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CALCULATIONS OF ZPR-3 FAST ASSEMBLIES USING A 26-GROUP ARGONNE CROSS-SECTION SET

by

D. Meneghetti and J. R. White

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Reactor Physics Division

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CALCULATIONS OF ZPR-3 FAST ASSEMBLIES USING A 26-GROUP ARGONNE CROSS-SECTION SET

by

D. Meneghetti and J. R. White

ABSTRACT

Calculations of a series of ZPR-3 fast critical assemblies using an Argonne 26-group cross-section set¹ are described. Critical masses, detector-response ratios, and prompt neutron lifetimes are compared with reported experimental values. Comparison of intragroup cross-section averaging by P1 and by consistent B1 are presented. Importances of reflectors in determination of prompt neutron lifetimes are also calculated.

I. INTRODUCTION

Improved knowledge of neutron cross sections, together with more involved procedures for determination of multigroup constants, have led to the development of an Argonne 26-group cross-section set. The basic data used and the generation of the cross sections are described by O'Shea *et al.*¹

Among the new data considered in generating the set were: the lower U^{235} fission cross sections between 0.1 and 1.0 MeV measured at Aldermaston,² and the corresponding lowering of other heavy-element cross sections based upon U^{235} fission normalization; the U^{235} and Pu^{239} capture-to-fission ratio data obtained at Los Alamos,³ and U^{235} data obtained at Oak Ridge;⁴ the data concerning $\nu(E)$ for fissile and fertile materials;⁵ the data for $\bar{\nu}$ for U^{238} and U^{235} from measurements at Argonne;⁵ and information on nuclear temperatures obtained at Duke University.⁶

The present paper reports on the calculations of a series of U^{235} -fueled fast critical assemblies using this set. Some of these results have previously been summarized in part in a more general paper on fast reactor physics.⁷ The multigroup cross sections used, furthermore, include values for group-transport and elastic-transfer cross sections for each core composition obtained by ultra-fine-group flux weighting using the ELMOE program^{8,9} in the consistent B1 option. (The ELMOE program obtains the fundamental mode solution using hundreds of fine-energy groups, and outputs the coarse-group cross sections.) Criticality analyses then used the spherical DSN transport code¹⁰ in S4 approximation. Criticalities were obtained by varying core radii.

Calculated integral quantities, compared with reported experimental values,¹¹⁻¹⁴ are the critical mass, central detector-response ratios, and prompt neutron lifetime.

Calculational comparisons are made of the use of the ELMOE code in both the Pl and consistent Bl approximations.

In the present calculations only the first 22 groups of the set were employed. For the relatively hard neutron-flux spectra of these assemblies, the 29-eV lower limit of group 22 more than suffices. The Argonne 26-group set is expected to undergo modifications as more information becomes available. The calculations reported herein have been made with the set No. 800 modification. This set is also equivalent to set No. 224 insofar as this series is concerned. The ELMOE-derived cross sections for the cores in this study are included herein for future use or reference. Cross sections other than ELMOE-derived quantities are listed in Ref. 1.

II. COMPOSITIONS OF ASSEMBLIES

The core compositions of the series of ZPR-3 fast assemblies calculated are given in Table I. The assemblies calculated were chosen to give a range of compositions representative of the much larger series of experimentally reported ZPR-3 assemblies. The reflectors were 30 cm thick. Reflector compositions were: 0.19 v/o U²³⁵, 83.3 v/o U²³⁸, and 7.31 v/o stainless steel. In addition, the reflector of Assembly No. 6F also contained 2.27 v/o aluminum.

TABLE I. Compositions Used in ZPR-3 Calculations
Core^a Volume Fractions

Assembly No.	(N = 0.048) U ²³⁵	(N = 0.048) U ²³⁸	(N = 0.0854) SST ^b	(N = 0.0603) Al	(N = 0.0717) C	(N = 0.096) O	(N = 0.0254) Na
6F	0.14	0.159	0.123	0.314	-	-	-
9A	0.117	0.380	0.142	0.215	-	-	-
12	0.095	0.355	0.092	-	0.357	-	-
14	0.094	0.007	0.093	-	0.745	-	-
22	0.094	0.701	0.093	-	-	-	-
23	0.093	0.007	0.092	0.428	-	-	-
25	0.071	0.741	0.093	-	-	-	-
29	0.0497	0.0997	0.248	0.244	-	0.145	-
32	0.093	0.007	0.81	-	-	-	-
33	0.093	0.007	0.636	-	-	-	0.158
34	0.0467	0.103	0.246	0.255	0.106	-	-
36	0.0937	0.495	0.127	-	-	-	0.158
41	0.0596	0.291	0.141	0.179	-	-	-

^aBlanket volume fractions: 0.19% U²³⁵, 83.3% U²³⁸, 7.31% stainless steel, except Assembly No. 6F, which contains, in addition, 2.27% aluminum. Blanket thickness: 30 cm.

^bStainless steel (assuming $N_{SST}^{Fe} = 0.0615$, $N_{SST}^{Cr} = 0.0162$, and $N_{SST}^{Ni} = 0.0077$ in SST).

III. CORE CROSS SECTIONS FOR TRANSPORT AND ELASTIC TRANSFER

The group-transport and elastic-transfer cross sections for each core composition were obtained by fundamental mode calculations using the ELMOE^{8,9} code, which employs hundreds of very-fine-energy groups. The data on the light-element angular scattering are provided by the ELMOE library. The details of the elastic-scattering resonances and the intracoarse-group flux dependence with energy are thus accounted for in these derived, coarse-group, homogenized-core cross sections.

