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DANDE—A Linked Code System for Core Neutronics/Depletion Analysis

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DANDE -- A LINKED CODE SYSTEM FOR CORE NEUTRONICS/DEPLETION ANALYSIS

by

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ABSTRACT

This report describes DANDE--a modular neutronics, depletion code system for reactor analysis. It consists of nuclear data processing, core physics, and fuel depletion modules, and allows one to use diffusion and transport methods interchangeably in core neutronics calculations. This latter capability is especially important in the design of small modular cores. Additional unique features include the capability of updating the nuclear data file during a calculation; a detailed treatment of depletion, burnable poisons as well as fuel; and the ability to make geometric changes such as control rod repositioning and fuel relocation in the course of a calculation. The detailed treatment of reactor fuel burnup, fission-product creation and decay, as well as inventories of higher-order actinides is a necessity when predicting the behavior of reactor fuel under increased burn conditions. The operation of the code system is made clear in this report by following a sample problem.

1. INTRODUCTION

The DANDE (Applied Nuclear Data, Core-Neutronics, Depletion) code system was initially developed for use in the analysis of advanced liquid Metal Fast Breeder Reactor (LMFBR) concepts, but its flexibility allows application to other reactor types as well. The philosophy of the DANDE development has been to use standard, validated codes, files, and data libraries, linking them on the Los Alamos Class VI, CRAY computer, and guiding their interaction with a locally written controller. The result is the three-module code system shown in Fig. 1 consisting of data processing, core neutronics, and depletion modules. In Fig. 1 the modules are shown as rectangles, and the circles in between represent standard files¹ for transferring data between modules. Thus, any appropriate code that can operate in the standard file environment can be used in the code modules.

Fig. 1. DANDE code system for reactor core analysis.

Currently the data processing module consists of the TRANSX code² operating on a fine-group library (80 groups) generated by the NJOY³ code from the ENDF/B-V⁴ basic nuclear data file. TRANSX produces neutron, photon, or coupled transport cross-section tables in the standard ISOTXS format. The code contains options for adjoint tables, mixtures, self-shielding/Doppler corrections, group collapse, cell homogenization, thermal upscatter, prompt or steady-state fission, transport corrections, elastic removal corrections, and flexible response function edits. As indicated in Fig. 1, fine-group weighting fluxes for group collapse computed in the core neutronics module are transferred to TRANSX via the standard RZFLUX file. Normally, the fine-group core neutronics model contains one dimension less than the final coarse-group model. In calculations for the FFTF experiments discussed in Section VI, for example, fluxes from a two-dimensional, cylindrical, 80-group diffusion calculation were used

in TRANSX to produce 12-group cross sections for the final three-dimensional hexagonal-Z model. In the course of a long time depletion calculation with control rod and/or fuel repositioning, it may be necessary to recalculate the fine-group core model and rerun the data processing module to produce an updated ISOTXS file. This can be done with the controller. On the other hand, because ISOTXS is a standard file, ISOTXS files produced with codes other than TRANSX from outside Los Alamos have also been used (see Sec. VI).

The codes currently being used in the core neutronics model include the DIF3D diffusion code⁵ (finite difference and nodal options in hexagonal and orthogonal geometries) and the TWODANT⁶ (cylindrical geometry) and TWOHEX⁷ (hexagonal geometry) discrete ordinates transport codes. The large, three-dimensional diffusion calculations discussed in Sec. VI run most efficiently on the Los Alamos largest CRAY machines (1.8-M word storage), and the core neutronics calculation takes about three minutes per time step. The running times for two-dimensional problems using the S_n codes are comparable to those for three-dimensional problems using the diffusion code.

The CINDER-3 code,⁸ an enhanced version of the CINDER-2 code,⁹⁻¹² is the only code used to date for the DANDE depletion module. Using data from the ISOTXS file and its own library data file and the RZFLUX file produced by the core neutronics module, this code does summation calculations over the various fission-product and actinide chains and provides updated nuclear densities for the principal nuclides in the ZNATDN file. The non-explicit actinides and fission products are grouped into two aggregates, respectively; densities for each are placed on the ZNATDN file, and microscopic cross sections for each are placed on the ISOTXS file in preparation for the core calculation for the next time step. A total of 223 fission products and 46 actinides in 186 chains are used in the CINDER-3 calculation; burnable poisons (e.g., B, Sm, Eu) are also handled in detail.

The local controller used to manipulate and/or monitor the three modules is written in CTL, a language developed at Los Alamos. CTL is used in a FORTRAN-like manner to loop through the time steps in a depletion problem, calling in the various codes and files in the proper sequence. Geometric changes (GEODST file), such as control rod repositioning and fuel relocation, can be made with CTL between depletion time steps. An example of CTL operation, namely, for the FFTF Cycle-1 depletion experiment, as described in the Large Core Computational Evaluation Working Group (LCCEWG) Benchmark No. 5 specifications,¹³ is given in Sec. V.

II. DATA PROCESSING MODULE

In most of our work to date, we have used two fine-group libraries in the DANDE data processing module (TRANSX), both of which were generated by the NJOY code using basic nuclear data from ENDF/B-V. The first of these, MATXS6,² is an 80-neutron $\times$ 24-photon group library intended for fast reactor analysis but also appropriate for fusion studies and shielding calculations. This library features extensive self-shielded cross sections for temperatures from 300 K to as high as 5000 K for some materials. Background cross sections (defined below) vary from infinity down to a lower limit that depends on the normal applications of the material. MATXS6 currently contains data for about 100 nuclides, but data for additional materials are constantly being added as the need arises. MATXS6 has been used in DANDE code applications, which include LMFBR advanced concept studies and LCCEWG-5 calculations discussed in Sec. VI.

The other library used, MATXS7, is a 69-group neutron-only library designed for light-water-reactor problems. It includes self-shielded cross sections for the important actinides. Thermal scattering data are given for all materials, with bound scattering for the important moderators. The group structure has 42 thermal groups extending up to 4.00 eV. MATXS7 has been used locally in DANDE applications to problems in thermal reactor design.

As an example of the use of the TRANSX code in the DANDE data-processing module, consider the production of the ISOTXS file for the LCCEWG-5 experiments discussed in Sec. VI. The processing path used is shown in Fig. 2. As indicated in the figure and mentioned above, the basic library used was MATXS6, the fine-group energy boundaries of which are given in Table I. Also given in Table I are the collapsed 12-group energy boundaries for the ISOTXS data file used in the final benchmark calculations.

Note in Fig. 2 that TRANSX must be run in two passes before the final 12-group ISOTXS file is produced. The purpose of the first pass is to provide an 80-group ISOTXS file for the two-dimensional flux calculation. The RZFLUX file produced is then used in the second TRANSX pass, which results in the 12-group ISOTXS file used in three-dimensional calculations. Normally, a default 80-group flux is employed in the first TRANSX pass, but in the case of preparation of the data file for LCCEWG-5, 80-group initial fluxes were available from preliminary FFTF calculations.

As an aid to understanding the operation of the TRANSX code, consider the input for the FFTF high power characterizer experiment (HPC) part of LCCEWG-5.

Fig. 2. DANDE data processing module configuration to produce the ISOTXS file for LCCEWG-5.

TABLE I
BOUNDARIES FOR 80-GROUP STRUCTURE

<u>Group</u>	<u>Energy(eV)</u>	<u>Group</u>	<u>Energy(eV)</u>
1	2.0000E+07*	41	1.5034E+04*
2	1.6905E+07	42	1.3268E+04
3	1.4918E+07	43	1.1709E+04
4	1.3499E+07	44	1.0333E+04
5	1.1912E+07	45	9.1188E+03
6	1.0000E+07	46	8.0473E+03
7	7.7880E+06	47	7.1017E+03
8	6.0653E+06	48	6.2673E+03
9	4.7237E+06	49	5.5308E+03*
10	3.6788E+06*	50	4.8810E+03
11	2.8650E+06	51	4.3074E+03
12	2.2313E+06	52	3.8013E+03
13	1.7377E+06	53	3.3546E+03
14	1.3534E+06*	54	2.9604E+03
15	1.1943E+06	55	2.6126E+03
16	1.0540E+06	56	2.3056E+03
17	9.3014E+05	57	2.0347E+03*
18	8.2085E+05	58	1.7956E+03
19	7.2440E+05	59	1.5846E+03
20	6.3928E+05	60	1.3984E+03
21	5.6416E+05	61	1.2341E+03
22	4.9787E+05*	62	1.0891E+03
23	4.3937E+05	63	9.6112E+02
24	3.8774E+05	64	7.4852E+02*
25	3.0197E+05*	65	5.8295E+02
26	2.3518E+05	66	4.5400E+02
27	1.8316E+05	67	3.5358E+02
28	1.4264E+05	68	2.7536E+02*
29	1.1109E+05*	69	1.6702E+02
30	8.6517E+04	70	1.0130E+02
31	6.7379E+04	71	6.1442E+01
32	5.2475E+04	72	3.7267E+01
33	4.0868E+04*	73	2.2603E+01
34	3.1828E+04	74	1.3710E+01
35	2.8088E+04	75	8.3153E+00
36	2.6058E+04	76	5.0435E+00
37	2.4788E+04	77	3.0590E+00
38	2.1875E+04	78	1.1254E+00
39	1.9305E+04	79	4.1399E-01
40	1.7036E+04	80	1.5230E-01
		Emin	1.3888e-04*

*12-Group Boundaries

The input for the TRANSX first pass is given in Table II, that for the second pass in Table III, and an R-Z model of the FFTF HPC core is shown in Fig. 3, homogenized regions being defined in Tables IV and V. In Table II, Record No. 2 indicates that the input library is MATXS6, that the output library is ISOTXS, and that an RZFLUX file is available for the computation. The flags on Record No. 3 select the following options:

IPRINT = 0, long print
 IOUT = 6, ISOTXS format
 IPROB = 0, Direct calculation
 ISET = 1, Neutron-neutron (NN) set produced
 IFORM = 1, Data on ISOTXS ordered by material
 ITIME = 1, Steady-state fission
 IDECAY = 0, Prompt fission
 ITRC = 3, Bell-Hansen-Sandmeier transport correction
 ICOLL = 0, No group collapse
 INITF = -14, Elastic scattering flux correction made for fluxes on
 RZFLUX file.

Some of the above need further clarification. For the approximate transport cross sections, $\sigma_{lg \leftarrow g}^{SN}$, it is convenient to write

$$\sigma_{lg \leftarrow g}^{SN} = \sigma_{lg \leftarrow g}^{PN} - (\sigma_{ltg}^{PN} - \sigma_{0tg}^{PN}) - \Delta_g^N \quad \text{and} \quad \sigma_g^{SN} = \sigma_{0tg}^{PN} - \Delta_g^N \quad (1)$$

where the σ^{PN} are the cross sections from the Legendre polynomial form of the Boltzmann equation, group averages of which are given by

$$\sigma_{ltg}^{PN} = \frac{\int_g \sigma_t(E) w_l(E) dE}{\int_g w_l(E) dE}, \quad \text{and} \quad (2)$$

$$\sigma_{lg \leftarrow g'}^{PN} = \frac{\int_g dE' \int_g dE \sigma_l(E' \rightarrow E) w_l(E')}{\int_{g'} dE' w_l(E')} \quad (3)$$

In these formulas, $\sigma_t(E)$ and $\sigma_l(E' \rightarrow E)$ are the basic energy-dependent total and scattering cross sections, and $w_l(E)$ is a weighting flux. The g and g' are group-to-group transfer indices and the l refers to the Legendre order.

TABLE II

80-GROUP TRANSX INPUT FOR 2-D MODEL OF FFTF HPC EXPERIMENT

```

1 *DEC 83 FFTF 80 GROUP RUN*/
2 *MATXS6* *ISOTXS* *RZFLUX*/
3 0 6 0 1 1 1 0 3 0 -14
4 80 0 1 70 0 19 19 171 9 9
5 *NAC* *BPC* *ABS* *DRL* *LRS* *RR1* *RR2* *ASF* *ARF* *INF* *DRI* *DR2* *GPF*
6 *CRS* *URS* *DRIA* *ICS* *APC* *CHI*
7 *NAC* 400./
8 *BPC* 400./
9 *ABS* 400./
10 *DRL* 400./
11 *LRS* 400./
12 *RR1* 400./
13 *RR2* 400./
14 *ASF* 400./
15 *ARF* 400./
16 *INF* 400./
17 *DRI* 740./
18 *DR2* 740./
19 *GPF* 400./
20 *CRS* 400./
21 *URS* 400./
22 *DRIA* 740./
23 *ICS* 740./
24 *APC* 400./
25 *CHI* 740./
26 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 4 4 6 4
27 1 1 *FENAT* .005159 0/
28 1 1 *CRNAT* .001515 0/
29 1 1 *NINAT* .001048 0/
30 1 1 *MONAT* .000105 0/
31 1 1 *MN55* .000129 0/
32 1 1 *NA23* .020028 0/
33 1 1 *CNAT* .000105 0/
34 2 2 *FENAT* .021429 0/
35 2 2 *CRNAT* .006295 0/
36 2 2 *NINAT* .004353 0/
37 2 2 *MONAT* .000435 0/
38 2 2 *MN55* .000536 0/
39 2 2 *NA23* .013359 0/
40 2 2 *CNAT* .000435 0/
41 3 3 *FENAT* .018057 0/
42 3 3 *CRNAT* .005304 0/
43 3 3 *NINAT* .003668 0/
44 3 3 *MONAT* .000367 0/
45 3 3 *MN55* .000451 0/
46 3 3 *NA23* .007158 0/
47 3 3 *B10* .006386 0/
48 3 3 *B11* .025868 0/
49 3 3 *CNAT* .007561 0/
50 4 4 *FENAT* .013151 0/

```

TABLE II (Cont.)

51	4	4	*CRNAT*	.003863	0/	101	10	10	*PU240*	1.E-10	1.E+10/
52	4	4	*NINAT*	.002671	0/	102	10	10	*CNAT*	.000259	0/
53	4	4	*MONAT*	.000267	0/	103	11	11	*PU239*	.001127	0/
54	4	4	*MN55*	.000328	0/	104	11	11	*PU240*	.000152	0/
55	4	4	*NA23*	.016758	0/	105	11	11	*PU241*	.000016	0/
56	4	4	*CNAT*	.000267	0/	106	11	11	*PU242*	.000002	0/
57	5	5	*FENAT*	.004737	0/	107	11	11	*AM241*	.000004	0/
58	5	5	*CRNAT*	.001391	0/	108	11	11	*U235*	.000026	0/
59	5	5	*NINAT*	.000962	0/	109	11	11	*U238*	.004390	0/
60	5	5	*MONAT*	.000096	0/	110	11	11	*O16*	.011218	0/
61	5	5	*MN55*	.000118	0/	111	11	11	*FENAT*	.01672	0/
62	5	5	*NA23*	.007400	0/	112	11	11	*CRNAT*	.00491	0/
63	5	5	*CNAT*	.000096	0/	113	11	11	*NINAT*	.0034	0/
64	6	6	*FENAT*	.016664	0/	114	11	11	*MONAT*	.00034	0/
65	6	6	*CRNAT*	.012394	0/	115	11	11	*MN55*	.00042	0/
66	6	6	*NINAT*	.043243	0/	116	11	11	*NA23*	.009113	0/
67	6	6	*MONAT*	.000241	0/	117	11	11	*CNAT*	.00034	0/
68	6	6	*MN55*	.000517	0/	118	12	12	*PU239*	.001591	0/
69	6	6	*NA23*	.003224	0/	119	12	12	*PU240*	.000224	0/
70	6	6	*CNAT*	.000241	0/	120	12	12	*PU241*	.000023	0/
71	7	7	*FENAT*	.021852	0/	121	12	12	*PU242*	.000004	0/
72	7	7	*CRNAT*	.013245	0/	122	12	12	*AM241*	.000007	0/
73	7	7	*NINAT*	.040722	0/	123	12	12	*U235*	.000034	0/
74	7	7	*MONAT*	.000355	0/	124	12	12	*U238*	.005124	0/
75	7	7	*MN55*	.000638	0/	125	12	12	*O16*	.013870	0/
76	7	7	*NA23*	.002178	0/	126	12	12	*FENAT*	.012423	0/
77	7	7	*CNAT*	.000355	0/	127	12	12	*CRNAT*	.003649	0/
78	8	8	*FENAT*	.038370	0/	128	12	12	*NINAT*	.002523	0/
79	8	8	*CRNAT*	.011270	0/	129	12	12	*MONAT*	.000252	0/
80	8	8	*NINAT*	.007790	0/	130	12	12	*MN55*	.000311	0/
81	8	8	*MONAT*	.000780	0/	131	12	12	*NA23*	.008919	0/
82	8	8	*MN55*	.000960	0/	132	12	12	*CNAT*	.000252	0/
83	8	8	*NA23*	.006400	0/	133	13	13	*FENAT*	.015779	0/
84	8	8	*CNAT*	.000780	0/	134	13	13	*CRNAT*	.004635	0/
85	9	9	*FENAT*	.013620	0/	135	13	13	*NINAT*	.003205	0/
86	9	9	*CRNAT*	.007120	0/	136	13	13	*MONAT*	.000321	0/
87	9	9	*NINAT*	.019350	0/	137	13	13	*MN55*	.000394	0/
88	9	9	*MONAT*	.000240	0/	138	13	13	*NA23*	.009113	0/
89	9	9	*MN55*	.000380	0/	139	13	13	*CNAT*	.000321	0/
90	9	9	*NA23*	.009640	0/	140	14	14	*FENAT*	.037803	0/
91	9	9	*CNAT*	.000240	0/	141	14	14	*CRNAT*	.011105	0/
92	10	10	*U235*	.000050	0/	142	14	14	*NINAT*	.007679	0/
93	10	10	*U238*	.007188	0/	143	14	14	*MONAT*	.000768	0/
94	10	10	*O16*	.014476	0/	144	14	14	*MN55*	.000945	0/
95	10	10	*FENAT*	.012769	0/	145	14	14	*NA23*	.006636	0/
96	10	10	*CRNAT*	.003751	0/	146	14	14	*CNAT*	.000768	0/
97	10	10	*NINAT*	.002594	0/	147	15	15	*FENAT*	.048027	0/
98	10	10	*MONAT*	.000259	0/	148	15	15	*CRNAT*	.014108	0/
99	10	10	*MN55*	.000319	0/	149	15	15	*NINAT*	.009755	0/
100	10	10	*PU239*	1.E-10	1.E+10/	150	15	15	*MONAT*	.000976	0/

TABLE II (Cont.)

