existence of a narrow resonance in Fe^{56} at 5 kev, with resonance parameters identical with the resonance in Ni^{58} at that energy, the absorption integral becomes 2.0 barns, the Fe^{56} σ_a at 2200 m/s is about right, and the error in reactivity prediction becomes $9 \pm 8\%$. Equally good agreement with absorption integral, σ_{2200} , and reactivity prediction might be possible by assuming several resonances with different parameters, but the existence of one or more such resonances in the 1 to 10 kev range seems virtually a certainty.

Although not evaluated cleanly, the absorption cross section of chromium is probably satisfactory. The computed absorption integral is 1.8 barns compared with 1.9 barns¹² and 2.6 ± 1.1 barns¹⁵ measured absorption.

¹¹R.B. Tattersall, et al, "Pile Oscillator Measurements of Resonance Absorption Integrals," AERE R-2887, 1959.

¹²Macklin and Pomerance, op cit.

¹³C.H. Westcott, "Effective Cross Sections for Well Moderated Thermal Reactor Spectra," CRRP-787, 1958 Revision.

¹⁴J. Hardy, Jr., et al, "The Resonance Fission Integrals of U^{235} , Pu^{239} , and Pu^{240} ," Nuclear Science and Engineering 9, (341), 1961

¹⁵Klimentov and Griazev, op cit.

The underprediction of molybdenum and niobium foil reactivities using fine energy detail is consistent with a known underestimate of absorption cross sections in the 1 to 100 kev range (but note the overprediction which nineteen-level cell corrections produce). The computed absorption integral of molybdenum as it stands is 24.2 barns compared with 13 barns measured absorption¹⁶ and 20.1 barns¹⁷ measured resonance plus $1/v$ contribution. It would seem that both of these measurements were perhaps not properly corrected for self shielding. The computed absorption integral increases to 29.7 barns when the newly measured values in the 1 to 100 kev range¹⁸ are included. The fact that the latter cross sections when used to predict the reactivity of the foil in this report change the 11% underprediction to a 17% overprediction probably means that the rather considerable addition to the absorption integral requires resonance structure for proper treatment herein. The measured absorption cross section¹⁸ between 1 and 100 kev does not sufficiently resolve the resonance structure for resonance parameter determination.

Somewhat the same comments as above apply to niobium. The computed absorption integral for niobium as it stands is 7.8 barns compared with 8.3 barns measured absorption¹⁶ and 13.5 barns measured resonance plus $1/v$ contribution.¹⁷ With the newly measured values in the 1 to 100 kev range¹⁸, the absorption integral increases to 13.5 barns in excellent agreement with the later measured value.¹⁷ The 22% underprediction of reactivity becomes a 44% overprediction with the additional absorption, but the reason is no doubt the lack of resonance detail in the very sizeable addition to the absorption integral.

¹⁶Macklin and Pomerance, op cit.

¹⁷Tattersall, et al, op cit.

¹⁸"Physics Revision Annual Report," ORNL-2910, April 4, 1960.