The ELMOE-derived core cross sections for transport and elastic transfer are given in Table II for these assemblies. The listed transport cross sections include the transport contributions of the heavy elements

TABLE II. ELMOE-determined Core Cross Sections for Transport and for Light-elements Elastic Transfer Using CBI Option

J	E _{LJ}	Assembly No. 6F		Assembly No. 9A		Assembly No. 12		Assembly No. 14		Assembly No. 22		Assembly No. 23		Assembly No. 25	
		Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$
1	3.68 MeV	(0.319) ^c	(0.00252) ^c	(0.418) ^c	(0.00206) ^c	(0.378) ^c	(0.0116) ^c	(0.247) ^c	(0.0235) ^c	(0.514) ^c	(0.000539) ^c	(0.214) ^c	(0.00300) ^c	(0.523) ^c	(0.000539) ^c
2	2.23	0.367	0.00523	0.473	0.00396	0.463	0.0183	0.358	0.0404	0.566	0.000662	0.256	0.00668	0.576	0.000661
3	1.35	0.404	0.00620	0.505	0.00468	0.495	0.0166	0.417	0.0354	0.581	0.000792	0.301	0.00809	0.592	0.000792
4	0.821	0.410	0.00760	0.510	0.00581	0.517	0.0208	0.470	0.0420	0.585	0.00100	0.308	0.00972	0.595	0.00100
5	0.498	0.482	0.00943	0.598	0.00706	0.619	0.0256	0.578	0.0505	0.685	0.00110	0.364	0.0128	0.698	0.00110
6	0.320	0.573	0.00999	0.725	0.00762	0.769	0.0303	0.714	0.0612	0.849	0.000963	0.412	0.0130	0.866	0.000977
7	0.183	0.651	0.0112	0.852	0.00899	0.919	0.0328	0.815	0.0673	1.041	0.00176	0.436	0.0134	1.062	0.00175
8	0.111	0.795	0.0116	1.048	0.00900	1.088	0.0351	0.925	0.0730	1.266	0.00135	0.502	0.0150	1.291	0.00136
9	0.0674	0.872	0.00941	1.179	0.00763	1.221	0.0348	0.993	0.0730	1.456	0.00162	0.519	0.0123	1.485	0.00164
10	0.0409	0.832	0.00748	1.173	0.00706	1.273	0.0354	0.999	0.0742	1.559	0.00205	0.470	0.00750	1.589	0.00207
11	0.0248	1.015	0.00804	1.402	0.00789	1.463	0.0370	1.198	0.0773	1.714	0.00257	0.520	0.00853	1.741	0.00267
12	0.0150	0.801	0.00433	1.196	0.00480	1.370	0.0363	1.048	0.0779	1.698	0.00390	0.375	0.00257	1.728	0.00382
13	9.12 keV	0.956	0.00631	1.377	0.00620	1.496	0.0342	1.150	0.0759	1.836	0.00310	0.502	0.00589	1.867	0.00309
14	4.31	1.236	0.00483	1.735	0.00496	1.769	0.0191	1.328	0.0459	2.181	0.00247	0.693	0.00457	2.219	0.00251
15	2.61	1.179	0.00527	1.749	0.00494	1.810	0.0314	1.208	0.0720	2.384	0.00256	0.597	0.00517	2.436	0.00253
16	2.03	1.171	0.0146	1.790	0.01395	1.889	0.0725	1.191	0.149	2.549	0.00656	0.559	0.0145	2.610	0.00655
17	1.23	1.264	0.00686	1.946	0.00664	2.033	0.0301	1.238	0.0700	2.786	0.00334	0.594	0.00651	2.854	0.00334
18	0.961	1.255	0.0168	1.766	0.0164	1.832	0.0734	1.318	0.149	2.346	0.00812	0.665	0.0163	2.372	0.00810
19	0.583	1.472	0.00773	2.110	0.00768	2.168	0.0292	1.408	0.0683	2.866	0.00396	0.746	0.00734	2.901	0.00397
20	0.275	1.524	0.00411	2.055	0.00397	2.091	0.0122	1.497	0.0343	2.647	0.00203	0.826	0.00390	2.651	0.00198
21	0.101	1.560	0.00258	1.842	0.00257	1.885	0.00571	1.656	0.0165	2.078	0.00132	0.951	0.00242	2.012	0.00132
22	29.0 eV	(1.691)	0	(1.901)	0	(1.853)	0	(1.664)	0	(2.059)	0	(1.048)	0	(1.954)	0