151	15	15	*MN55*	.001201	0/	201	3	*NFTOT*/
152	15	15	*NA23*	.002438	0/	202	4	*CHI*/
153	15	15	*CNAT*	.000976	0/	203	5	*NA*/
154	16	16	*PU239*	.001371	0/	204	6	*NP*/
155	16	16	*PU240*	.000186	0/	205	7	*N2N*/
156	16	16	*PU241*	.000019	0/	206	8	*ND*/
157	16	16	*PU242*	.000003	0/	207	9	*NT*/
158	16	16	*AM241*	.000005	0/	208		*STOP*/
159	16	16	*U235*	.000031	0/			
160	16	16	*U238*	.005330	0/			
161	16	16	*O16*	.013630	0/			
162	16	16	*FENAT*	.013415	0/			
163	16	16	*CRNAT*	.003941	0/			
164	16	16	*NINAT*	.002725	0/			
165	16	16	*MONAT*	.000272	0/			
166	16	16	*MN55*	.000336	0/			
167	16	16	*NA23*	.009113	0/			
168	16	16	*CNAT*	.000272	0/			
169	17	17	*FENAT*	.031772	0/			
170	17	17	*CRNAT*	.009333	0/			
171	17	17	*NINAT*	.006454	0/			
172	17	17	*MCNAT*	.000645	0/			
173	17	17	*MN55*	.000394	0/			
174	17	17	*NA23*	.009113	0/			
175	17	17	*CNAT*	.000645	0/			
176	18	18	*FENAT*	.020458	0/			
177	18	18	*CRNAT*	.006010	0/			
178	18	18	*NINAT*	.004156	0/			
179	18	18	*MONAT*	.000416	0/			
180	18	18	*MN55*	.000511	0/			
181	18	18	*NA23*	.007164	0/			
182	18	18	*CNAT*	.000416	0/			
183	19	19	*PU239*	.001310	0/			
184	19	19	*PU240*	.000177	0/			
185	19	19	*PU241*	.000019	0/			
186	19	19	*PU242*	.000003	0/			
187	19	19	*AM241*	.000006	0/			
188	19	19	*U235*	.000037	0/			
189	19	19	*U238*	.005335	0/			
190	19	19	*O16*	.013499	0/			
191	19	19	*FENAT*	.013513	0/			
192	19	19	*CRNAT*	.003969	0/			
193	19	19	*NINAT*	.002745	0/			
194	19	19	*MONAT*	.000274	0/			
195	19	19	*MN55*	.000338	0/			
196	19	19	*NA23*	.009113	0/			
197	19	19	*CNAT*	.000274	0/			
198			*STRPL* *SNGAM* *SFIS* *CHISO* *SNALF* *SNP* *SN2N* *SND* *SNT*					
199	1		*TRD*/					
200	2		*NG*/					

TABLE III

12-GROUP TRANSX INPUT FOR 2-D MODEL OF FFTF HPC EXPERIMENT

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1 *JAN 84 FFTF COLLAPSE TO 8 GROUPS*/
2 *MATXS6* *ISOTXS* *RZFLUX*/
3 0 6 0 1 1 1 0 3 80 -14
4 12 0 1 24 0 195 19 352 9 9
5 *NAC* *BPC* *ABS* *DRL* *LRS* *RR1* *RR2* *ASF* *ARF* *INF* *DR1* *DR2* *GPF*
6 *CRS* *URS* *DR3* *ICS* *APC* *CH1*
7 *FENAC* *CRNAC* *NINAC* *MONAC* *MNNAC* *NANAC* *CNAC* *FEBPC* *CRBPC* *NIBPC*
8 *MOBPC* *MNEPC* *NABPC* *CBPC* *FEABS* *CRABS* *NIABS* *MOABS* *MNABS* *NAABS*
9 *B1OABS* *B1IABS* *CABS* *FEDRL* *CRDRL* *NIDRL* *MODRL* *MNDRL* *NADRL*
10 *CDRL* *FELRS* *CRLRS* *NILRS* *MOLRS* *MNLRS* *NALRS* *CLRS*
11 *FERR1* *CRRR1* *NIRR1* *MORR1* *MNRR1* *NARR1* *CRR1* *FERR2* *CRRR2*
12 *NIRR2* *MORR2* *MNRR2* *NARR2* *CRR2* *FEASF* *CRASF* *NIASF* *MOASF*
13 *MNASF* *NAASF* *CAS* *FEARF* *CRARF* *NIARF* *MOARF* *MNARF* *NAARF*
14 *CARF* *U35INF* *U38INF* *OINF* *FEINF* *CRINF* *NIINF* *MOINF* *MNINF*
15 *P39INF* *P40INF* *FPINF*
16 *CINF* *P39D1* *P40D1* *P41D1* *P42D1* *A41D1* *U35D1* *U38D1* *FPD1*
17 *OD1* *FED1* *CRD1* *NID1* *MOD1* *MND1* *NAD1* *CD1*
18 *P39D2* *P40D2* *P41D2* *P42D2* *A41D2* *U35D2* *U38D2* *FPD2* *OD2*
19 *FED2* *CRD2* *NID2* *MOD2* *MND2* *NAD2* *CD2*
20 *FEGPF* *CRGPF* *NIGPF* *MOGPF* *MNGPF* *NAGPF* *CGPF*
21 *FECRS* *CRCRS* *NICRS* *MOCRS* *MNCRS* *NACRS* *CCRS*
22 *FEURS* *CRURS* *NIURS* *MOURS* *MNURS* *NAURS* *CURS*
23 *P39D3* *P40D3* *P41D3* *P42D3* *A41D3* *U35D3* *U38D3* *FPD3* *OD3*
24 *FED3* *CRD3* *NID3* *MOD3* *MND3* *NAD3* *CD3*
25 *FEICS* *CRICS* *NIICS* *MOICS* *MNICS* *NAICS* *CICS*
26 *FEAPC* *CRAPC* *NIAPC* *MOAPC* *MNAPC* *NAAPC* *CAPC*
27 *P39CH1* *P40CH1* *P41CH1* *P42CH1* *A41CH1* *U35CH1* *U38CH1* *FPCH1*
28 *OCH1* *FECH1* *CRCH1* *NICH1* *MOCH1* *MNCH1* *NACH1* *CCH1*
29 *NAC* 400./
30 *BPC* 400./
31 *ABS* 400./
32 *DRL* 400./
33 *LRS* 400./
34 *RR1* 400./
35 *RR2* 400./
36 *ASF* 400./
37 *ARF* 400./
38 *INF* 400./
39 *DR1* 740./
40 *DR2* 740./
41 *GPF* 400./
42 *CRS* 400./
43 *URS* 400./
44 *DR1A* 740./
45 *ICS* 740./
46 *APC* 400./
47 *CH1* 740./
48 8 9 10 11 12 13 14 1 2 3 4 5 6 7 15 4 4 16 4
49 1 1 *FENAT* .005159 0/
50 1 1 *CRNAT* .001515 0/

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TABLE III (Cont.)

51	1	1	*NINAT*	.001048	0/	101	8	8	*CRNAT*	.01127	0/
52	1	1	*MONAT*	.000105	0/	102	8	8	*NINAT*	.00779	0/
53	1	1	*MN55*	.000129	0/	103	8	8	*MONAT*	.00078	0/
54	1	1	*NA23*	.020028	0/	104	8	8	*MN55*	.00096	0/
55	1	1	*CNAT*	.000105	0/	105	8	8	*NA23*	.00640	0/
56	2	2	*FENAT*	.021429	0/	106	8	8	*CNAT*	.00078	0/
57	2	2	*CRNAT*	.006295	0/	107	9	9	*FENAT*	.01362	0/
58	2	2	*NINAT*	.004353	0/	108	9	9	*CRNAT*	.00712	0/
59	2	2	*MONAT*	.000435	0/	109	9	9	*NINAT*	.01935	0/
60	2	2	*MN55*	.000536	0/	110	9	9	*MONAT*	.00024	0/
61	2	2	*NA23*	.013359	0/	111	9	9	*MN55*	.00038	0/
62	2	2	*CNAT*	.000435	0/	112	9	9	*NA23*	.00964	0/
63	3	3	*FENAT*	.018057	0/	113	9	9	*CNAT*	.00024	0/
64	3	3	*CRNAT*	.005304	0/	114	10	10	*U235*	.000050	0/
65	3	3	*NINAT*	.003668	0/	115	10	10	*U238*	.007188	0/
66	3	3	*MONAT*	.000367	0/	116	10	10	*O16*	.014476	0/
67	3	3	*MN55*	.000451	0/	117	10	10	*FENAT*	.012769	0/
68	3	3	*NA23*	.007158	0/	118	10	10	*CRNAT*	.003751	0/
69	3	3	*B10*	.006386	0/	119	10	10	*NINAT*	.002594	0/
70	3	3	*B11*	.025868	0/	120	10	10	*MONAT*	.000259	0/
71	3	3	*CNAT*	.007561	0/	121	10	10	*MN55*	.000319	0/
72	4	4	*FENAT*	.013151	0/	122	10	10	*PU239*	1.E-10	1.E+10/
73	4	4	*CRNAT*	.003863	0/	123	10	10	*PU240*	1.E-10	1.E+10/
74	4	4	*NINAT*	.002671	0/	124	10	10	*HEDLFP*	1.E-10	1.E+10/
75	4	4	*MONAT*	.000267	0/	125	10	10	*CNAT*	.000259	0/
76	4	4	*MN55*	.000328	0/	126	11	11	*PU239*	.001127	0/
77	4	4	*NA23*	.016758	0/	127	11	11	*PU240*	.000152	0/
78	4	4	*CNAT*	.000267	0/	128	11	11	*PU241*	.000016	0/
79	5	5	*FENAT*	.004737	0/	129	11	11	*PU242*	.000002	0/
80	5	5	*CRNAT*	.001391	0/	130	11	11	*AM241*	.000004	0/
81	5	5	*NINAT*	.000962	0/	131	11	11	*U235*	.000026	0/
82	5	5	*MONAT*	.000096	0/	132	11	11	*U238*	.0043900	0/
83	5	5	*MN55*	.000118	0/	133	11	11	*HEDLFP*	1.E-10	1.E+10/
84	5	5	*NA23*	.007400	0/	134	11	11	*O16*	.011218	0/
85	5	5	*CNAT*	.000096	0/	135	11	11	*FENAT*	.01672	0/
86	6	6	*FENAT*	.016664	0/	136	11	11	*CRNAT*	.00491	0/
87	6	6	*CRNAT*	.012394	0/	137	11	11	*NINAT*	.0034	0/
88	6	6	*NINAT*	.043243	0/	138	11	11	*MONAT*	.00034	0/
89	6	6	*MONAT*	.000241	0/	139	11	11	*MN55*	.00042	0/
90	6	6	*MN55*	.000517	0/	140	11	11	*NA23*	.009113	0/
91	6	6	*NA23*	.003224	0/	141	11	11	*CNAT*	.000340	0/
92	6	6	*CNAT*	.000241	0/	142	12	12	*PU239*	.001591	0/
93	7	7	*FENAT*	.021852	0/	143	12	12	*PU240*	.000224	0/
94	7	7	*CRNAT*	.013245	0/	144	12	12	*PU241*	.000023	0/
95	7	7	*NINAT*	.040722	0/	145	12	12	*PU242*	.000004	0/
96	7	7	*MONAT*	.000355	0/	146	12	12	*AM241*	.000007	0/
97	7	7	*MN55*	.000638	0/	147	12	12	*U235*	.000034	0/
98	7	7	*NA23*	.002178	0/	148	12	12	*U238*	.005124	0/
99	7	7	*CNAT*	.000355	0/	149	12	12	*HEDLFP*	1.E-10	1.E+10/
100	8	8	*FENAT*	.038370	0/	150	12	12	*O16*	.013870	0/

TABLE III (Cont.)