J	E _{LJ}	Assembly No. 29		Assembly No. 32		Assembly No. 33		Assembly No. 34		Assembly No. 36		Assembly No. 41	
		Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$	Σ_{tr}^a	$\Sigma_{J-J+1}^{el,b}$
1	3.68 MeV	(0.339) ^c	(0.00993) ^c	(0.469) ^c	(0.00469) ^c	(0.397) ^c	(0.00418) ^c	(0.295) ^c	(0.00617) ^c	(0.426) ^c	(0.00123) ^c	(0.322) ^c	(0.00185) ^c
2	2.23	0.369	0.00914	0.524	0.00618	0.447	0.00601	0.356	0.0109	0.474	0.00200	0.365	0.00347
3	1.35	0.430	0.0147	0.565	0.00760	0.479	0.00700	0.399	0.0114	0.488	0.00212	0.393	0.00412
4	0.821	0.512	0.0260	0.524	0.00908	0.462	0.00902	0.402	0.0145	0.500	0.00306	0.395	0.00513
5	0.498	0.523	0.0199	0.596	0.0121	0.544	0.0127	0.475	0.0187	0.602	0.00402	0.462	0.00660
6	0.320	0.691	0.0326	0.671	0.0126	0.606	0.0124	0.563	0.0205	0.723	0.00397	0.558	0.00702
7	0.183	0.709	0.0254	0.677	0.0126	0.614	0.0127	0.621	0.0217	0.867	0.00505	0.649	0.00787
8	0.111	0.787	0.0266	0.760	0.0142	0.694	0.0136	0.734	0.0251	1.044	0.00449	0.792	0.00847
9	0.0674	0.867	0.0256	0.964	0.0174	0.870	0.0162	0.810	0.0246	1.205	0.00509	0.891	0.00751
10	0.0409	0.831	0.0214	1.148	0.0176	1.007	0.0168	0.782	0.0210	1.291	0.00540	0.888	0.00619
11	0.0248	1.012	0.0307	1.201	0.0273	1.095	0.0239	0.936	0.0295	1.431	0.00680	1.037	0.00861
12	0.0150	0.780	0.0178	1.044	0.0152	0.935	0.0144	0.732	0.0180	1.382	0.00594	0.882	0.00358
13	9.12 keV	1.036	0.0206	1.893	0.0289	1.600	0.0247	0.988	0.0202	1.549	0.00683	1.058	0.00606
14	4.31	1.482	0.0170	3.036	0.0310	2.587	0.0271	1.418	0.0164	1.945	0.00731	1.378	0.00501
15	2.61	1.201	0.0201	2.077	0.0256	2.613	0.0720	1.142	0.0191	2.528	0.0547	1.347	0.00430
16	2.03	1.138	0.0452	1.806	0.0512	1.554	0.0566	1.081	0.0417	2.135	0.0140	1.358	0.0128
17	1.23	1.219	0.0184	1.953	0.0206	1.658	0.0163	1.162	0.0177	2.244	0.00496	1.477	0.00564
18	0.961	1.249	0.0476	2.266	0.0583	1.900	0.0474	1.189	0.0444	1.937	0.0137	1.332	0.0151
19	0.583	1.385	0.0191	2.428	0.0257	2.041	0.0193	1.323	0.0185	2.334	0.00645	1.580	0.00695
20	0.275	1.428	0.00839	2.665	0.0124	2.239	0.00910	1.362	0.00824	2.208	0.00334	1.524	0.00339
21	0.101	1.443	0.00333	2.912	0.00669	2.455	0.00573	1.368	0.00332	1.847	0.00225	1.327	0.00237
22	29.0 eV	(1.401)	0	(2.865)	0	(2.435)	0	(1.332)	0	(1.856)	0	(1.325)	0

^aThree times the effective transport cross sections of the cores, in units of cm⁻¹.

^bThe effective elastic-transfer cross sections of the light-elements contribution, in units of cm⁻¹. (²³⁵U and ²³⁸U elastic-transfer contributions are not included in the listed values.)

^cValues in parentheses are direct homogenized values from the 26-group cross-section set; i.e., they have not been ELMOE-averaged.

U^{235} and U^{238} . The listed elastic-transfer cross sections do not include the elastic transfer of the U^{235} and U^{238} . The elastic transfers for the latter elements given in the 26-group set compilation were added to the values listed. Cross sections other than these ELMOE-derived values are given in the report by O'Shea *et al.*¹

The data in Table II are included here to allow the effects of subsequent changes in the 26-group set to be analyzed in many instances by recalculation of these systems without repeating the complete ELMOE-averaging calculations.

IV. CALCULATED CRITICAL MASSES COMPARED WITH EXPERIMENTAL VALUES

The criticality calculations for the reflected systems were made by using the DSN neutron-transport code in S4 approximation. These calculations assume homogeneous spherical cores. The DSN results were corrected to account for the increased reactivity effects of the thin fuel-plate heterogeneities¹⁵ and, where necessary, for the cylindrical-core geometries. Thus, the directly calculated values were corrected to heterogeneous, spherical, or cylindrical values. The relatively small corrections for experimental irregular boundaries and for assembly center-gap were not included in these analyses.

The estimated increase in reactivity due to core heterogeneity was taken as 1% in k except for the few cases in which direct calculational analyses were available.¹⁵ The reactivity increment was then related to the incremental change in core peripheral fuel mass through the ratio $(\Delta M/M)/(\Delta k/k)$. The latter ratios were calculated by means of the DSN code. The subsequent corrections to convert calculated spherical heterogeneous critical-mass values to cylindrical geometry were based upon estimated shape factors (ratio of spherical critical mass to corresponding cylindrical critical mass) except for the few cases for which direct shape-factor calculations were available. In the estimated cases, the shape-factor values were taken to be 0.94, 0.93, or 0.92, depending upon whether the core size was considered relatively small, moderate, or large, respectively, in the limited range of core sizes studied here. The reported general shape-factor studies of Lowenstein and Main¹⁶ and of Davey,¹⁷ together with a few direct calculations by the authors, were used as guides in the choices of shape factors. For Assembly No. 36, which has a large L/D ratio, the shape factor was estimated from available^{11,16,17} curves of shape-factor dependence upon L/D value. The reactivity and corresponding critical-mass corrections are listed in Table III with the resultant adjusted calculated critical masses. Reported experimental values^{11,12,13} are also listed for comparison.

TABLE III. Calculated Critical Masses and Corrections

Assembly No.	L/D Ratio	Estimated Shape Factor	Estimated Reactivity Addition due to Heterogeneity	Ratio of Fractional Increase in Critical Mass, $\Delta M/M$ (at Core Edge) to Reactivity, $\Delta k/k$	Spherical Homogeneous Calculated Critical Mass, kg U ²³⁵	Critical Mass Addition due to Heterogeneity, kg U ²³⁵	Critical Mass Addition due to Shape Factor, kg U ²³⁵	Calculated Critical Mass, Corrected for Shape and Heterogeneity, kg U ²³⁵	Experimental Critical Mass, kg U ²³⁵	Percent Error in Critical Mass	Percent Error in Reactivity
6F	Sphere	-	0.01	4.6	129.3	-5.9	-	123.4	131.1	-5.9	+1.3
9A	Sphere	-	0.01	5.3	149.9	-7.9	-	142.0	146.2	-2.8	+0.5
12	0.87	0.94	0.01	5.7	165.7	-9.4	+10.0	166.3	176.8	-5.9	+1.0
14	0.99	0.94	0.012 ^a	4.3	125.1	-6.5	+7.6	126.2	136.1	-7.3	+1.7
22	0.88	0.93	0.008 ^a	7.2	248.1	-14.3	+17.6	251.4	243.7	+3.2	-0.4
23	0.84	0.94 ^a	0.011 ^a	4.6	237.5	-12.0	+13.4	238.9	258.1	-7.4	+1.6
25	0.90	0.92	0.01	11.6	603.5	-70.0	+46.4	579.9	581.6	-0.3	0.0
29	0.79	0.92	0.01	5.3	361.6	-19.2	+29.8	372.2	421.0	-11.6	+2.2
32	1.17	0.932 ^a	0.01	4.3	197.9	-8.5	+13.8	203.2	227.5	-10.7	+2.5
33	1.14	0.93	0.01	4.4	207.0	-9.1	+14.9	212.8	238.0	-10.6	+2.4
34	0.94	0.92	0.01	5.4	441.6	-23.8	+36.3	454.1	503.0	-9.7	+1.8
36	1.43	0.87	0.01	6.3	219.8	-13.8	+30.8	236.8	242.7	-2.4	+0.4
41	0.98	0.92	0.01	6.6	455.0	-30.0	+37.0	462.0	489.9	-5.7	+0.9

^aDirectly calculated.

Fig. 1. Excess Reactivity versus Atomic Density of Light Elements in Core

The reactivity excess of the calculated values, relative to the experimental value, varies from about zero to +2.5% k. The cores containing the greater atomic densities of nonfuel and nonfertile materials result in the greater deviations from experiment. This is shown in Fig. 1, where the calculated reactivity excess is plotted as a function of atomic densities of light elements in the core. Because of uncertainties in the shape factor and heterogeneity corrections, it is estimated that the indicated percent errors in reactivities should be assessed on the assumption that of the order of 0.5 to 1% error in k can be due to these uncertainties.

V. COMPARISON OF CBI AND PI ELMOE-DERIVED TRANSPORT AND ELASTIC-TRANSFER CROSS SECTIONS AND EFFECT UPON CRITICAL MASS

As previously noted, the ELMOE-derived multigroup core cross sections for transport and elastic transfer were obtained by using the consistent B1 option of the code. The change in critical mass, by using the simpler P1 option (for the intragroup cross-section averagings), has been calculated for four of the assemblies. These are assemblies numbered 14, 22, 23, and 32 which have graphite, U²³⁸, aluminum, and stainless steel, respectively, as primary diluent in the cores. These cores all include also the stainless-steel matrix structure in addition to the primary diluent. The U²³⁸ diluent case therefore has only the steel of the matrix structure treated as nonheavy scattering material, i.e., ELMOE fine-structure treated.

The ratios of the Pl-ELMOE evaluated, homogenized, core-transport cross sections and of the core light-elements elastic-transfer cross sections, relative to the corresponding CBl values, are shown in Table IV for these four assemblies.