151	12	12	*FENAT*	.012423	0/	201	17	17	*CNAT*	.000645	0/
152	12	12	*CRNAT*	.003649	0/	202	18	18	*FENAT*	.020458	0/
153	12	12	*NINAT*	.002523	0/	203	18	18	*CRNAT*	.006010	0/
154	12	12	*MONAT*	.000252	0/	204	18	18	*NINAT*	.004156	0/
155	12	12	*MN55*	.000311	0/	205	18	18	*MONAT*	.000416	0/
156	12	12	*NA23*	.008919	0/	206	18	18	*MN55*	.000511	0/
157	12	12	*CNAT*	.000252	0/	207	18	18	*NA23*	.007164	0/
158	13	13	*FENAT*	.015779	0/	208	18	18	*CNAT*	.000416	0/
159	13	13	*CRNAT*	.004635	0/	209	19	19	*PU239*	.001310	0/
160	13	13	*NINAT*	.003205	0/	210	19	19	*PU240*	.000177	0/
161	13	13	*MONAT*	.000321	0/	211	19	19	*PU241*	.000019	0/
162	13	13	*MN55*	.000394	0/	212	19	19	*PU242*	.000003	0/
163	13	13	*NA23*	.009113	0/	213	19	19	*AM241*	.000006	0/
164	13	13	*CNAT*	.000321	0/	214	19	19	*U235*	.000037	0/
165	14	14	*FENAT*	.037803	0/	215	19	19	*U238*	.005335	0/
166	14	14	*CRNAT*	.011105	0/	216	19	19	*HEDLFP*	1.E-10	1.E+10/
167	14	14	*NINAT*	.007679	0/	217	19	19	*O16*	.013499	0/
168	14	14	*MONAT*	.000768	0/	218	19	19	*FENAT*	.013513	0/
169	14	14	*MN55*	.000945	0/	219	19	19	*CRNAT*	.003969	0/
170	14	14	*NA23*	.006636	0/	220	19	19	*NINAT*	.002745	0/
171	14	14	*CNAT*	.000768	0/	221	19	19	*MONAT*	.000274	0/
172	15	15	*FENAT*	.048027	0/	222	19	19	*MN55*	.000338	0/
173	15	15	*CRNAT*	.014108	0/	223	19	19	*NA23*	.009113	0/
174	15	15	*NINAT*	.009755	0/	224	19	19	*CNAT*	.000274	0/
175	15	15	*MONAT*	.000976	0/	225	20	1	*FENAT*	1 -1/	
176	15	15	*MN55*	.001201	0/	226	21	1	*CRNAT*	1 -2/	
177	15	15	*NA23*	.002438	0/	227	22	1	*NINAT*	1 -3/	
178	15	15	*CNAT*	.000976	0/	228	23	1	*MONAT*	1 -4/	
179	16	16	*PU239*	.001371	0/	229	24	1	*MN55*	1 -5/	
180	16	16	*PU240*	.000186	0/	230	25	1	*NA23*	1 -6/	
181	16	16	*PU241*	.000019	0/	231	26	1	*CNAT*	1 -7/	
182	16	16	*PU242*	.000003	0/	232	27	2	*FENAT*	1 -8/	
183	16	16	*AM241*	.000005	0/	233	28	2	*CRNAT*	1 -9/	
184	16	16	*U235*	.000031	0/	234	29	2	*NINAT*	1 -10/	
185	16	16	*U238*	.005330	0/	235	30	2	*MONAT*	1 -11/	
186	16	16	*HEDLFP*	1.E-10	1.E+10/	236	31	2	*MN55*	1 -12/	
187	16	16	*O16*	.013630	0/	237	32	2	*NA23*	1 -13/	
188	16	16	*FENAT*	.013415	0/	238	33	2	*CNAT*	1 -14/	
189	16	16	*CRNAT*	.003941	0/	239	34	3	*FENAT*	1 -15/	
190	16	16	*NINAT*	.002725	0/	240	35	3	*CRNAT*	1 -16/	
191	16	16	*MONAT*	.000272	0/	241	36	3	*NINAT*	1 -17/	
192	16	16	*MN55*	.000336	0/	242	37	3	*MONAT*	1 -18/	
193	16	16	*NA23*	.009113	0/	243	38	3	*MN55*	1 -19/	
194	16	16	*CNAT*	.000272	0/	244	39	3	*NA23*	1 -20/	
195	17	17	*FENAT*	.031772	0/	245	40	3	*B10*	1 -21/	
196	17	17	*CRNAT*	.009333	0/	246	41	3	*B11*	1 -22/	
197	17	17	*NINAT*	.006454	0/	247	42	3	*CNAT*	1 -23/	
198	17	17	*MONAT*	.000645	0/	248	43	4	*FENAT*	1 -24/	
199	17	17	*MN55*	.000794	0/	249	44	4	*CRNAT*	1 -25/	
200	17	17	*NA23*	.009113	0/	250	45	4	*NINAT*	1 -26/	

TABLE III (Cont.)

251	46	4	*MONAT*	1	-27/	301	96	10	*CNAT*	1	-77/
252	47	4	*MN55*	1	-28/	302	97	11	*PU239*	1	-78/
253	48	4	*NA23*	1	-29/	303	98	11	*PU240*	1	-79/
254	49	4	*CNAT*	1	-30/	304	99	11	*PU241*	1	-80/
255	50	5	*FENAT*	1	-31/	305	100	11	*PU242*	1	-81/
256	51	5	*CRNAT*	1	-32/	306	101	11	*AM241*	1	-82/
257	52	5	*NINAT*	1	-33/	307	102	11	*U235*	1	-83/
258	53	5	*MONAT*	1	-34/	308	103	11	*U238*	1	-84/
259	54	5	*MN55*	1	-35/	309	104	11	*HEDLFP*	1	-85/
260	55	5	*NA23*	1	-36/	310	105	11	*O16*	1	-86/
261	56	5	*CNAT*	1	-37/	311	106	11	*FENAT*	1	-87/
262	57	6	*FENAT*	1	-38/	312	107	11	*CRNAT*	1	-88/
263	58	6	*CRNAT*	1	-39/	313	108	11	*NINAT*	1	-89/
264	59	6	*NINAT*	1	-40/	314	109	11	*MONAT*	1	-90/
265	60	6	*MONAT*	1	-41/	315	110	11	*MN55*	1	-91/
266	61	6	*MN55*	1	-42/	316	111	11	*NA23*	1	-92/
267	62	6	*NA23*	1	-43/	317	112	11	*CNAT*	1	-93/
268	63	6	*CNA1*	1	-44/	318	113	12	*PU239*	1	-94/
269	64	7	*FENAT*	1	-45/	319	114	12	*PU240*	1	-95/
270	65	7	*CRNAT*	1	-46/	320	115	12	*PU241*	1	-96/
271	66	7	*NINAT*	1	-47/	321	116	12	*PU242*	1	-97/
272	67	7	*MONAT*	1	-48/	322	117	12	*AM241*	1	-98/
273	68	7	*MN55*	1	-49/	323	118	12	*U235*	1	-99/
274	69	7	*NA23*	1	-50/	324	119	12	*U238*	1	-100/
275	70	7	*CNAT*	1	-51/	325	120	12	*HEDLFP*	1	-101/
276	71	8	*FENAT*	1	-52/	326	121	12	*O16*	1	-102/
277	72	8	*CRNAT*	1	-53/	327	122	12	*FENAT*	1	-103/
278	73	8	*NINAT*	1	-54/	328	123	12	*CRNAT*	1	-104/
279	74	8	*MONAT*	1	-55/	329	124	12	*NINAT*	1	-105/
280	75	8	*MN55*	1	-56/	330	125	12	*MONAT*	1	-106/
281	76	8	*NA23*	1	-57/	331	126	12	*MN55*	1	-107/
282	77	8	*CNAT*	1	-58/	332	127	12	*NA23*	1	-108/
283	78	9	*FENAT*	1	-59/	333	128	12	*CNAT*	1	-109/
284	79	9	*CRNAT*	1	-60/	334	129	13	*FENAT*	1	-110/
285	80	9	*NINAT*	1	-61/	335	130	13	*CRNAT*	1	-111/
286	81	9	*MONAT*	1	-62/	336	131	13	*NINAT*	1	-112/
287	82	9	*MN55*	1	-63/	337	132	13	*MONAT*	1	-113/
288	83	9	*NA23*	1	-64/	338	133	13	*MN55*	1	-114/
289	84	9	*CNAT*	1	-65/	339	134	13	*NA23*	1	-115/
290	85	10	*U235*	1	-66/	340	135	13	*CNAT*	1	-116/
291	86	10	*U238*	1	-67/	341	136	14	*FENAT*	1	-117/
292	87	10	*O16*	1	-68/	342	137	14	*CRNAT*	1	-118/
293	88	10	*FENAT*	1	-69/	343	138	14	*NINAT*	1	-119/
294	89	10	*CRNAT*	1	-70/	344	139	14	*MONAT*	1	-120/
295	90	10	*NINAT*	1	-71/	345	140	14	*MN55*	1	-121/
296	91	10	*MONAT*	1	-72/	346	141	14	*NA23*	1	-122/
297	92	10	*MN55*	1	-73/	347	142	14	*CNAT*	1	-123/
298	93	10	*PU239*	1	-74/	348	143	15	*FENAT*	1	-124/
299	94	10	*PU240*	1	-75/	349	144	15	*CRNAT*	1	-125/
300	95	10	*HEDLFP*	1	-76/	350	145	15	*NINAT*	1	-126/

TABLE III (Cont.)

351	146	15	*MONAT*	1	-127/	402	1	*TRD*/
352	147	15	*MN55*	1	-128/	403	2	*NG*/
353	148	15	*NA23*	1	-129/	404	3	*NFTOT*/
354	149	15	*CNAT*	1	-130/	405	4	*CHI*/
355	150	16	*PU239*	1	-131/	406	5	*NA*/
356	151	16	*PU240*	1	-132/	407	6	*NP*/
357	152	16	*PU241*	1	-133/	408	7	*N2N*/
358	153	16	*PU242*	1	-134/	409	8	*ND*/
359	154	16	*AM241*	1	-135/	410	9	*NT*/
360	155	16	*U235*	1	-136/	411	9	4 8 3 4 4 8 8 8 7 4 13/
361	156	16	*U238*	1	-137/	412		*STOP*/
362	157	16	*HEDLFP*	1	-138/			
363	158	16	*O16*	1	-139/			
364	159	16	*FENAT*	1	-140/			
365	160	16	*CRNAT*	1	-141/			
366	161	16	*NINAT*	1	-142/			
367	162	16	*MONAT*	1	-143/			
368	163	16	*MN55*	1	-144/			
369	164	16	*NA23*	1	-145/			
370	165	16	*CNAT*	1	-146/			
371	166	17	*FENAT*	1	-147/			
372	167	17	*CRNAT*	1	-148/			
373	168	17	*NINAT*	1	-149/			
374	169	17	*MONAT*	1	-150/			
375	170	17	*MN55*	1	-151/			
376	171	17	*NA23*	1	-152/			
377	172	17	*CNAT*	1	-153/			
378	173	18	*FENAT*	1	-154/			
379	174	18	*CRNAT*	1	-155/			
380	175	18	*NINAT*	1	-156/			
381	176	18	*MONAT*	1	-157/			
382	177	18	*MN55*	1	-158/			
383	178	18	*NA23*	1	-159/			
384	179	18	*CNAT*	1	-160/			
385	180	19	*PU239*	1	-161/			
386	181	19	*PU240*	1	-162/			
387	182	19	*PU241*	1	-163/			
388	183	19	*PU242*	1	-164/			
389	184	19	*AM241*	1	-165/			
390	185	19	*U235*	1	-166/			
391	186	19	*U238*	1	-167/			
392	187	19	*HEDLFP*	1	-168/			
393	188	19	*O16*	1	-169/			
394	189	19	*FENAT*	1	-170/			
395	190	19	*CRNAT*	1	-171/			
396	191	19	*NINAT*	1	-172/			
397	192	19	*MONAT*	1	-173/			
398	193	19	*MN55*	1	-174/			
399	194	19	*NA23*	1	-175/			
400	195	19	*CNAT*	1	-176/			
401			*STRPL*					
			SNGAM					
			SFIS					
			CHISO					
			SNALF					
			SNP					
			SN2N					
			SND					
			SNT

Fig. 3. FFTF/HPC R-Z model. Control assemblies inserted about halfway into core. Tables IV and V identify the reactor regions given in the legend. The control assembly is labelled ABS and the fuel regions are labelled DR1 and DR2.

TABLE IV
REGION VERTICAL BOUNDARIES AFTER HOMOGENIZATION

1	62.4	Axial Shield-Fuel	ASF
1	62.4	Lower Radial Shield	LRS
1	62.4	Control Assembly Shield	CRS
2	79.86	Axial Reflector-Fuel	ARF
3	81.91	Insulator-Fuel	INF
4	110.91	Sodium Channel-Control Assemblies inserted halfway	NAC
5	130.41	Below Poison Channel-Control Assemblies inserted halfway	BPC
6	154.55	Sodium Channel-Safety Assemblies withdrawn	NAC
7	174.05	Various Fuel, Characterizer, and Experimental Assemblies	*
7	174.05	Below Poison Channel-Safety Assemblies withdrawn	BPC
8	176.1	Insulator-Fuel	INF
9	190.69	Axial Reflector-Fuel	ARF
10	222.55	Absorber-Control Assemblies inserted halfway	ABS
11	257.1	Above Poison Channel Assemblies inserted halfway	APC
12	266.19	Absorber-Safety Assemblies withdrawn	ABS
13	300.74	Gas Plenum-Fuel Region	GPF
13	300.74	Above Poison Channel of Safety Assemblies	APC
13	300.74	Driveline-Control Assemblies	DRL
13	300.74	Upper Radial Shield	URS

*Included are fuel types-F31, F32, F41, F42 (homogenized fuel DR1, DR2, DR1A); In-Core Shim Assemblies-ICS; Vibration Open Test Assemblies-VOT; Blanket Test Assemblies-SR1, SR2, W18, and W42; Absorber Test Assemblies-HA3 and HA6; and Reactor Characterizer Assemblies-CH1, CH2, CH3, CH4, and CH5.

TABLE V
RADII FOR R-Z HOMOGENIZATION AT Z = 81.91 cm

<u>No.</u>	<u>Inner Radius</u>	<u>Outer Radius</u>	<u>Region Name</u>	<u>Region Designation</u>
1	0.0	16.76	Driver-1	DR1
2	16.76	20.03	Safety Assembly	NAC
3	20.03	38.53	Driver-1	DR1
4	38.53	41.54	Control Assembly	NAC
5	41.54	60.43	Driver-2	DR2
6	60.43	71.39	Radial Reflector-1	RR1
7	71.39	89.36	Radial Reflector-2	RR2
8	89.36	115.25	Shield	URS

In Eq. (1), Δ_g^N can be chosen to minimize the effects of truncating the Legendre expansion at $l = N$, and five recipes for Δ_g^N are available in TRANSX. The one selected for the LCCEWG-5 ISOTX file is ITRC = 3, the Bell-Hansen-Sandmeier (BHS) or extended transport approximation

$$\Delta_g^N = \sigma_{0tg}^{PN} - \sigma_{N+1,tg}^{PN} + \sum_{g'} \sigma_{N+1,g'+g}^{PN} \quad (4)$$

The value of -14 chosen for the INITF flag above indicates that the elastic removal correction in TRANSX has been selected. This correction is necessary because the downscatter for the heavier materials occurs from a range of energies close to the bottom of the group, although a group size can be diminished to the point that weighting fluxes are adequate for the vector cross sections (e.g., capture, fission). This makes the elastic removal cross sections very sensitive to any difference between the ratio of the actual flux near the bottom of the group to the actual group average flux and this same ratio for the model flux. In TRANSX, the flux is smoothed by averaging over several groups above and below the group in question. This results in an effective slope for the flux near the bottom of the group, which is then used to correct the removal. Thus, a good first-pass flux is needed in TRANSX for accurate computation of the BHS transport and elastic removal corrections, even though no group collapse is selected.

Several parameters are selected on Record No. 4 in Table II as follows:

NGN = 80, number of neutron groups, i.e., no collapse on first pass.

NGG = 0, no gamma groups.

NL = 1, single table cross-section set.

NTABL = 70, scattering table length.

NUP = 0, no upscatter.

NMIX = 19, number of output mixtures.

NREG = 19, number of regions, i.e., 1 macroscopic mixture per region.

NMIXS = 171, number of mix specifications = $\sum_{i=1}^{19} n_i$, where n_i is the number of materials in mixture (region) i.

NED = 9, extra edit positions on ISOTX file (Record 198).

NEDS = 9, Corresponding edit specifications from MATXS file (Records 199-207).

Although a single, transport-corrected table ISOTXS file is indicated by the above set of parameters, TRANSX was used in some preliminary LCCEWG-5 calculations to generate a P_3 set of cross sections. These were then used in determining the effects of higher order scattering for the HPC experiment (see Sec. VI).

Records 5 and 6 in Table II give the names of the mixtures on the ISOTXS file. These exactly correspond to the names of the regions shown in Fig. 3 and described in Tables IV and V. Thus, in the fine-group neutronics calculations, every region will be assigned a mixture density of one.

The names of the mixtures are repeated in Records 7-25, but with a temperature (C) assigned to each. These temperatures are used in the TRANSX Doppler broadening calculations. Record 26 gives the RZFLUX region number to be used for each corresponding mixture in the TRANSX calculation. The actual isotope names from the MATXS file along with corresponding densities for each mixture are given on Records 27-197 in Table II. Also, the zeros on these cards indicate that "homogeneous" cell (i.e., no cell) calculations are done in TRANSX.

In the MATXS library generated by the NJOY code, resonance Doppler broadening and self-shielding are accounted for by the Bondarenko method¹⁴ or Background Cross Section Method.¹⁵ The model flux for group averages for isotope i is written as

$$\phi^i(E) = \frac{C(E)}{[\sigma_0^i + \sigma_t^i(E)]} , \quad (5)$$

where $C(E)$ is the smooth part of the shape of the flux, and σ_0^i is called the background cross section. The effect of the total cross section in the denominator is to put a dip in the flux for each peak in the cross section, and σ_0 controls the relative size of the dip.

For an infinite homogeneous mixture, the appropriate background cross section for group g is

$$\sigma_{0g}^i = \frac{1}{N_i} \sum_{j \neq i} N_j \sigma_{tg}^j(\sigma_{0g}^j) , \quad (6)$$

where N_i is the number density for the isotope. Since σ_t depends on σ_0 , finding σ_0 is clearly an iterative process that is performed in TRANSX using the input isotope densities for a given mixture.