TABLE IV. Ratios of Pl/CBl ELMOE-derived Core Cross Sections

Group	E_{Lower}	Assembly No.							
		14		22		23		32	
		Transp.	EL. R.	Transp.	EL. R.	Transp.	EL. R.	Transp.	EL. R.
1	3.68 MeV	*	*	*	*	*	*	*	*
2	2.23	1.10	0.99	0.99	1.00	0.97	1.00	0.91	1.00
3	1.35	0.96	1.00	0.99	1.00	0.96	1.00	0.91	1.00
4	0.821	0.99	1.00	0.99	1.00	0.96	1.00	0.91	1.00
5	0.498	0.99	1.00	0.99	1.00	0.97	1.00	0.92	1.00
6	0.302	0.98	1.00	0.99	1.00	0.97	1.00	0.94	1.00
7	0.183	0.98	1.00	1.00	1.00	0.96	1.00	0.94	1.00
8	0.111	0.97	1.00	0.99	1.00	0.98	1.00	0.97	1.00
9	0.0674	0.97	1.00	1.00	1.00	0.97	1.00	0.98	1.01
10	0.0409	0.98	1.00	1.00	1.00	0.93	1.00	0.94	1.00
11	0.0248	0.95	1.00	0.99	1.00	0.97	1.00	0.99	1.00
12	0.0150	1.00	1.00	0.99	1.00	0.91	1.00	0.90	1.00
13	9.12 keV	0.96	1.00	0.99	1.00	0.96	1.00	0.95	1.00
14	4.31	0.96	1.00	0.99	1.00	0.95	1.00	0.94	1.00
15	2.61	0.96	1.00	0.99	1.00	0.94	1.00	0.94	1.00
16	2.03	0.95	1.00	0.99	1.00	0.95	1.00	0.93	1.00
17	1.23	0.95	1.00	0.99	1.00	0.96	1.00	0.93	1.00
18	0.961	0.94	1.00	0.99	1.00	0.96	1.00	0.93	1.00
19	0.583	0.94	1.00	0.99	1.00	0.97	1.00	0.94	1.00
20	0.275	0.94	1.00	0.99	1.00	0.97	1.00	0.94	1.00
21	0.101	0.92	1.00	0.99	1.00	0.97	1.00	0.94	1.00
22	29.0 eV	*	*	*	*	*	*	*	*

*These groups not ELMOE-treated.

The Pl transport cross sections generally tend to be smaller than the CBl values. The elastic transfers remain substantially the same. Similar results have also been noted by Hummel and Rago⁸ for the comparison between Pl and consistent-Pl-averaged cross sections for other systems. The Pl transport cross sections differ from the CBl essentially because of the consistent treatment and not because of the Pl or Bl aspect of the option. Use of either consistent-Pl- or consistent-Bl-averaged cross sections in a

subsequent criticality code such as the DSN transport code would give closely similar results.

TABLE V. Percent Difference in Criticality by Use of Pl Relative to CBl ELMOE-derived Cross-section Averages

Assembly No.	Principal Diluent	Difference	
		Critical Volume	Reactivity
14	C	0.9%	-0.2%
22	U ²³⁸	0.7%	-0.1%
23	Al	1.6%	-0.4%
32	Steel	5.3%	-1.2%

The percent difference in calculated critical volumes (and reactivities) obtained by use of the Pl ELMOE-derived cross sections is indicated in Table V for these four assemblies.

The Pl ELMOE-derived group cross sections result in the subsequent DSN solutions being less reactive, i.e., larger critical mass. For Assembly 22, containing U^{238} as the primary diluent, the -0.1% k reactivity decrease results from the ~10 v/o steel included to account for the steel tubes and drawers comprising the critical-facility honeycomb array.

VI. CENTRAL FLUX SPECTRA AND DETECTOR-RESPONSE RATIOS

Ability to calculate neutron flux spectra is often indicated by comparing calculated central fission and capture detector responses and prompt neutron lifetimes with corresponding experimental values. Whereas the central detector responses are determined essentially by the composition and cross sections of the core, the prompt neutron lifetime can be greatly influenced by the composition and cross sections of the reflector region as well.

Central core values of the neutron-flux spectra calculated by the DSN code using the CBl ELMOE-derived core cross sections are listed in Table VI for this series of assemblies. Use of Pl ELMOE-derived cross sections results in essentially identical central DSN flux spectra.

TABLE VI. Calculated Neutron Multigroup Flux Spectra at Core Centers

Group*	Assembly Number											
	6F	9A	12	14	22	23	25	29	32	33	34	41
1	0.0333	0.0254	0.0258	0.0342	0.0196	0.0311	0.0157	0.0167	0.0171	0.0198	0.0167	0.0220
2	0.0615	0.0461	0.0465	0.0637	0.0341	0.0598	0.0274	0.0371	0.0392	0.0441	0.0336	0.0393
3	0.0924	0.0691	0.0705	0.1083	0.0495	0.0965	0.0402	0.0578	0.0722	0.0802	0.0584	0.0583
4	0.1309	0.1148	0.1048	0.1196	0.0974	0.1282	0.0846	0.0789	0.1252	0.1270	0.0930	0.1042
5	0.1748	0.1754	0.1398	0.1193	0.1740	0.1597	0.1642	0.1445	0.1783	0.1702	0.1298	0.1716
6	0.1736	0.1853	0.1450	0.1061	0.1980	0.1636	0.1966	0.1149	0.1915	0.1877	0.1448	0.1934
7	0.1365	0.1500	0.1321	0.0942	0.1650	0.1360	0.1703	0.1384	0.1551	0.1504	0.1362	0.1594
8	0.0916	0.1056	0.1062	0.0791	0.1184	0.0919	0.1279	0.1147	0.0980	0.0986	0.1064	0.1144
9	0.0576	0.0674	0.0827	0.0684	0.0738	0.0660	0.0841	0.0949	0.0562	0.0568	0.0882	0.0698
10	0.0298	0.0361	0.0597	0.0560	0.0412	0.0422	0.0507	0.0804	0.0344	0.0335	0.0749	0.0390
11	0.0118	0.0156	0.0386	0.0437	0.0186	0.0156	0.0240	0.0426	0.0147	0.0151	0.0408	0.0176
12	0.0047	0.0064	0.0236	0.0336	0.0068	0.0073	0.0092	0.0404	0.0114	0.0107	0.0382	0.0073
13	0.0012	0.0019	0.0133	0.0257	0.0025	0.0013	0.0034	0.0200	0.0035	0.0034	0.0197	0.0025
14	0.0004	0.0006	0.0081	0.0248	0.0009	0.0004	0.0013	0.0114	0.0017	0.0016	0.0116	0.0009
15	0.0001	0.0001	0.0020	0.0100	0.0002	0.0001	0.0002	0.0043	0.0008	0.0004	0.0045	0.0001
16	0.0000	0.0000	0.0005	0.0037	0.0000	0.0000	0.0000	0.0012	0.0002	0.0003	0.0013	0.0001
17	0.0000	0.0000	0.0004	0.0046	0.0000	0.0000	0.0000	0.0012	0.0002	0.0002	0.0012	0.0000
18	0.0000	0.0000	0.0001	0.0016	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0003	0.0000
19	0.0000	0.0000	0.0001	0.0018	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0002	0.0000
20	0.0000	0.0000	0.0000	0.0011	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000
21	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
22	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

*Group-energy limits as in Table IV.

The calculated central-detector response ratios are compared in Table VII with reported experimental values.^{11,12,13} The calculated U^{238}/U^{235} fission-response ratios deviate from experiment by about -7 to +5%. The U^{233}/U^{235} fission ratios deviate from experiment by about +3 to +9%. The Pu^{239}/U^{235} and Pu^{240}/U^{235} ratios deviate from experiment by about -6 to +5% and -14 to +4%, respectively. The listed experimental fission-ratio values of U^{238}/U^{235} , U^{234}/U^{235} , and Pu^{240}/U^{235} include the indicated corrections for counter-wall thickness.¹⁸

TABLE VII. Central-detector Response Ratios

Assembly No.	$\sigma_f^{U238}/\sigma_f^{U235}$		$\sigma_f^{U233}/\sigma_f^{U235}$		$\sigma_f^{U234}/\sigma_f^{U235}$		$\sigma_f^{Pu239}/\sigma_f^{U235}$		$\sigma_f^{Pu240}/\sigma_f^{U235}$		$\sigma_c^{U238}/\sigma_f^{U235}$	
	Fission Counter ^a	Radio-chemical	Calculated	Experimental	Calculated	Experimental ^b	Calculated	Experimental	Calculated	Experimental ^b	Calculated	Experimental Corrected ^c
6F	-	0.069	0.0729	-	1.564	-	0.459	-	1.256	-	0.485	0.084
9A	0.055	-	0.0543	-	1.570	0.447	0.392	1.30	1.225	-	0.409	-
12	0.048	0.045	0.0495	1.46	1.544	0.305	0.322	1.10	1.137	-	0.338	0.100
14	0.059	0.060	0.0618	1.45	1.503	0.317	0.331	1.05	1.074	-	0.354	0.123
22	0.039	0.041	0.0398	1.53	1.574	0.305	0.335	1.16	1.200	0.346	0.345	0.091
23	0.0732	0.079	0.0711	1.48	1.558	0.418	0.438	1.18	1.237	-	0.463	0.089
25	0.0315	-	0.0316	-	1.573	0.263	0.292	1.17	1.173	-	0.298	0.092
29	0.0384	-	0.0358	1.47	1.534	0.269	0.253	1.06	1.076	0.301	0.263	0.115
32	0.0487	-	0.0485	1.51	1.572	0.382	0.387	1.20	1.218	0.397	0.405	-
33	0.052	-	0.0542	1.51	1.569	0.385	0.400	1.21	1.223	0.416	0.420	-
34	0.0366	0.040	0.0352	1.454	1.537	0.257	0.259	1.067	1.084	0.282	0.270	0.122
36	0.0443	-	0.0460	1.47	1.572	0.324	0.357	1.19	1.209	0.350	0.370	0.097
41	0.0395	-	0.0402	1.430	1.567	0.297	0.322	1.164	1.180	-	0.333	-

^aIncludes +8% correction for counter-wall thickness.^bIncludes +4% correction for counter-wall thickness.^cExperimental $\times 1.227$; see text.

For comparison of the calculated (U^{238} capture/ U^{235} fission) ratios with experiments, two lists of experimental values are tabulated. The first gives the reported values.^{11,12,13} The calculated values deviate from these by about +1 to +24%, the average deviation being +13.5%. Reported calculations using the 16-group cross section set of Yiftah, Okrent, and Moldauer also have had similar large deviations for this detector ratio.¹⁸ Recent investigation by Armani,²⁰ however, has indicated possible systematic errors in the reported radiochemically derived values of the U^{238} capture responses. The listed corrected experimental data were obtained by increasing the former experimental values by the factor 1.227, suggested by Armani. For this series of assemblies, this results in a range of deviations of the calculations from experiments of -18 to +1%, the average deviation being -7.5%. Thus with this correction to the experiments, the calculated values correlate better, although they now tend to be smaller than the experimental values.

In this regard, the present cross-section set with ELMOE-averagings has been found to calculate suitably the U^{238} capture to U^{235} fission values for the British Zebra-2 system²¹ and the Russian BFS-12 system.²² The deviations from reported experimental values are about -5% and zero, respectively.