Self-shielded cross sections for the MATXS libraries were computed with the NJOY code using Eqs. (2) and (3), together with the flux model of Eq. (5), for a preselected set of temperatures and background cross sections. To obtain a cross section at some other temperature and background, it is necessary to interpolate between the values in the library.

There are no problems in carrying out this interpolation for temperature. A single Nth order Lagrangian interpolation scheme on $\sigma(T)$ and T is used in TRANSX, where T is the temperature and there are N values in the temperature grid.

For σ_0 , however, the shielding curve has a shape of a hyperbolic tangent function.¹⁶ It has a limited radius of convergence and no single polynomial can be used to represent it for all σ_0 . The following scheme is used in TRANSX. For $\sigma_0 \geq \sigma_2$ in a table of N values, the cross section is assumed to vary linearly with $1/\sigma_0$, a slope being determined by σ_1 and σ_2 ; for $\sigma_2 > \sigma_0 \geq \sigma_N$, the cross section is represented by an order N-1 Lagrangian scheme using $\ln\sigma$ vs $\ln\sigma_0$; and for $\sigma_0 < \sigma_N$, the cross section is assumed to vary linearly with σ_0^2 , a slope being determined by σ_N and σ_{N-1} . In the above, $\sigma_1 > \sigma_2 > \sigma_3 \dots \sigma_N$ are the σ_0 values found on the MATXS file and $\sigma_1 = \infty$ (actually 1×10^{10} barns).

The 80-group ISOTXS file produced by TRANSX is next used in the neutronics code module to produce an 80-group RZFLUX file for the second pass through TRANSX. For LCCEWG-5 calculations, the specifications for the two-dimensional, region homogenized model shown in Fig. 3, as well as the 80-group ISOTXS file, were used as input to the DIF3D code. The resulting 80-group RZFLUX file with the input shown in Table III was fed back into TRANSX for the second pass. The purpose of the second pass is not only to collapse to 12 groups, but to provide region-dependent, microscopic cross sections for all explicit isotopes in the ISOTXS file. The differences between the two runs are reflected in Table III.

On Record 3 in Table III, ICOLL = 80 means that 80 fine-groups will be collapsed to NGN = 12 groups with a table length NTABL = 24, both of the latter being on Record 4. A total of 195 mixtures and materials are also now specified on Record 4 (NMIX = 195). The names of these, shown on Records 5-28, are mnemonically compatible with the region names; e.g., ²³⁹Pu in region DR1 is designated as P39D1.

Temperatures for the 19 mixtures (regions) are given on Records 29-47, and isotope names and densities for each mixture are given on Records 49-224. Note, however, that names not previously specified in Table II, because of zero density (the HEDL FP lump), are now specified in Table III. Also the numbers given on Record 48 now refer to regions on the new RZFLUX file.

Records 225-400 relate region-dependent isotope cross-section names given in Records 7-28 (HMIKN) to the isotope names given on the MATXS file (HEDNAM), Records 49-224. For example, the ISOTXS name FENAC is related to the MATXS name FENAT on the first card (Record 49) of the mixture-density cards, and this is designated by the -1 on Record 225. More generally, P39D1, the ^{239}Pu in Driver Region No. 1 (DR1), which occurs in the eleventh region (Record 126) is flagged with a -78 on Record 302 because it occurs as the 78th card of the set of mixture specifications. (It is as well the 78th name in the ISOTXS isotope list.)

The edits (Record 401) and edit specifications (Records 402-410) are identical to those in in Table II. An additional record (411) is given in Table III to specify the group collapse. The 9 on this card means that the first nine fine-groups are collapsed into broad-group No. 1, the 4 means the next four fine-groups are collapsed into broad-group No. 2, etc. The group collapse schemes used in TRANSX for fine-groups g into broad-group G with weighting fluxes ϕ are the conventional ones:

$$\sigma_{tG} = \frac{\sum_{g \in G} \sigma_{tg} \phi_g}{\sum_{g \in G} \phi_g} \quad (\text{total cross section}) \quad (7)$$

$$\sigma_{G \leftarrow G'} = \frac{\sum_{g' \in G'} \sum_{g \in G} \sigma_{g \leftarrow g'} \phi_{g'}}{\sum_{g' \in G'} \phi_{g'}} \quad (\text{transfer cross sections from } G' \text{ to } G) \quad (8)$$

$$\nu_G \sigma_{fG} = \sum_{g \in G} \sum_{g'} \sigma_{fg' \leftarrow g} \quad (\text{nu-fission}) \quad (9)$$

$$\chi_G = \frac{S_G}{\sum_{G'} S_{G'}} \quad \text{where} \quad (\text{fission spectrum}) \quad (10)$$

$$S_G = \sum_{g \in G} \sum_{g'} \sigma_{fg' \leftarrow g} \phi_{g'}$$

$$\sigma_{EG} = \frac{\sum_{g \in G} \sigma_{Eg} \phi_g}{\sum_{g \in G} \phi_g} \quad (\text{elastic cross section}). \quad (11)$$

The 12-group ISOTXS file produced from the second TRANSX pass is ready for use in the core neutronics and depletion modules for three-dimensional FFTF HPC and Cycle 1 depletion calculations. Although, as is indicated in Figs. 1 and 2, this file could be updated during depletion steps by suitable application of the CTL controller, in fact only one 12-group ISOTXS file was generated for LCCEWG-5.

III. CORE NEUTRONICS MODULE

Any core neutronics code that operates in the standard file environment can be used in the core neutronics module. To date we have used DIF3D, TWODANT, and TWOHEX in LCCEWG-5 calculations. The principal calculations were made with the diffusion code DIF3D; comparison transport calculations were made with TWODANT and TWOHEX.

DIF3D was developed at Argonne National Laboratory and is a computer code that uses the mesh-centered finite-difference approximation to obtain numerical solutions of the multigroup diffusion equations in one, two, or three dimensions for fast reactor applications. The code was written to employ the rigorous strategies of the PDQ-7 code,¹⁷ and significant efforts were expended during development to provide efficient, yet flexible, data management and data structures.

Incorporated in DIF3D for the solution of two- and three-dimensional hexagonal geometry problems is a nodal option that uses input data virtually identical to that of the finite difference option. Comparison of the nodal option with the finite-difference option for a typical LMFBR core design has shown that the accuracy of the nodal solution is superior to that of a standard (6-mesh cells per hexagon, 5-cm axial mesh spacing) finite difference calculation, and that this improved accuracy is achieved with a significant reduction in computational cost for a three-dimensional calculation. In the course of preliminary calculations for LCCEWG-5, the largest problem we have run on our CRAY machines is a 1/3-core model of the FFTF core in hexagonal-Z geometry with 13 axial planes and 80 groups. This problem ran in 12 minutes. More typical full-core models with 17 planes and 12 groups run in 3-4 minutes on the CRAY machines. These problems run efficiently only on our largest machines (1.8 M word storage).

TWODANT, developed at Los Alamos, is a code package for two-dimensional, diffusion-accelerated, neutral-particle transport. It is designed to solve

the two-dimensional, time-independent, multigroup discrete-ordinates form of the Boltzmann transport equation. Major TWODANT features include:

- (1) a free-field format card-image input capability designed with the user in mind;
- (2) highly sophisticated, standardized data- and file-management techniques as defined and developed by the committee on computer code coordination (CCCC), as described in Ref. 1;
- (3) the use of a diffusion synthetic acceleration scheme to accelerate the iterative process;
- (4) direct (forward) or adjoint capability;
- (5) (x, y)- and (r, z)-geometry options;
- (6) arbitrary anisotropic scattering order;
- (7) vacuum, reflective, periodic, and white boundary condition options;
- (8) inhomogeneous (fixed) source or k-effective calculation options;
- (9) "diamond-differencing" for solution of the transport equation;
- (10) a new diffusion solution that uses the multigrid method;
- (11) user flexibility in using either card-image or sequential file input;
- (12) user flexibility in controlling execution; and
- (13) extensive, user oriented error diagnostics.

We have employed TWODANT in preliminary FFTF studies using the R-Z model in Fig. 3 to compare both transport and high order (P_3) scattering in our calculations. The 80-group RZFLUX file from a TWODANT calculation was used in TRANSX to produce a P_3 ISOTXS file for comparison purposes. Results are discussed in Sec. VI.

TWOHEX is also a Los Alamos code that solves the two-dimensional multigroup form of the neutral-particle, steady-state Boltzmann equation, but on an equilateral triangular mesh in the x-y plane. The discrete-ordinates form of the approximation is used for treating the angular variation of the particle distribution, and a linear characteristic/nodal scheme is used for spatial discretization. A standard inner (within-group) iteration, outer (energy-group-dependent source) iteration technique is applied. Both inner and outer iterations are accelerated using the Chebyshev acceleration method.¹⁸

The "whole core" domain for a hexagonal model is a 60° parallelogram with vacuum boundary conditions on each face. The "third core" domain is a 120°

parallelogram with two vacuum and two rotational boundary conditions, and the "sixth core" domain is a 60° parallelogram with two vacuum and two rotational boundary conditions. Presently the rectangular region of solution (NTRIAG = 2 in Ref. 1) is not an option in TWOHEX. Consequently, some GEODST files generated by DIF3D, in which NTRIAG = 2 is specified, cannot be used by TWOHEX. This is not the case, however, for orthogonal geometries in TWODANT and DIF3D.

As an example of the operation of the core neutronics module, consider the DIF3D input for the FFTF Cycle 1 depletion experiment LCCEWG-5 shown in Table VI. The mid-core layout of the FFTF at the beginning of Cycle 1 (BOC1) is found in Fig. 4. It is seen that BOC1 is not beginning-of-life (BOL) of the FFTF, and the fuel assemblies have had differing irradiation histories. This is reflected in the region description (Type 30) cards, Records 17-186, in Table VI, and in Fig. 4. Table VII provides a description of the irradiation history for each type of fueled assembly.

To reach the BOC-1 configuration, a DANDE run was made from FFTF BOL to BOC1 (see Sec. VI). Evidence that BOC1 is different from BOL is seen from examining the material density cards (Type 14), Records 192-335, in Table VI. For example, the densities for the fission-product aggregates, FPD2 and FPD3, in the various materials are generally nonzero and different. In fact, as discussed in Sec. IV, the fission-product aggregate microscopic cross sections on the ISOTXS file were also updated during the DANDE run from FFTF BOL to BOC1.

Two-dimensional model DIF3D-TWOHEX comparisons were also made in the course of the FFTF Cycle 1 experimental studies. In these problems the vertical height was represented by a vertical buckling obtained by matching the two-dimensional with the three-dimensional DIF3D eigenvalues. Results are discussed in Sec. VI.

Fig. 4. FFTF mic-core plan of calculational model for BOC-1A. Table VII identifies the reactor region abbreviations given in the legend. Control assemblies ABS are diagonally striped red (ring 5). Safety assemblies NAC are diagonally striped green.

TABLE VI
DIF3D INPUT FOR FFTF CYCLE-1 DEPLETION

```

1 BLOCK=OLD
2 DATASET=ISOTXS
3 BLOCK=STP021
4 UNFORM=A.HMG4C
5 02 10000 0 0 0 0 1
6 UNFORM=A.DIF3D
7 01          LCCEWG5, FFTF CYCLE 1A MODEL. 08/23/84.
8 02 10000 1400000
9 04 1 1 0 1 011 i1 100 1 0 3
10 06 0.0 .001 .04 395.6E+6
11 UNFORM=A.NIP3
12 01          LCCEWG5, FFTF CYCLE 1A MODEL. 08/23/84.
13 02 0 1 10000 0 500000 500000 0 1 0 0
14 03 120
15 04 2 2 2 2 2 2
16 29 12.065
17 30 ASF 1 0 0 0.0 62.4
18 30 ARF 1 0 0 62.4 79.86
19 30 INF 1 0 0 79.86 81.91
20 30 F32C 1 0 0 81.91 174.05
21 30 INF 1 0 0 174.05 176.1
22 30 ARF 1 0 0 176.1 190.69
23 30 GPF 1 0 0 190.69 300.74
24 30 ASF 2 0 0 0.0 62.4
25 30 ARF 2 0 0 62.4 79.86
26 30 INF 2 0 0 79.86 81.91
27 30 F32 2 0 0 81.91 174.05
28 30 INF 2 0 0 174.05 176.1
29 30 ARF 2 0 0 176.1 190.69
30 30 GPF 2 0 0 190.69 300.74
31 30 ICS 2 1 0 62.4 300.74
32 30 ASF 3 0 0 0.0 62.4
33 30 ARF 3 0 0 62.4 79.86
34 30 INF 3 0 0 79.86 81.91
35 30 F32 3 0 0 81.91 174.05
36 30 INF 3 0 0 174.05 176.1
37 30 ARF 3 0 0 176.1 190.69
38 30 GPF 3 0 0 190.69 300.74
39 30 CRS 3 3 0 0.0 62.4
40 30 NAC 3 3 0 62.4 154.55
41 30 BPC 3 3 0 154.55 174.05
42 30 ABS 3 3 0 174.05 266.19
43 30 APC 3 3 0 266.19 300.74
44 30 CRS 3 7 0 0.0 62.4
45 30 NAC 3 7 0 62.4 154.55
46 30 BPC 3 7 0 154.55 174.05
47 30 ABS 3 7 0 174.05 266.19
48 30 APC 3 7 0 266.19 300.74
49 30 CRS 3 11 0 0.0 62.4
50 30 NAC 3 11 0 62.4 154.55

```

TABLE VI (Cont.)

51	30	BPC	3	11	0	154.55	174.05		
52	30	ABS	3	11	0	174.05	266.19		
53	30	APC	3	11	0	266.19	300.74		
54	30	DE2B	3	1	0	81.91	174.05		
55	30	F42E	3	2	0	81.91	174.05		
56	30	F42E	3	5	0	81.91	174.05		
57	30	F42E	3	6	0	81.91	174.05		
58	30	F32B	3	8	0	81.91	174.05		
59	30	F32B	3	10	0	81.91	174.05		
60	30	DE1R	3	12	0	81.91	174.05		
61	30	ASF	4	0	0	0.0	62.4		
62	30	ARF	4	0	0	62.4	79.86		
63	30	INF	4	0	0	79.86	81.91		
64	30	F32	4	0	0	81.91	174.05		
65	30	INF	4	0	0	174.05	176.1		
66	30	ARF	4	0	0	176.1	190.69		
67	30	GPF	4	0	0	190.69	300.74		
68	30	ICS	4	7	8	62.4	300.74		
69	30	ICS	4	12	0	62.4	300.74		
70	30	ICS	4	14	0	62.4	300.74		
71	30	ICS	4	18	0	62.4	300.74		
72	30	ICS	4	2	0	81.91	190.69		
73	30	F32D	4	10	0	81.91	174.05		
74	30	F42B	4	3	4	81.91	174.05		
75	30	F42B	4	11	0	81.91	174.05		
76	30	F42B	4	15	17	81.91	174.05		
77	30	F32B	4	13	0	81.91	174.05		
78	30	F42	4	9	0	81.91	174.05		
79	30	ASF	5	0	0	0.0	62.4		
80	30	ARF	5	0	0	62.4	79.86		
81	30	INF	5	0	0	79.86	81.91		
82	30	F31	5	0	0	81.91	174.05		
83	30	INF	5	0	0	174.05	176.1		
84	30	ARF	5	0	0	176.1	190.69		
85	30	GPF	5	0	0	190.69	300.74		
86	30	CRS	5	4	0	0.0	62.4		
87	30	NAC	5	4	0	62.4	105.01		
88	30	BPC	5	4	0	105.01	124.51		
89	30	ABS	5	4	0	124.51	216.65		
90	30	APC	5	4	0	216.65	251.2		
91	30	DRL	5	4	0	251.2	300.74		
92	30	CRS	5	6	0	0.0	62.4		
93	30	NAC	5	6	0	62.4	105.01		
94	30	BPC	5	6	0	105.01	124.51		
95	30	ABS	5	6	0	124.51	216.65		
96	30	APC	5	6	0	216.65	251.2		
97	30	DRL	5	6	0	251.2	300.74		
98	30	CRS	5	12	0	0.0	62.4		
99	30	NAC	5	12	0	62.4	105.01		
100	30	BPC	5	12	0	105.01	124.51		
101	30	ABS	5	12	0	124.51	216.65		
102	30	APC	5	12	0	216.65	251.2		
103	30	DRL	5	12	0	251.2	300.74		
104	30	CRS	5	14	0	0.0	62.4		
105	30	NAC	5	14	0	62.4	105.01		
106	30	BPC	5	14	0	105.01	124.51		
107	30	ABS	5	14	0	124.51	216.65		
108	30	APC	5	14	0	216.65	251.2		
109	30	DRL	5	14	0	251.2	300.74		
110	30	CRS	5	20	0	0.0	62.4		
111	30	NAC	5	20	0	62.4	105.01		
112	30	BPC	5	20	0	105.01	124.51		
113	30	ABS	5	20	0	124.51	216.65		
114	30	APC	5	20	0	216.65	251.2		
115	30	DRL	5	20	0	251.2	300.74		
116	30	CRS	5	22	0	0.0	62.4		
117	30	NAC	5	22	0	62.4	105.01		
118	30	BPC	5	22	0	105.01	124.51		
119	30	ABS	5	22	0	124.51	216.65		
120	30	APC	5	22	0	216.65	251.2		
121	30	DRL	5	22	0	251.2	300.74		
122	30	CRS	5	9	0	0.0	62.4		
123	30	BPC	5	9	0	62.4	81.91		
124	30	SRB	5	9	0	81.91	174.05		
125	30	APC	5	9	0	174.05	300.74		
126	30	F31A	5	13	0	81.91	174.05		
127	30	F41B	5	23	0	81.91	174.05		
128	30	F31B	5	1	0	81.91	174.05		
129	30	DE5	5	2	0	81.91	174.05		
130	30	DE6	5	3	0	81.91	174.05		
131	30	F31B	5	7	0	81.91	174.05		
132	30	F31B	5	10	0	81.91	174.05		
133	30	DE3B	5	18	0	81.91	174.05		
134	30	F31B	5	24	0	81.91	174.05		
135	30	ASF	6	0	0	0.0	62.4		
136	30	ARF	6	0	0	62.4	79.86		
137	30	INF	6	0	0	79.86	81.91		
138	30	F31	6	0	0	81.91	174.05		
139	30	INF	6	0	0	174.05	176.1		
140	30	ARF	6	0	0	176.1	190.69		
141	30	GPF	6	0	0	190.69	300.74		
142	30	F31A	6	16	0	81.91	174.05		
143	30	VOT	6	19	0	62.4	300.74		
144	30	CRS	6	9	0	0.0	62.4		
145	30	BPC	6	9	0	62.4	81.91		
146	30	HA6	6	9	0	81.91	174.05		
147	30	APC	6	9	0	174.05	300.74		
148	30	CRS	6	22	0	0.0	62.4		
149	30	BPC	6	22	0	62.4	81.91		
150	30	W42B	6	22	0	81.91	174.05		

TABLE VI (Cont.)

151	30	APC	6	22	0	174.05	300.74				
152	30	CRS	6	11	0	0.0	62.4				
153	30	BPC	6	11	0	62.4	81.91				
154	30	SRB	6	11	0	81.91	174.05				
155	30	APC	6	11	0	174.05	300.74				
156	30	DE4	6	3	0	81.91	174.05				
157	30	F31A	6	12	0	81.91	174.05				
158	30	F41E	6	15	0	81.91	174.05				
159	30	F31A	6	16	0	81.91	174.05				
160	30	LRS	7	0	0	0.0	62.4				
161	30	RR1	7	0	0	62.4	190.69				
162	30	URS	7	0	0	190.69	300.74				
163	30	CRS	7	24	0	0.0	62.4				
164	30	BPC	7	24	0	62.4	81.91				
165	30	HA3	7	24	0	81.91	174.05				
166	30	APC	7	24	0	174.05	300.74				
167	30	CRS	7	36	0	0.0	62.4				
168	30	BPC	7	36	0	62.4	81.91				
169	30	ABS	7	36	0	81.91	174.05				
170	30	APC	7	36	0	174.05	300.74				
171	30	W18B	7	3	0	81.91	174.05				
172	30	LRS	8	0	0	0.0	62.4				
173	30	RR2	8	0	0	62.4	190.69				
174	30	URS	8	0	0	190.69	300.74				
175	30	LRS	9	0	0	0.0	62.4				
176	30	RR2	9	0	0	62.4	190.69				
177	30	URS	9	0	0	190.69	300.74				
178	30	USNA	9	1	2	0.0	300.74				
179	30	USNA	9	8	10	0.0	300.74				
180	30	USNA	9	16	18	0.0	300.74				
181	30	USNA	9	24	26	0.0	300.74				
182	30	USNA	9	32	34	0.0	300.74				
183	30	USNA	9	40	42	0.0	300.74				
184	30	USNA	9	48	0	0.0	300.74				
185	30	URS	10	0	0	0.0	300.74				
186	30	URS	11	0	0	0.0	300.74				
187	09	Z	1	62.4	1	79.86	1	81.91			
188	09	Z	2	105.01	2	124.51	2	154.55			
189	09	Z	2	174.05	1	176.1	1	190.69			
190	09	Z	2	216.65	1	251.2	1	266.19			
191	09	Z	1	300.74							
192	14	ZON1	ASF			1.000000					
193	14	ZON2	ARF			1.000000					
194	14	ZON3	U35INF			0.000050	U38INF	0.007188	OINF	0.014476	
195	14	ZON3	FEINF			0.012769	CRINF	0.003751	NIINF	0.002594	
196	14	ZON3	MOINF			0.000259	MNINF	0.000319	CINF	0.000259	
197	14	ZON3	NAD3			0.009113					
198	14	ZON7	CRS			1.000000					
199	14	ZON6	GPF			1.000000					
200	14	ZON8	NAC			1.000000					
201	14	ZON9	BPC			1.000000					
202	14	ZON10	ABS			1.000000					
203	14	ZON11	DRL			1.000000					

TABLE VI (Cont.)

204	14	ZON12	FELRS	0.047370	CRLRS	0.013910	NILRS	0.009620
205	14	ZON12	MOLRS	0.000960	MNLRS	0.001180	NALRS	0.007400
206	14	ZON12	CLRS	0.000960				
207	14	ZON13	RR1	1.000000				
208	14	ZON14	RR2	1.000000				
209	14	ZON15	URS	1.000000				
210	14	ZUSNA	NAC	0.500000	URS	0.500000		
211	14	ZON17	ICS	1.000000				
212	14	ZON18	APC	1.000000				
213	14	ZON24	P39D3	0.001355	P40D3	0.000195	P41D3	0.000020
214	14	ZON24	P42D3	0.000003	A41D3	0.000006	U35D3	0.000037
215	14	ZON24	U38D3	0.005568	FPD3	0.000049	OD3	0.014185
216	14	ZON24	FED3	0.012769	CRD3	0.003751	NID3	0.002594
217	14	ZON24	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
218	14	ZON24	CD3	0.000259				
219	14	ZND1R	P39D3	0.001354	P40D3	0.000196	P41D3	0.000020
220	14	ZND1R	P42D3	0.000003	A41D3	0.000006	U35D3	0.000037
221	14	ZND1R	U38D3	0.005567	FPD3	0.000050	OD3	0.014185
222	14	ZND1R	FED3	0.012769	CRD3	0.003751	NID3	0.002594
223	14	ZND1R	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
224	14	ZND1R	CD3	0.000259				
225	14	ZND2B	P39D3	0.001365	P40D3	0.000193	P41D3	0.000020
226	14	ZND2B	P42D3	0.000003	A41D3	0.000006	U35D3	0.000038
227	14	ZND2B	U38D3	0.005579	FPD3	0.000030	OD3	0.014185
228	14	ZND2B	FED3	0.012769	CRD3	0.003751	NID3	0.002594
229	14	ZND2B	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
230	14	ZND2B	CD3	0.000259				
231	14	ZON24B	P39D3	0.001367	P40D3	0.000192	P41D3	0.000020
232	14	ZON24B	P42D3	0.000003	A41D3	0.000006	U35D3	0.000038
233	14	ZON24B	U38D3	0.005581	FPD3	0.000027	OD3	0.014185
234	14	ZON24B	FED3	0.012769	CRD3	0.003751	NID3	0.002594
235	14	ZON24B	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
236	14	ZON24B	CD3	0.000259				
237	14	ZON24C	P39D3	0.001368	P40D3	0.000191	P41D3	0.000020
238	14	ZON24C	P42D3	0.000003	A41D3	0.000006	U35D3	0.000038
239	14	ZON24C	U38D3	0.005582	FPD3	0.000026	OD3	0.014185
240	14	ZON24C	FED3	0.012769	CRD3	0.003751	NID3	0.002594
241	14	ZON24C	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
242	14	ZON24C	CD3	0.000259				
243	14	ZON24D	P39D3	0.001376	P40D3	0.000189	P41D3	0.000020
244	14	ZON24D	P42D3	0.000003	A41D3	0.000006	U35D3	0.000039
245	14	ZON24D	U38D3	0.005591	FPD3	0.000012	OD3	0.014185
246	14	ZON24D	FED3	0.012769	CRD3	0.003751	NID3	0.002594
247	14	ZON24D	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
248	14	ZON24D	CD3	0.000259				
249	14	ZON25	P39D2	0.001667	P40D2	0.000234	P41D2	0.000025
250	14	ZON25	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036
251	14	ZON25	U38D2	0.005254	FPD2	0.000034	OD2	0.014233
252	14	ZON25	FED2	0.012769	CRD2	0.003751	NID2	0.002594
253	14	ZON25	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
254	14	ZON25	CD2	0.000259				
255	14	ZND3B	P39D2	0.001675	P40D2	0.000232	P41D2	0.000025
256	14	ZND3B	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036

TABLE VI (Cont.)

257	14	ZND3B	U38D2	0.005258	FPD2	0.000024	OD2	0.014233
258	14	ZND3B	FED2	0.012769	CRD2	0.003751	NID2	0.002594
259	14	ZND3B	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
260	14	ZND3B	CD2	0.000259	ND147	0.000000	ND148	0.000000
261	14	ZND4	P39D2	0.001665	P40D2	0.000234	P41D2	0.000025
262	14	ZND4	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036
263	14	ZND4	U38D2	0.005252	FPD2	0.000038	OD2	0.014233
264	14	ZND4	FED2	0.012769	CRD2	0.003751	NID2	0.002594
265	14	ZND4	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
266	14	ZND4	CD2	0.000259				
267	14	ZND5	P39D2	0.001659	P40D2	0.000235	P41D2	0.000025
268	14	ZND5	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036
269	14	ZND5	U38D2	0.005247	FPD2	0.000047	OD2	0.014233
270	14	ZND5	FED2	0.012769	CRD2	0.003751	NID2	0.002594
271	14	ZND5	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
272	14	ZND5	CD2	0.000259				
273	14	ZND6	P39D2	0.001660	P40D2	0.000235	P41D2	0.000025
274	14	ZND6	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036
275	14	ZND6	U38D2	0.005248	FPD2	0.000045	OD2	0.014233
276	14	ZND6	FED2	0.012769	CRD2	0.003751	NID2	0.002594
277	14	ZND6	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
278	14	ZND6	CD2	0.000259				
279	14	ZON25A	P39D2	0.001674	P40D2	0.000232	P41D2	0.000025
280	14	ZON25A	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036
281	14	ZON25A	U38D2	0.005258	FPD2	0.000024	OD2	0.014233
282	14	ZON25A	FED2	0.012769	CRD2	0.003751	NID2	0.002594
283	14	ZON25A	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
284	14	ZON25A	CD2	0.000259				
285	14	ZON25B	P39D2	0.001673	P40D2	0.000232	P41D2	0.000025
286	14	ZON25B	P42D2	0.000004	A41D2	0.000007	U35D2	0.000036
287	14	ZON25B	U38D2	0.005258	FPD2	0.000026	OD2	0.014233
288	14	ZON25B	FED2	0.012769	CRD2	0.003751	NID2	0.002594
289	14	ZON25B	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
290	14	ZON25B	CD2	0.000259				
291	14	ZON26	P39D3	0.001540	P40D3	0.000223	P41D3	0.000021
292	14	ZON26	P42D3	0.000003	A41D3	0.000004	U35D3	0.000012
293	14	ZON26	U38D3	0.005346	FPD3	0.000047	OD3	0.014164
294	14	ZON26	FED3	0.012769	CRD3	0.003751	NID3	0.002594
295	14	ZON26	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
296	14	ZON26	CD3	0.000259				
297	14	ZON27B	P39D2	0.001814	P40D2	0.000257	P41D2	0.000025
298	14	ZON27B	P42D2	0.000004	A41D2	0.000004	U35D2	0.000011
299	14	ZON27B	U38D2	0.005074	FPD2	0.000024	OD2	0.014196
300	14	ZON27B	FED2	0.012769	CRD2	0.003751	NID2	0.002594
301	14	ZON27B	MOD2	0.000259	MND2	0.000319	NAD2	0.009113
302	14	ZON27B	CD2	0.000259				
303	14	ZON26B	P39D3	0.001554	P40D3	0.000220	P41D3	0.000021
304	14	ZON26B	P42D3	0.000003	A41D3	0.000004	U35D3	0.000012
305	14	ZON26B	U38D3	0.005357	FPD3	0.000027	OD3	0.014164
306	14	ZON26B	FED3	0.012769	CRD3	0.003751	NID3	0.002594
307	14	ZON26B	MOD3	0.000259	MND3	0.000319	NAD3	0.009113
308	14	ZON26B	CD3	0.000259				
309	14	ZON26E	P39D3	0.001571	P40D3	0.000215	P41D3	0.000021
310	14	ZON26E	P42D3	0.000003	A41D3	0.000004	U35D3	0.000012

TABLE VI (Cont.)

311	14	ZON26E	U38D3	0.005371	OD3	0.014164	FED3	0.012769
312	14	ZON26E	CRD3	0.003751	NID3	0.002594	MOD3	0.000259
313	14	ZON26E	MND3	0.000319	NAD3	0.009113	CD3	0.000259
314	14	ZON26E	FPD3	0.000000				
315	14	ZON27E	P39D2	0.001832	P40D2	0.000253	P41D2	0.000025
316	14	ZON27E	P42D2	0.000004	A41D2	0.000004	U35D2	0.000011
317	14	ZON27E	U38D2	0.005085	OD2	0.014196	FED2	0.012769
318	14	ZON27E	CRD2	0.003751	NID2	0.002594	MOD2	0.000259
319	14	ZON27E	MND2	0.000319	NAD2	0.009113	CD2	0.000259
320	14	ZON27E	FPD2	0.000000				
321	14	ZON28	FED2	0.009471	CRD2	0.002782	NID2	0.001924
322	14	ZON28	MOD2	0.000192	MND2	0.000237	NAD2	0.018041
323	14	ZON28	CD2	0.000192				
324	14	ZON29	B10ABS	0.014664	B11ABS	0.021995	FERR1	0.009177
325	14	ZON29	CRRR1	0.001696	NIRR1	0.001864	MORR1	0.000186
326	14	ZON29	MNRR1	0.000229	NARR1	0.009237	CRR1	0.009165
327	14	ZON30	B10ABS	0.004167	B11ABS	0.016670	FED2	0.014143
328	14	ZON30	CRD2	0.004154	NID2	0.002873	MOD2	0.000287
329	14	ZON30	MND2	0.000354	NAD2	0.007523	CD2	0.005209
330	14	ZON31B	FERR1	0.009284	CRRR1	0.002727	NIRR1	0.001886
331	14	ZON31B	MORR1	0.000189	MNRR1	0.000232	NARR1	0.005943
332	14	ZON31B	CRR1	0.000189	U35INF	0.000022	U38INF	0.012544
333	14	ZON31B	OINF	0.021540				
334	14	ZON32B	U35D2	0.000022	U38D2	0.012321	OD2	0.021171
335	14	ZON32B	FED2	0.009284	CRD2	0.002727	NID2	0.001886
336	14	ZON32B	MOD2	0.000189	MND2	0.000232	NAD2	0.005943
337	14	ZON32B	CD2	0.000189				
338	15	ZON1	ASF					
339	15	ZON2	ARF					
340	15	ZON3	INF					
341	15	ZON6	GPF					
342	15	ZON7	CRS					
343	15	ZON8	NAC					
344	15	ZON9	BPC					
345	15	ZON10	ABS					
346	15	ZON11	DRL					
347	15	ZON12	LRS					
348	15	ZON13	RR1					
349	15	ZON14	RR2					
350	15	ZON15	URS					
351	15	ZON17	ICS					
352	15	ZON18	APC					
353	15	ZON24	F32					365 15 ZND1R DE1R
354	15	ZON25	F31					366 15 ZND2B DE2B
355	15	ZON26B	F42B					367 15 ZND3B DE3B
356	15	ZON26	F42					368 15 ZND4 DE4
357	15	ZON26E	F42E					369 15 ZND5 DE5
358	15	ZON27B	F41B SRB					370 15 ZND6 DE6
359	15	ZON27E	F41E					371 15 ZON24B F32B
360	15	ZON28	VOT					372 15 ZON24C F32C
361	15	ZON29	HA3					373 15 ZON24D F32D
362	15	ZON30	HA6					374 15 ZON25A F31A
363	15	ZON31B	W18B					375 15 ZON25B F31B
364	15	ZON32B	W42B					376 15 ZUSNA USNA