Calculated normal-mode, consistent-B1, adjoint fluxes for the present series of ZPR-3 assemblies are given in Table VIII.

TABLE VIII. Calculated Bare-core Neutron Multigroup Adjoint-Flux Spectra

Group*	Assembly Number												
	6F	9A	12	14	22	23	25	29	32	33	34	36	41
1	0.0396	0.0470	0.0477	0.0296	0.0598	0.0349	0.0665	0.0401	0.0350	0.0347	0.0410	0.0534	0.0509
2	0.0385	0.0445	0.0449	0.0316	0.0542	0.0352	0.0598	0.0402	0.0353	0.0350	0.0407	0.0494	0.0482
3	0.0370	0.0414	0.0414	0.0329	0.0492	0.0353	0.0538	0.0390	0.0352	0.0348	0.0392	0.0453	0.0445
4	0.0339	0.0353	0.0353	0.0346	0.0387	0.0351	0.0418	0.0372	0.0349	0.0345	0.0368	0.0368	0.0377
5	0.0334	0.0344	0.0358	0.0372	0.0372	0.0350	0.0402	0.0369	0.0339	0.0341	0.0368	0.0359	0.0368
6	0.0361	0.0372	0.0383	0.0400	0.0395	0.0370	0.0417	0.0392	0.0357	0.0357	0.0388	0.0382	0.0389
7	0.0387	0.0393	0.0398	0.0422	0.0403	0.0389	0.0410	0.0400	0.0376	0.0376	0.0402	0.0397	0.0401
8	0.0413	0.0409	0.0409	0.0439	0.0402	0.0411	0.0397	0.0410	0.0407	0.0407	0.0414	0.0404	0.0407
9	0.0427	0.0417	0.0415	0.0453	0.0398	0.0423	0.0386	0.0419	0.0439	0.0439	0.0421	0.0408	0.0408
10	0.0434	0.0420	0.0421	0.0465	0.0395	0.0428	0.0379	0.0425	0.0457	0.0457	0.0427	0.0409	0.0408
11	0.0451	0.0428	0.0428	0.0477	0.0393	0.0441	0.0371	0.0436	0.0466	0.0468	0.0437	0.0410	0.0410
12	0.0445	0.0427	0.0434	0.0485	0.0393	0.0431	0.0371	0.0443	0.0479	0.0479	0.0444	0.0412	0.0411
13	0.0470	0.0442	0.0449	0.0497	0.0398	0.0480	0.0374	0.0468	0.0512	0.0513	0.0467	0.0422	0.0426
14	0.0507	0.0480	0.0474	0.0508	0.0437	0.0522	0.0413	0.0491	0.0524	0.0526	0.0489	0.0460	0.0462
15	0.0527	0.0505	0.0494	0.0515	0.0466	0.0536	0.0442	0.0507	0.0540	0.0537	0.0505	0.0486	0.0488
16	0.0526	0.0505	0.0495	0.0515	0.0468	0.0533	0.0444	0.0503	0.0528	0.0529	0.0501	0.0486	0.0488
17	0.0522	0.0501	0.0494	0.0515	0.0464	0.0531	0.0440	0.0498	0.0512	0.0517	0.0496	0.0481	0.0483
18	0.0514	0.0494	0.0499	0.0516	0.0466	0.0525	0.0446	0.0490	0.0469	0.0476	0.0486	0.0479	0.0476
19	0.0532	0.0519	0.0516	0.0523	0.0494	0.0541	0.0477	0.0525	0.0536	0.0535	0.0524	0.0507	0.0510
20	0.0542	0.0540	0.0534	0.0528	0.0529	0.0549	0.0518	0.0540	0.0543	0.0541	0.0539	0.0535	0.0536
21	0.0554	0.0553	0.0547	0.0538	0.0546	0.0562	0.0538	0.0555	0.0555	0.0553	0.0553	0.0550	0.0552
22	0.0564	0.0565	0.0559	0.0546	0.0561	0.0571	0.0554	0.0564	0.0559	0.0558	0.0562	0.0563	0.0565

*Group energy limits as in Table IV.

VII. PROMPT NEUTRON LIFETIMES AND AVERAGE CORE SPECTRA

Calculated prompt neutron lifetimes for the series of assemblies are compared in Table IX with reported experimental lifetimes^{11,14} derived from Rossi- α experiments. The calculated values were obtained by insertion of $1/v$ poison into the analyses. The last two columns allow the ratios of experimental to calculated values to be compared with the corresponding ratios based upon calculations reported by Davey,²³ who used a modification of the cross-section set of Yiftah *et al.*¹⁹ The present set results in a decrease in the average deviations and in the range of the deviations. For this series the discrepancies of experimental to calculated values are on the average about 50% smaller.

TABLE IX. Calculated Prompt Neutron Lifetimes
Compared with Experimental Values

Assembly No.	ℓ_p^{Calc} $\times 10^8$ sec	ℓ_p^{Exp} $\times 10^8$ sec	Exp/Calc	Exp/Calc*
6F	6.8	7.7	1.13	1.71
9A	6.7	8.3	1.24	1.46
12	8.9	10.5	1.18	1.30
14	15.3	18.7	1.22	1.30
22	6.3	7.1	1.13	1.39
23	11.0	12.1	1.10	1.25
25	7.5	8.1	1.08	1.30
29	21.2	23.5	1.11	1.34
32	11.3	12.6	1.11	1.24
33	11.3	12.5	1.11	1.26
34	22.0	24.7	1.12	1.46
36	7.2	7.8	1.08	1.38
41	11.9	13.1	1.10	1.38

*Calculated values from Ref. 23.

In interpreting the improved calculated lifetimes in terms of more degraded neutron-flux spectra, one must consider the average core spectra rather than the central, or normal-mode, spectra. This is because of the effect of the reflectors upon the average flux spectra in the cores. Indicative of the reflector importance are the ratios of calculated reflected-core lifetimes to bare-core lifetimes listed in Table X. These ratios range from 1.02 to 1.36 for this series of assemblies. Changes in multigroup cross sections of U^{238} , which is present in very large proportion in the reflectors of this series, can therefore change the prompt neutron lifetimes in many of the systems.

TABLE X. Ratios of Reflected- to Bare-core Prompt Neutron Lifetimes

Assembly No.	$\frac{\ell_p^{(Refl)}}{\ell_p^{(Bare)}}$	Assembly No.	$\frac{\ell_p^{(Refl)}}{\ell_p^{(Bare)}}$
6F	1.36	29	1.02
9A	1.22	32	1.16
12	1.10	33	1.18
14	1.05	34	1.02
22	1.11	36	1.14
23	1.26	41	1.07
25	1.04		

Improvements in lifetime calculations may also result from changes in cross sections of core materials. For example, the presence of U^{238} in the core region of Assembly 22 also results in lifetime improvement.

Calculated bare-core lifetimes using Y.O.M., ELMOE-Y.O.M. and the present set are compared in Table XI for four assemblies. The sets using the Y.O.M. and the

ELMOE-Y.O.M. cross sections contained the conservative $\nu_j^{U^{235}}$ values.¹⁹ The ELMOE-Y.O.M. set contained the results of ELMOE averaging for the light elements. This was done so that lifetime changes due to ELMOE procedure and non-ELMOE cross-section changes might be compared. These calculated values of the ratio, $\ell_p(\text{present set})/\ell_p(\text{Y.O.M.})$, for the bare cores generally are not sufficiently large to account for the improvements in the calculated reflected-core lifetimes. Changes in the cross sections of U^{238} , which is the major constituent of the reflectors, contribute considerably to the improvement of the lifetime calculations. For the second case (Assembly No. 22), the presence of the U^{238} as primary diluent in the core region also contributes to the improved lifetime. For the graphite diluent case, improvement is due largely to the use of the ELMOE procedure. This is seen by comparing the results using Y.O.M., ELMOE-Y.O.M., and present set for the bare cases. This does not imply that the reflector does not modify the average spectrum in this core. Rather it is modified in a manner that does not as significantly affect the lifetime; i.e., the spectral maximum in the spatial average of the core spectrum is shifted toward lower energies with a simultaneous lowering of the intensity of the low-energy tail.

TABLE XI. Intercomparisons of Bare-core Prompt Neutron Lifetimes with Corresponding Values Derived from Y.O.M. Cross Sections

Assembly No.	Principal Diluent	$\ell_p \times 10^8 \text{ sec}$			$\frac{\ell_p(\text{ELMOE-Y.O.M.})}{\ell_p(\text{Y.O.M.})}$	$\frac{\ell_p(\text{present set})}{\ell_p(\text{Y.O.M.})}$
		Y.O.M.	ELMOE-Y.O.M.	Present Set		
14	C	13.6	14.4	14.7	1.06	1.08
22	U^{238}	(5.17)*	5.17	5.75	~1.00	1.11
23	Al	8.77	8.32	8.83	0.95	1.01
32	SS	9.98	9.54	9.81	0.96	0.98

*Not directly calculated, assumed equal to ELMOE-Y.O.M. value because only small amount of steel in core is affected by ELMOE treatment.

VIII. CONCLUSIONS

For this series of ZPR-3 assemblies, this cross-section set results in deviations of calculated critical masses, relative to reported experimental values, from about zero to about +2.5% k in reactivity. Assemblies having core compositions containing larger amounts of light materials, such as aluminum, sodium, steel, etc., deviate most from the experimental values. Use of Pl ELMOE-derived group-transport and elastic-transfer cross sections result in smaller deviations from experiment than use of the more accurate consistent-B1 values.

The spectra at the core center generally tend to be more degraded with this set relative to that of Y.O.M. These central spectral degradations are only in part responsible for the improved calculated lifetimes. To a large extent the lifetime improvement results from cross-section modifications in the U^{238} , which is present in large quantities in all the reflectors and in some of the cores. (This results largely from the more-degraded inelastic-transfer cross sections, coupled with employment of a larger number of inelastic transfer-in groups, i.e., 12 instead of the six in Y.O.M.) Thus comparisons of the increases in calculated bare-core lifetimes are generally much less than in the reflected cases. (This indicates that although the calculated lifetimes of the assemblies are significantly improved, corresponding central boron reactivity calculations²³ would not be analogously improved relative to boron central-substitution measurements.)

Exploratory calculations of Meneley and White,²⁴ incorporating the effects of a lowered U^{235} fission cross section below about 200 keV, as indicated by the data of P. H. White,²⁵ together with revised values of U^{235} and U^{238} delayed neutron fractions reported by Keepin,²⁶ suggest that these additional modifications may further improve the correlations of calculated lifetimes with experiments.

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