TABLE VII
DESIGNATIONS OF CORE REGIONS FOR LCCEWG-5 FFTF CYCLE-1 MODEL

Region Number	Region Name	Zone Number	Assembly Type	Exposure (days)
1	ASF	1	Axial Shield-Fuel	-
2	ARF	2	Axial Reflector-Fuel	-
3	INF	3	Insulator-Fuel	-
4	F32C	21	DFA-3.2	15.0
5	GPF	5	Gas Plenum-Fuel	-
6	F32	17	DFA-3.2	32.4
7	ICS	15	ICSA	-
8	CRS	4	Control Assembly Shield	-
9	NAC	6	S.R. Na Channel	-
10	BPC	7	Below Poison Channel	-
11	ABC	8	C.R. Absorber	-
12	APC	16	Above Poison Channel	-
13	DE2B	19	DE1-2	19.0
14	F42E	33	DFA-4.2	0.0
15	F32B	20	DFA-3.2	19.0
16	DE1R	18	DE1-1R	32.4
17	F32D	22	DFA-3.2	10.0
18	F42B	32	DFA-4.2	19.0
19	F42	30	DFA-4.2	32.4
20	F31	23	DFA-3.1	32.4
21	DRL	9	Driveline-Control Assembly	-
22	SRB	31	SRF-1 and 2	19.0
23	F31A	28	DFA-3.1	24.0(23.6)
24	F41B	31	DFA-4.1	19.0
25	F31B	29	DFA-3.1	19.0
26	DE5	26	DE1-5	32.4
27	DE6	27	DE1-6	32.4
28	DE3B	24	DE1-3	19.0
29	VOT	35	VOTA	-
30	HA6	37	HA006	-
31	W42B	39	WB042	19.0
32	DE4	25	DE1-4	32.4
33	F41E	34	DFA-4.1	0.0
34	LRS	10	Lower Radial Shield	-
35	RR1	11	Radial Reflector #1	-
36	URS	13	Upper Radial Shield	-
37	HA3	36	HA003	-
38	W18B	38	WB018	19.0
39	RR2	12	Radial Reflector #2	-
40	USNA	14	50% Upper Shield, 50% Na	-

IV. DEPLETION MODULE

The code currently used for the DANDE depletion module is the CINDER-3 code, an enhanced version of the CINDER-2 code, and thus a member of the generic CINDER⁹⁻¹¹ summation code family. CINDER resolves the coupled system of decay equations into a collection of linear chains using a Markov model. The linear chains can then be solved analytically and evaluated numerically.

Versions of CINDER have been incorporated into reactor physics codes, such as PDQ-HARMONY¹⁹ and EPRI-CELL,²⁰ for 20 years or more. Typically, in the past, fission-product neutron absorption has been treated by describing only a few major absorbers and/or groupings of fission-product neutron absorption in one or more fictitious "lumps" generated independently of the spatial physics code. Neutron absorption in higher actinides (Am and Cm) has often been ignored. In DANDE, however, three-dimensional physics calculations of the core neutronics module are performed with accurate actinide inventory; "lumped" fission-product and higher-actinide reaction data are rapidly calculated by CINDER-3 for each volume element by summing the calculated values of all contributing nuclides.

The data processing and core neutronics modules provide initial nuclide atom densities (ZNATDN file), energy-group fluxes (RZFLUX file), and resonance self-shielded cross sections for abundant, explicitly-treated nuclides (ISOTXS file) for each volume element. CINDER-3 returns end-of-time-step atom densities of the explicit nuclides, and it groups non-explicit fission-product and actinide quantities for use in the next-time-step calculation of the core neutronics module. These aggregate quantities, accumulated separately for non-explicit fission products and actinides, include atom densities and cross sections for (n,n), (n,n'), (n,2n), (n, γ), and total neutron absorption in the energy-group structure specified in the ISOTXS file. The data for the individual fission-product and actinides are written to another file and are thus available for further exposure in the next call to the depletion module.

CINDER-3, shown schematically in Fig. 5, combines the functions of the CINDER-2 nuclide inventory code and its ENDF/B-V based data library with the TOAFEW-V¹² collapsing code that uses a library of 154-group cross sections processed from ENDF/B-V augmented with (n,2n) cross sections from HEDL model calculations.²¹ All calculations use the chain library, which contains the basic nuclear data describing the various nuclide couplings by fission yield, radioactive decay, and neutron absorption. Inventories within each region at the

Fig. 5. CINDER-3 code package in DANDE depletion module.

end of a time step (EOS) are calculated using the energy group fluxes, nuclide atom densities, and group cross sections associated with the region at the beginning of the time step (BOS), as indicated in Fig. 5 by the RZFLUX, ZNATDN, and ISOTXS standard files, respectively.

In accordance with values assigned to input flags, CINDER-3 responds differently to (a) an initial or first-time-step call for a particular region, (b) a subsequent call for a region that has undergone previous irradiation, (c) a call not to deplete the region at all, and (d) a call for shutdown, i.e., no power, only continue chain decay for that time step. In the initial call to the depletion module, coarse group cross sections for reactions cited above are prepared for all fission products and non-explicit actinides in the chain library in a group structure defined in the ISOTXS file. As indicated in Fig. 5, this is achieved by AFEW, a modification of the TOAFEW-V collapsing code, operating on the 154-group cross-section library and using the same fine-group flux file for weighting that was used by TRANSX, discussed above in Sec. II. These nonexplicit nuclide cross sections are used in conjunction with the cross-section and density data for explicit nuclides and the fluxes from the core neutronics calculation to produce cumulative EOS results (exposure, burn-up, atom densities, cross sections, etc.) used for the next time step. The calculated depletion is reflected by altering the lumped fission product and actinide microscopic cross sections on the ISOTXS file and the densities of the explicit nuclides on the ZNATDN file. Region cross sections and densities for the individual fission products and non-explicit actinides are stored on the CINDER-3 fission history file shown in Fig. 5. In the next and subsequent, non-initial time steps the fission history file is used as input at BOS and regenerated as output at EOS. Thus, this file must be saved in addition to the ISOTXS, ZNATDN, and RZFLUX files for continuation of an interrupted run.

In the course of performing depletion calculations, CINDER-3 currently follows fission products yielded by the neutron-induced and/or spontaneous fission of 31 actinides initially present and/or produced within the fuel. Fission rates are calculated with the average of BOS and EOS atom densities. Thermal (0.0253 eV), fast (500 keV), or high energy (14 MeV) neutron-induced fission yields may be selected by the user. The yield data currently in CINDER-3 are from ENDF/B-V. Details of the operation of CINDER-3 as the DANDE depletion module are given in Sec. V, in which an actual depletion run is followed.

V. CTL AND SAMPLE PROBLEM

The core neutronics module and the depletion module of the DANDE system communicate via numerous files. Often the application requires that fuel rods be repositioned or that fuel elements be changed between depletion time steps. Running multi-step problems by hand is extremely tedious and error prone. Therefore, a controller written in the language CTL is composed for each application, allowing the problem to be run in interactive or production mode. We chose the second part of LCCEWG-5, namely, the calculation of the FFTF Cycle 1 depletion experiment to illustrate the operation of a typical CTL controller. Note, however, that this calculation starts at the beginning of Cycle 1 (BOC1) and not at the beginning of life (BOL), so that files generated from previous DANDE runs to bring the reactor from BOL to the BOC1 configuration have to be accessed by CTL for this run (see Sec. VI).

The Cycle 1 experiment requires seven depletion steps; the control rod positions, exposure times and cooling times for these steps are given in Table VIII. A listing of the controller that supervised the execution of these seven steps is given in Table IX. In the discussion that follows, the line numbers refer to this table. Line 1 identifies the CTL procedure. Lines 2 and 3 define the mass storage root nodes for retrieval of codes and libraries (line 2) and retrieval and storage of data files specific to this run (line 3). Line 5 limits the execution time of any code step to 10 minutes, and line 4 will cause all communications to be written to the CTL log file. To begin the cycle, the neutronics code, DIF3D, is obtained (line 6) and run (line 9); it requires only a cross section file, ISOTXS (line 7), and an input file (line 8), which were discussed in Sections II and III. At completion of DIF3D, the k-effective for

TABLE VIII
DEPLETION STEPS OF CYCLE 1-A AND CYCLE 1-B COMBINED

Rod Position (cm)	Exposure (Days)	Cumulative Exposure (Days)	Cooling Time (Days)	Elapsed Time (Days)
42.6	17.0	17.0	0.0	17.0
47.7	17.1	34.1	0.0	34.1
53.1	0.0	34.1	94.0	128.1
54.4	16.95	51.05	0.0	145.05
63.4	16.95	68.00	0.0	162.00
72.4	16.95	84.95	0.0	178.95
81.3	16.95	101.90	0.0	195.90

TABLE IX
CTL CONTROLLER FOR FFTF CYCLE 1 DEPLETION EXPERIMENT

```

1 *PROCEDURE CINDIF
2 *SELECT ROOT2=/084023/DIF3D/DIFTOCIN */CODES AND MAIN FILES ON THIS NODE
3 *SELECT ROOT3=/063271/CARBID/LCCEWG5/FFTF */RUN-SPECIFIC FILES ON THIS NODE
4 *SELECT MESSAGES=LONG
5 *SELECT TASKTIMELIMIT=10.
6 *GET DIFX:/CT1GRFEN/DIF3D/DIF22JUN */GET NEUTRONICS CODE - DIF3D
7 *G3 ISOTXS:CYCL1A1/ISO3 */ CROSS SECTION FILES
8 *G3 INPUT:CYCL1C/INPUT
9 *DIFX */RUN DIF3D
10 *FRED OUTPUT */PRINT K-EFF ON LOG
11 TP*\TIVE =
12 END
13 *HSP -UC -CC OUTPUT MAJOR="DIF1" */SEND DIF3D OUTPUT TO PRINTER
14 *S3 DIR=CYCL1C NDXSRF GEODST LABELS ZNATDN RZFLUX PWDINT */SAVE FILES
15 *DESTROY ALWITH. A. */DESTROY UNNEEDED FILES
16 *DESTROY ARC COMPTS D3EDIT DIF3D DIF3DA NHFLUX PKEDIT PWDINT RTFLUX
17 *S3 SCRO01 TAPE10
18 *COPY NDXSRF TAPE7 */GET READY FOR DEPLETION
19 *SWITCH ISOTXS TAPE3
20 *SWITCH ZNATDN TAPE8
21 *SWITCH RZFLUX TAPE4
22 *G2 DT4:DTG12B TAPE15:TAPE15B TAPE16:TAPE16B */GET DEPL CODE AND LIBS
23 *G3 TAPE2:HPC/RZF80A */80 GROUP FLUX FILE
24 *G3 TAPE11:CYCL1A/CIN6 */CIN6 CONTAINS DEPLETED DENSITIES OF NUCLIDES
25 *FILE N=DTIN */INPUT FILE FOR DEPLETION STEP
26 39 0 0 0 0 0 0 0 0 0 0 0 0 0 0 4 4 4 4 4 5 5 5 5 5 5 5 4 5 4 -4 -5 0 0 0 0 0
27 777.6 408.0 1 0
28 *DT4 INPUT=DTIN */RUN DEPLETION STEP
29 *HSP -UC TAPE9 MAJOR="CINDER1" */SEND OUTPUT TO PRINTER
30 *LET I=0 */ I IS INDEX OF DEPLETION STEP
31 *LOOP: LET I=I+1 */START OF LOOP
32 *S3 DIR=CYCL1C TAPE17:DEN\I\ TAPE18:ISO\I\ TAPE10:CIN\I\ */ SAVE FILES
33 *SWITCH TAPE10 CIN */CHANGE FILE NAMES FOR DIF3D
34 *SWITCH TAPE17 ZNATDN
35 *SWITCH TAPE18 ISOTXS
36 *IF I.EQ.7 THEN GOTO RUNIT */LAST DIF3D RUN - DO NOT MOVE RODS
37 *G3 INPUT:CYCL1C/DIFIN\I\ */GET DIF3D INPUT WITH NEW ROD POSITIONS
38 *DESTROY GEODST */DESTROY GEOMETRY FILE SO DIF3D WILL GET INFO FROM INPUT
39 *RUNIT:DIFX */RUN DIF3D
40 *S3 DIR=CYCL1C RZFLUX:RZF\I\ PWDINT:PWD\I\ */SAVE FILES
41 *FRED OUTPUT */PRINT K-EFF ON LOG
42 TP*\TIVE =
43 END
44 *HSP -UC -CC OUTPUT MAJOR="DIFX" */PRINT OUTPUT
45 *IF I.GE.7 THEN GOTO FINISH */SEVEN DEPLETION STEPS
46 *DESTROY ALWITH. A. */DELETE UNNEEDED FILES
47 *DESTROY ARC COMPTS D3EDIT DIF3D DIF3DA NHFLUX PKEDIT PWDINT RTFLUX
48 *DESTROY SCRO01 TAPE10 TAPE4 TAPE3 TAPE8 TAPE11
49 *G3 DTIN:CYCL1C/DTIN\I\ */INPUT FILE FOR DEPLETION
50 *SWITCH CIN TAPE11 */SWITCH FILES NAMES FOR DEPLETION
51 *SWITCH RZFLUX TAPE4
52 *SWITCH ZNATDN TAPE8
53 *SWITCH ISOTXS TAPE3
54 *DT4 INPUT=DTIN */RUN DEPLETION
55 *HSP -UC TAPE9 MAJOR="CINDER" */PRINT OUTPUT
56 *GOTO LOOP */GO DO NEXT TIME STEP
57 *FINISH:RETURN */QUIT
58 *END

```

this step is printed on the log (lines 10-12) and the output file is printed (line 13). DIF3D produces several standard interface files, some of which are required by the depletion code (see Table X). Some of these files are saved (line 14), some destroyed (lines 15-17), and the names of some are changed for the depletion code (lines 18-21).

As discussed in Section IV, CINDER-3, the depletion code, requires, in addition to the files produced by DIF3D, a fine-group flux file, TAPE2, a multi-group cross section library, TAPE15, a nuclide decay chain library, TAPE16 (lines 22, 23), and optionally a file containing depletion information from the previous time step, TAPE11 (line 24). The input file to CINDER-3 consists of the two lines 26 and 27, containing the following variables:

Line 1

NZC - number of zones in core neutronics problem - in this example there are 39 zones; zone/region correspondence is give above in Table VII.

IFZ(I), I = 1, NZC - for each zone

- (a) If IFZ = 0, do not deplete this zone.
- (b) If IFZ > 0, IFZ is the number of the zone on the fine group RZFLUX file to be used to collapse zone I.
- (c) If IFZ < 0, TIME $\neq$ 0 and I is a new region (i.e., new fuel or different fuel) [IABS (IFZ) as in (b) above].

Table VII (Sec. III) gives the correspondence of zone number to assembly type. Zones 1-16 and 35-39 are non-fuel assemblies and receive an IFZ value of zero. Zones 17-32 have received exposure previous to BOC1 and are assigned an IFZ value of 4 or 5 depending on whether the fuel assembly is in the inner core or the outer core. When the DIF3D 80-group problem was run to generate the 80-group flux file, only two fuel zones were specified, an inner zone and an outer. Zone assignment can be ascertained by looking at the DIF3D output. Zones 33 and 34 have been given IFZ values of -4 and -5 because they have no exposure history, i.e., they were inserted at the beginning of BOC1. The minus sign is a flag to the CINDER interface that a new zone is to be depleted and that no information about this zone will be found on the CINDER TAPE11.

Line 2

TIME = total amount of time in hours that the reaction has been running, in this case 777.6 h from BOL to BOC1.

BURNT = burn-up step length in hours, 408.0 h.

NTS = constant power subdivisions of BURNT (LE 25), 1.
 ISIG = cross-section collapse flag (see Section IV).
 ISIG = 0 no effect
 ISIG = 1 call AFEW for cross-section collapse
 ISIG = -1 shutdown time step

TABLE X

INTERFACE FILES OF DIF3D-CINDER SYSTEM

<u>File Name</u>	<u>Description</u>	<u>Local CINDER Name (Input)</u>	<u>Local CINDER Name (Output)</u>	<u>Needed for Subsequent DIF3D Runs</u>
GEODST	geometry	—	no	yes, if control rods are not re- positioned or fuel elements changed
ISOTXS	cross section	TAPE3	TAPE18	yes
LABELS	names of regions and zones	—	no	yes
NDXSRF	cross reference of densities and zones	TAPE7	no	yes
ZNATDN	explicit nuclide mixture densities	TAPE8	TAPE17	yes
RZFLUX	coarse-group fluxes by zone	TAPE4	no	no
PWDINT	power density by group and zone	—	no	no
RTFLUX	pointwise fluxes	—	no	no
—	CINDER history	TAPE11	TAPE10	—
—	multigroup cross- section library	TAPE15	—	—
—	nuclide decay chain library	TAPE16	—	—

In the LCCEWG-5 example ISIG is 0 because a DANDE run was made from FFTF BOL to the beginning of Cycle 1. At each depletion time step CINDER writes a file, TAPE10, which contains densities and cross sections of the non-explicit nuclides reflecting the varied irradiation history of the fuel assemblies comprising the FFTF core. At the next depletion step, CINDER will read this file

(its name now having been changed to TAPE11) if ISIG = 0. Hence, in this example, the CINDER file written at the last depletion step of the DANDE run from BOL to BOC1 is retrieved (see line 24), so that CYCLE 1 will begin with the correct irradiation history.

When the first depletion step is completed, the output file is sent to the printer (line 29), and the controller enters the main loop (line 31). The loop index is I, which is the count of the number of completed depletion steps. At entry to the loop, I has the value "one." CINDER produces a file containing the new densities of the explicit nuclides, TAPE17, which will become the ZNATDN file for the next DIF3D calculation. A file containing new cross sections for the fission product and actinide lumps is also written, TAPE18, that will become the ISOTXS file. These files and the TAPE10 previously discussed are saved under the names DEN, ISO, and CIN, respectively, with a suffix of "I" appended to each name. Hence, after the first depletion step, when I = 1, DEN1, ISO1 and CIN1 are saved (line 32). TAPE10 is a scratch file to DIF3D; therefore the CINDER TAPE10's name is switched to preserve its integrity for the next CINDER step (line 33). The density and cross-section files are given the names expected by DIF3D (lines 34, 35).

The LCCEWG-5 experiment consists of seven depletion steps, but an eighth DIF3D calculation must be carried out to obtain the neutronics information after the last depletion. One can think of the DIF3D runs as bracketing the CINDER depletion calculations. For each of the first seven DIF3D runs, the control rod position is different. DIF3D will use whatever standard files exist and will use the information on the file called INPUT only if data are not obtainable from a standard file. The GEODST file contains the geometric information including the control rod position; therefore, for all but the last DIF3D run, GEODST must be destroyed (line 38) and a new INPUT file must be accessed (line 37). The new INPUT file will vary from that in Table VI; the 09 cards (records 187-191) must be changed to reflect the new position of the control rod. In this example, a rod position of 42.5 cm gives boundaries at 105.01, 124.51, 216.65, and 251.2. For the next rod position of 47.7 cm, the new boundaries would be 110.11, 129.61, 221.75, and 256.3. Additionally, all 30 cards (records 17-186) containing the original boundaries must be changed to the new numbers. For example, record 105 would become 30 NAC 5 14 0 62.4 110.11. The test on line 36 of Table IX skips the rod position adjustment for the last DIF3D run.

DIF3D executes (line 39) and files are printed and saved as before (lines 40-44). The test on line 45 will transfer control out of the loop if complete (line 57); if not, unneeded files are destroyed (lines 46-48) and work continues by preparing for the next CINDER-3 run. A new INPUT file is obtained (line 49); the names of required files are changed (lines 50-53); CINDER-3 executes (line 54); the output file is printed (line 55); and at line 56 control is transferred to the beginning of the loop (line 31). The new CINDER-3 input is similar to that shown in Table IX, except that the minus signs are removed from line 26, as regions 33 and 34 are no longer "new" and the time is incremented for the next step on line 27, i.e, $TIME = 777.6 + 408.0$ and $BURNT = 410.4$.

The power and flexibility of the CTL language permit other forms of control strategy. For example, it is possible to retrieve the value of k-effective using built-in CTL functions. A reactor model can be constructed that runs continuously close to criticality by testing the k-effective after each time step and moving the control rods if the value of k-effective drops below a certain test value. Similarly, tests can be inserted that require fuel elements to be relocated at appropriate times. Fuel relocation strategies, however, require that the CINDER history file be reordered to correspond to the new configuration. At this time, reordering is not automatic to the DANDE system.

VI. DANDE VALIDATION

Los Alamos participation during the past five years in the Large Core Code Evaluation Working Group (LCCEWG) provided us with the opportunity of validating the DANDE code system by calculating the LCCEWG fifth benchmark problem. The LCCEWG was a group of representatives from several laboratories founded by the U.S. Department of Energy (DOE) whose function had been to validate codes used in reaction design analysis. LCCEWG-5 is based on measurements made in the Fast Flux Test Facility (FFTF), a 400-Mw(th) sodium cooled fast reactor located near Richland, Washington, and operated for the Department of Energy by Westinghouse Hanford Company (WHC). The benchmark includes two experiments:

- (1) the high power characterizer (HPC) experiment, in which several prototypic assemblies containing extensive dosimetry were irradiated for eight full-power days; and

- (2) the cycle-1 depletion experiment in which pellet burnup measurements were made on fuel from two driver fuel assemblies removed at the end of Cycle 1 operation.

The advantage of using LCCEWG-5 in DANDE validation is that, in addition to being able to compare with experimental results, comparisons can be made with calculations made by other participants using different codes and methods.²²

A. The HPC Experiment

The full-core layout for the FFTF high power characterization (HPC) run is shown in Fig. 6. Various assemblies are shown including the fuel assemblies (F31, F32, F41, F42), characterizer assemblies (CH1, CH2, CH3, CH4, CH5), in-core shim assemblies (ICS), safety and control rod assemblies, reflector assemblies (RR1, RR2), and several different type test assemblies. The vertical description of the homogenized model of the FFTF is shown above in Fig. 3 and Tables IV and V above.

As discussed in Sec. II, the nuclear cross-section data used in our preliminary FFTF/HPC calculations were ENDF/B-V processed by the NJOY code into the 80-group MATXS6 fine-group library. Broad-group sets (12 groups) appropriate for FFTF/HPC calculations were then derived from MATXS6 using the TRANSX code. The 80-group RZFLUX file needed for collapsing was produced by the DIF3D code using the R-Z model of the FFTF/HPC.

In addition to the R-Z model, shown in Fig. 3, and the full-core model, shown in Fig. 6, a symmetric one-third core FFTF/HPC model was designed. In this model the control and safety assemblies and the in-core shim and central characterizer assemblies were kept as separate regions; all other assemblies were homogenized. Note in Fig. 6 that the control and safety assemblies are arranged in third-core symmetry and that five of the six ICSA assemblies are located in Ring No. 4, two are in contact, and two are separated by a single fuel assembly. A third core layout can be arranged so that all ICSA are in Ring No. 4, symmetrically positioned with a fuel assembly between each pair (Fig. 7). This symmetric model was designed for use in code/transport/anisotropic scattering comparison studies and control assembly worth calculations.

These FFTF/HPC calculations to determine code/model/transport/anisotropic scattering effects are summarized in Table XI. Included in this table are problems run with both the nodal and finite difference options of the DIF3D

Fig. 6. FFTF/HPC full-core plan at $Z = 154.55$. Control assemblies designated ABS are diagonally striped red and safety assemblies BPC are solid blue.

Fig. 7. FFtF/HPC third-core plan at $Z = 154.55$. Control assemblies ABS are diagonally striped purple and safety assemblies BPC are diagonally striped green. Fuel regions have been homogenized into DR1, solid yellow, and DR2, solid red.

TABLE XI

CODE/TRANSPORT/ANISOTROPIC SCATTERING/GEOMETRY COMPARISONS FOR FFTF/HPC MODELS

Prob. No.	Code	Option	Geometry (Mesh)	ISOTXS	K-eff	Remarks
12	DIF3D	Nodal	Full Core HEX-Z (17)	ISO12A	0.98935	R.T. = 344.5s, Region chis, isotope densities
13	DIF3D	Nodal	1/3 Core HEX-Z (17)	ISO12A	1.00287	R.T. = 122.5s, Region chis, isotope densities
15	DIF3D	Finite difference	R-Z (27x57)	ISO12A	0.98186	R.T. = 20s, Region chis, isotope densities
16	DIF3D	Finite difference	R-Z (27x57)	I12MP3CH	0.98176	R.T. = 15s, Region chis, Region densities
17	DIF3D	Finite difference	R-Z (27x57)	I12MP3CH	0.98229	R.T. = 15s, set chi, Region densities
18	TWODANT	P-3, S-8	R-Z (27x57)	I12MP3CH	0.98914	R.T. = 69s
19	TWODANT	P-2, S-8	R-Z (27x57)	I12MP3CH	0.98923	R.T. = 54s
20	TWODANT	P-1, S-8	R-Z (27x57)	I12M33CH	0.98832	R.T. = 50s
21	TWODANT	P-0, S-8	R-Z (27x57)	I12MP3CH	1.02164	R.T. = 45s
22	TWODANT	P-1, S-2	R-Z (27x57)	I12MP3CH	0.98940	R.T. = 34s
23	DIF3D	Finite difference (P_0 corrected)	1/3 core-Triangular	ISO12A	0.98630	Bucklings from 13, R.T. = 9.5s
24	TWOHEX	S-4/R (P_0 corrected)	1/3 core-Triangular	ISO12A	0.99093	Bucklings from 13, R.T. = 90.5s
25	TWOHEX	S-4/C P_0	1/3 core-Triangular	I12MP3CH	1.00910	Bucklings from 13, R.T. = 52.6s
26	TWOHEX	S-2 (P_0 Corrected)	1/3 core-Triangular	ISO12A	0.98883	Bucklings from 13, R.T. = 37.5s
27	TWOHEX	S-4/C (P_0 Corrected)	1/3 core-Triangular	ISO12A	0.99058	Bucklings from 13, R.T. = 50.8s
28	TWOHEX	S-4/C P_3	1/3 core-Triangular	I12MP3CH	0.98995	Bucklings from 13, R.T. = 128 s
29	DIF3D	Finite difference	R-Z (39x79)	I12MP3CH	0.98041	R.T. = 30s Region chis
30	DIF3D	Finite difference	R-Z (39 x 79)	I12MP3CH	0.98093	R.T. = 28s, Set chi
31	DIF3D	Finite difference	1/3 core-Triangular	I12MP3CH	0.98676	Bucklings from 13, R.T. = 11 s, set chi
32	DIF3D	NODAL	1/3 core HEX-Z (17)	ISO12A	0.99762	control assemblies inserted 5 cm.
33	DIF3D	NODAL	1/3 core HEX-Z (19)	ISO12A	1.00797	control assemblies withdrawn 5 cm.

code and problems run with the discrete ordinates codes with quadrature up to S-8 and anisotropic scattering up to P-3. The two basic ISOTXS libraries, both using the homogenized resonance self-shielding options in TRANSX, included a P_0 -transport corrected 12-group set (labelled IS012A in Table V and a P_3 anisotropic scattering set, also in 12 groups (labelled I12MP3CH). It should be noted that DIF3D has the capability of correctly using the P_3 library for a diffusion calculation. Both libraries were modified to contain set chi values, required by the discrete ordinates codes, as well as region chi values, default for DIF3D.

An ISOTXS nuclear data file, which we have designated as ISOMANA, also used in the HPC benchmark calculations, was supplied by F. Mann of Hanford Engineering Development Laboratory (HEDL), as specified in the benchmark write-up. An additional nuclear data library, supplied by HEDL, contained reaction cross sections used to calculate specified reaction rates. Unfortunately, the HEDL ISOTXS library did not contain data for threshold reactions explicitly--these were lumped in an "absorption" cross section--which were required in our depletion module (Fig. 5). As a result, we had to run all depletion leading up to the HPC run using our ISOTXS file (IS012A).

The depletion calculation consisted of two 10-day runs of all fueled assemblies except the characterizers plus a single 8-day run of all fueled assemblies including the characterizers. The Ring 3 safety rods were banked in the withdrawn position and the Ring 5 control rods were banked at the half-way out position, 19.1 in. withdrawn, for all runs. The nodal option of DIF3D was used as the core calculational module (Fig. 1) with the full-core, hexagonal-Z model of the FFTF/HPC as input. As stated above, the Los Alamos data library was used for the depletion runs; beginning-of-cycle (BOC) and end-of-cycle (EOC) calculations were repeated using the HEDL ISOTXS file.

The k_{eff} at BOC using IS012A was 0.98935; at EOC it was 0.98006, a loss of about 1% in k . This is to be compared with 0.98572 and 0.97567, respectively, for runs with ISOMANA and with the HEDL reference eigenvalue of 0.984 reported in Ref. 22. In the depletion calculations using IS012A, a $\Delta k/k$ loss of 0.00679 was observed after the first 20-day run. Using the HEDL determined value of $\beta_{eff} = 0.00318$ for the FFTF gives a value of 10.69¢/day reactivity loss. This compares very favorably with the HEDL reported value of 10.75¢/day. Incidentally, using the number of fissions from the CINDER-3 output and values of $\bar{\nu}_d$ and $\bar{\nu}_t$ derived from ENDF/B-V for the various fissioning nuclides, we determined a value of $\beta = 0.00349$.

Also, as stated in the benchmark specifications, the control assembly bank was withdrawn 2.6 cm during the 8-day characterizer run. Our $\delta k/k$ calculated loss for this period was 0.0026, indicating a rod worth of 1 milli-k/cm. As can be seen for Table XI, this is the value we calculate for the control assembly bank at mid-core.

Mid-plane group fluxes for each characterizer and calculated with both the ISOMANA and ISO12A data libraries are shown in Tables XII and XIII. The ratios of the two sets of fluxes are shown in Table XIV. As is evident from this table, except for the characterizer in Row No. 8 (3811), in the reflector, fluxes computed with ISO12A are generally higher than those calculated with ISOMANA. Major differences can be accounted for by the fact that ISOMANA was generated using fluxes from a one-dimensional model with corrections for spatial self-shielding; whereas, ISO12A was generated, as discussed in Sec. II, using two-dimensional fluxes without the spatial self-shielding corrections (homogenized cell).

Flux comparisons were also made with results from calculations performed by HEDL (Hanford Engineering Development Laboratory) for the FFTF HPC experiment. Ratios of HEDL to Los Alamos National Laboratory fluxes are shown in Tables XV and XVI, in which ISOMANA and ISO12A were used, respectively, in the Los Alamos results. The ratios in Table XV are, for the most part, near "one," indicating equivalence in HEDL and Los Alamos modeling and methods (the reference HEDL diffusion calculations were done with the 3DB code²³). Discrepancies of about a factor of two, however, are seen in the outer reflector region (Ring 9). These are due to the fact that the HEDL model included extra rings to represent the reactor vessel, thus preventing the larger leakage (lower flux) of the outer regions of the Los Alamos model.

The flux ratios given in Table XVI more or less reflect the same cross-section comparisons seen in Table XIV. The effects of these cross-section differences on reaction rates are shown in Tables XVII (generated using ISOMANA), XVIII (generated using ISO12A), and XIX (ratio of XVII to XVIII).

Atom densities for the principal nuclides in the fueled characterizers at beginning-of-cycle (BOC) and end-of-cycle (EOC) for the HPC 8-day run are shown in Table XX. Because explicit threshold reaction information is required by the CINDER code in the DANDE depletion module, only the ISO12A library could be used for the depletion calculation, as these reactions were lumped into a

single "absorption" cross section in ISOMANA. At present, we have neither experimental nor calculational data from another source with which to compare our Table XX results.

TABLE XII
MID-PLANE CHARACTERIZER FLUXES (ISOMANA)

Group	2101	2402	3404	2503	2603	2704	3811	2909
1	1.26e+14	8.06e+13	8.09e+13	6.77e+13	4.70e+13	6.53e+12	3.74e+11	6.69e+10
2	6.73e+14	4.46e+14	5.05e+14	3.64e+14	2.47e+14	5.49e+13	8.24e+12	2.62e+12
3	1.44e+15	9.54e+14	1.23e+15	7.66e+14	5.33e+14	2.29e+14	9.11e+13	4.27e+13
4	7.52e+14	5.15e+14	6.83e+14	4.05e+14	2.82e+14	1.54e+14	8.28e+13	4.13e+13
5	1.74e+15	1.18e+15	1.50e+15	9.14e+14	6.32e+14	3.14e+14	1.62e+14	7.85e+13
6	1.45e+15	9.82e+14	1.23e+15	7.47e+14	5.29e+14	3.01e+14	1.70e+14	8.12e+13
7	8.32e+14	5.80e+14	6.93e+14	4.38e+14	3.01e+14	1.38e+14	8.32e+13	4.24e+13
8	4.43e+14	3.11e+14	4.11e+14	2.26e+14	1.59e+14	9.17e+13	4.72e+13	2.35e+13
9	1.80e+14	1.24e+14	1.97e+14	9.04e+13	7.32e+13	7.62e+13	4.18e+13	2.07e+13
10	1.51e+14	1.14e+14	1.87e+14	7.96e+13	7.20e+13	8.85e+13	5.18e+13	2.54e+13
11	4.01e+13	3.08e+13	5.97e+13	2.09e+13	2.61e+13	5.92e+13	3.83e+13	1.88e+13
12	6.57e+12	4.72e+12	1.36e+13	3.30e+12	1.75e+13	1.22e+14	1.04e+14	5.45e+13

TABLE XIII
MID-PLANE CHARACTERIZER FLUXES (ISO12A)

Group	2101	2402	3404	2503	2603	2704	3811	2909
1	1.31e+14	8.45e+13	8.21e+13	7.08e+13	4.95e+13	6.86e+12	3.64e+11	7.10e+10
2	6.95e+14	4.65e+14	5.08e+14	3.80e+14	2.59e+14	5.75e+13	7.64e+12	2.71e+12
3	1.49e+15	9.94e+14	1.23e+15	7.98e+14	5.56e+14	2.33e+14	7.24e+13	4.23e+13
4	8.34e+14	5.69e+14	7.40e+14	4.45e+14	3.09e+14	1.64e+14	6.55e+13	4.18e+13
5	1.75e+15	1.20e+15	1.47e+15	9.34e+14	6.44e+14	3.07e+14	1.16e+14	7.32e+13
6	1.38e+15	9.47e+14	1.14e+15	7.18e+14	5.11e+14	2.86e+14	1.22e+14	7.65e+13
7	9.07e+14	6.38e+14	7.30e+14	4.71e+14	3.16e+14	1.27e+14	5.59e+13	3.52e+13
8	4.92e+14	3.44e+14	4.53e+14	2.54e+14	1.85e+14	1.17e+14	4.76e+13	3.04e+13
9	1.66e+14	1.10e+14	1.79e+14	8.32e+13	6.86e+13	7.32e+13	3.19e+13	2.05e+13
10	1.90e+14	1.44e+14	2.27e+14	1.01e+14	8.73e+13	9.79e+13	4.45e+13	2.86e+13
11	5.34e+13	4.11e+13	7.67e+13	2.76e+13	3.33e+13	7.35e+13	3.58e+13	2.34e+13
12	1.01e+13	7.69e+12	2.31e+13	4.95e+12	2.36e+13	1.61e+14	9.57e+13	7.14e+13

TABLE XIV
FLUX RATIOS (TABLE XII DIVIDED BY TABLE XIII)

Group	2101	2402	3404	2503	2603	2704	3811	2909
1	0.96	0.95	0.99	0.96	0.95	0.95	1.03	0.94
2	0.97	0.96	0.99	0.96	0.95	0.96	1.08	0.97
3	0.97	0.96	1.00	0.96	0.96	0.98	1.26	1.01
4	0.90	0.90	0.92	0.91	0.91	0.94	1.26	0.99
5	0.99	0.98	1.02	0.98	0.98	1.02	1.39	1.07
6	1.05	1.04	1.08	1.04	1.04	1.05	1.40	1.06
7	0.92	0.91	0.95	0.93	0.95	1.09	1.49	1.20
8	0.90	0.90	0.91	0.89	0.86	0.78	0.99	0.77
9	1.09	1.12	1.10	1.09	1.07	1.04	1.31	1.01
10	0.80	0.79	0.82	0.79	0.82	0.90	1.16	0.89
11	0.75	0.75	0.78	0.76	0.78	0.81	1.07	0.81
12	0.65	0.61	0.59	0.67	0.74	0.76	1.09	0.76

TABLE XV
FLUX RATIOS (HANFORD ENGINEERING/LOS ALAMOS) USING HANFORD LIBRARY

Group	2101	2402	3404	2503	2603	2704	3811	2909
1	1.00	1.01	0.90	1.01	1.02	0.98	1.27	2.00
2	0.99	1.01	0.92	1.01	1.01	0.98	0.99	1.42
3	1.00	1.01	0.96	1.01	1.02	1.01	0.87	1.54
4	1.00	1.01	0.98	1.01	1.02	1.03	0.87	1.68
5	1.00	1.02	0.96	1.01	1.03	1.04	0.93	1.82
6	1.00	1.01	0.98	1.01	1.03	1.06	0.95	1.97
7	1.00	1.01	1.02	1.01	1.03	1.06	1.05	2.03
8	1.00	1.01	0.93	1.01	1.03	1.06	1.03	2.06
9	1.00	1.01	0.96	1.01	1.02	1.07	0.99	2.04
10	1.00	0.99	1.00	0.99	1.02	1.08	1.03	2.07
11	1.00	0.99	1.07	1.00	1.02	1.10	1.01	2.07
12	1.00	1.01	1.58	1.17	1.02	1.15	0.98	2.09

TABLE XVI
FLUX RATIOS (HANFORD ENGINEERING/LOS ALAMOS) USING LOS ALAMOS LIBRARY

Group	2101	2402	3404	2503	2603	2704	3811	2909
1	0.95	0.95	0.89	0.95	0.95	0.92	1.29	1.87
2	0.95	0.95	0.91	0.95	0.95	0.92	1.06	1.35
3	0.96	0.96	0.95	0.95	0.96	0.97	1.08	1.53
4	0.89	0.90	0.89	0.90	0.91	0.95	1.09	1.64
5	0.98	0.98	0.97	0.98	0.99	1.05	1.27	1.94
6	1.04	1.04	1.04	1.04	1.04	1.10	1.31	2.06
7	0.91	0.90	0.95	0.93	0.96	1.14	1.55	2.41
8	0.89	0.90	0.83	0.89	0.87	0.82	1.00	1.56
9	1.07	1.12	1.04	1.08	1.07	1.09	1.28	2.03
10	0.78	0.77	0.81	0.77	0.83	0.96	1.18	1.82
11	0.73	0.73	0.82	0.74	0.79	0.87	1.07	1.65
12	0.64	0.61	0.91	0.76	0.76	0.85	1.05	1.59

TABLE XVII

REACTION RATES USING HANFORD ENGINEERING LIBRARY

B-10(N,A)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	2.09e-08	1.56e-08	1.86e-08	1.30e-08	1.04e-08	7.59e-09	3.86e-09	1.98e-09
-38	1.41e-08	1.11e-08	1.45e-08	8.62e-09	6.85e-09	9.44e-09	5.84e-09	3.05e-09
-20	1.71e-08	1.27e-08	1.71e-08	9.84e-09	8.10e-09	1.16e-08	7.70e-09	4.00e-09
0	1.81e-08	1.25e-08	1.80e-08	9.14e-09	7.83e-09	1.15e-08	8.30e-09	4.23e-09
20	1.53e-08	9.26e-09	1.49e-08	6.15e-09	5.89e-09	9.01e-09	7.02e-09	3.51e-09
38	1.09e-08	6.09e-09	1.07e-08	4.03e-09	3.93e-09	6.05e-09	4.91e-09	2.42e-09
54	1.25e-08	4.18e-09	1.05e-08	3.69e-09	4.60e-09	4.13e-09	3.05e-09	1.46e-09

Li-6(N,A)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	6.31e-09	4.75e-09	5.62e-09	3.94e-09	3.06e-09	2.12e-09	1.06e-09	5.44e-10
-38	5.68e-09	4.31e-09	5.46e-09	3.42e-09	2.59e-09	2.76e-09	1.63e-09	8.48e-10
-20	7.28e-09	5.27e-09	6.86e-09	4.17e-09	3.20e-09	3.43e-09	2.17e-09	1.12e-09
0	7.78e-09	5.29e-09	7.26e-09	3.96e-09	3.12e-09	3.42e-09	2.34e-09	1.18e-09
20	6.55e-09	4.00e-09	6.01e-09	2.74e-09	2.34e-09	2.66e-09	1.98e-09	9.83e-10
38	4.49e-09	2.57e-09	4.15e-09	1.74e-09	1.52e-09	1.77e-09	1.38e-09	6.73e-10
54	3.90e-09	1.50e-09	3.30e-09	1.25e-09	1.39e-09	1.16e-09	8.45e-10	4.02e-10

Na-23(N,2N)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.10e-15	9.52e-16	8.55e-16	7.90e-16	4.52e-16	7.67e-17	6.08e-18	1.16e-18
-38	4.85e-15	3.45e-15	3.13e-15	3.11e-15	2.10e-15	2.81e-16	1.35e-17	2.56e-18
-20	7.09e-15	4.83e-15	4.62e-15	4.25e-15	2.88e-15	3.99e-16	2.09e-17	3.73e-18
0	7.64e-15	4.85e-15	4.91e-15	4.04e-15	2.81e-15	3.92e-16	2.27e-17	4.05e-18
20	6.40e-15	3.76e-15	4.03e-15	2.95e-15	2.10e-15	2.96e-16	1.90e-17	3.32e-18
38	3.99e-15	2.16e-15	2.45e-15	1.74e-15	1.26e-15	1.73e-16	1.15e-17	2.07e-18
54	7.56e-16	4.18e-16	5.47e-16	3.23e-16	2.11e-16	3.92e-17	4.95e-18	8.80e-19

Sc-45(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.87e-10	1.42e-10	1.65e-10	1.17e-10	8.63e-11	5.47e-11	2.70e-11	1.38e-11
-38	2.09e-10	1.56e-10	1.95e-10	1.23e-10	9.03e-11	7.50e-11	4.17e-11	2.16e-11
-20	2.71e-10	1.94e-10	2.50e-10	1.52e-10	1.12e-10	9.41e-11	5.56e-11	2.85e-11
0	2.89e-10	1.97e-10	2.65e-10	1.46e-10	1.10e-10	9.39e-11	6.00e-11	3.02e-11
20	2.44e-10	1.51e-10	2.20e-10	1.03e-10	8.25e-11	7.30e-11	5.07e-11	2.51e-11
38	1.67e-10	9.82e-11	1.50e-10	6.64e-11	5.36e-11	4.81e-11	3.52e-11	1.71e-11
54	1.21e-10	5.59e-11	1.03e-10	4.37e-11	4.11e-11	3.03e-11	2.16e-11	1.02e-11

TABLE XVII (cont.)

Ti-46(N,P)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.51e-12	1.31e-12	1.18e-12	1.09e-12	6.22e-13	1.09e-13	9.50e-15	2.04e-15
-38	6.59e-12	4.68e-12	4.28e-12	4.22e-12	2.85e-12	3.91e-13	2.10e-14	4.45e-15
-20	9.63e-12	6.57e-12	6.32e-12	5.77e-12	3.91e-12	5.55e-13	3.23e-14	6.51e-15
0	1.04e-11	6.59e-12	6.71e-12	5.48e-12	3.82e-12	5.45e-13	3.51e-14	7.04e-15
20	8.69e-12	5.11e-12	5.51e-12	4.00e-12	2.85e-12	4.12e-13	2.93e-14	5.77e-15
38	5.41e-12	2.94e-12	3.35e-12	2.36e-12	1.71e-12	2.41e-13	1.78e-14	3.58e-15
54	1.04e-12	5.79e-13	7.60e-13	4.46e-13	2.91e-13	5.59e-14	7.72e-15	1.54e-15

Cr-50(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.33e-10	1.01e-10	1.17e-10	8.24e-11	6.17e-11	4.04e-11	1.95e-11	9.95e-12
-38	1.28e-10	9.64e-11	1.29e-10	7.53e-11	5.76e-11	5.54e-11	3.00e-11	1.55e-11
-20	1.61e-10	1.17e-10	1.61e-10	8.99e-11	6.97e-11	6.91e-11	3.99e-11	2.04e-11
0	1.71e-10	1.17e-10	1.70e-10	8.50e-11	6.75e-11	6.89e-11	4.31e-11	2.16e-11
20	1.44e-10	8.83e-11	1.41e-10	5.87e-11	5.08e-11	5.36e-11	3.64e-11	1.80e-11
38	1.02e-10	5.84e-11	9.90e-11	3.86e-11	3.37e-11	3.55e-11	2.53e-11	1.23e-11
54	8.66e-11	3.80e-11	7.41e-11	3.01e-11	2.95e-11	2.25e-11	1.56e-11	7.39e-12

Mn-55(N,2N)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	5.34e-14	4.64e-14	4.16e-14	3.84e-14	2.20e-14	3.74e-15	2.96e-16	5.63e-17
-38	2.36e-13	1.68e-13	1.52e-13	1.52e-13	1.02e-13	1.37e-14	6.58e-16	1.25e-16
-20	3.45e-13	2.35e-13	2.25e-13	2.07e-13	1.40e-13	1.94e-14	1.02e-15	1.82e-16
0	3.72e-13	2.36e-13	2.39e-13	1.97e-13	1.37e-13	1.91e-14	1.11e-15	1.97e-16
20	3.12e-13	1.83e-13	1.96e-13	1.44e-13	1.02e-13	1.44e-14	9.25e-16	1.62e-16
38	1.94e-13	1.05e-13	1.19e-13	8.48e-14	6.12e-14	8.43e-15	5.60e-16	1.01e-16
54	3.68e-14	2.04e-14	2.66e-14	1.57e-14	1.03e-14	1.91e-15	2.41e-16	4.29e-17

Ni-58(N,P)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.81e-11	1.55e-11	1.47e-11	1.27e-11	7.41e-12	1.68e-12	2.58e-13	8.56e-14
-38	6.80e-11	4.87e-11	4.75e-11	4.33e-11	2.91e-11	5.12e-12	5.44e-13	1.76e-13
-20	9.94e-11	6.85e-11	7.01e-11	5.93e-11	4.01e-11	7.26e-12	8.17e-13	2.58e-13
0	1.07e-10	6.91e-11	7.45e-11	5.68e-11	3.91e-11	7.15e-12	8.90e-13	2.77e-13
20	8.97e-11	5.36e-11	6.12e-11	4.14e-11	2.92e-11	5.41e-12	7.43e-13	2.27e-13
38	5.59e-11	3.10e-11	3.72e-11	2.44e-11	1.74e-11	3.17e-12	4.61e-13	1.41e-13
54	1.27e-11	7.16e-12	9.76e-12	5.40e-12	3.54e-12	8.79e-13	2.08e-13	6.36e-14

TABLE XVII (cont.)

Fe-54(N,P)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.33e-11	1.14e-11	1.07e-11	9.35e-12	5.43e-12	1.18e-12	1.64e-13	5.03e-14
-38	5.08e-11	3.63e-11	3.52e-11	3.24e-11	2.18e-11	3.69e-12	3.51e-13	1.06e-13
-20	7.43e-11	5.11e-11	5.20e-11	4.44e-11	2.99e-11	5.25e-12	5.31e-13	1.55e-13
0	8.01e-11	5.16e-11	5.52e-11	4.24e-11	2.92e-11	5.16e-12	5.78e-13	1.67e-13
20	6.70e-11	4.00e-11	4.53e-11	3.09e-11	2.18e-11	3.91e-12	4.83e-13	1.37e-13
38	4.17e-11	2.31e-11	2.76e-11	1.82e-11	1.30e-11	2.28e-12	2.98e-13	8.45e-14
54	9.29e-12	5.24e-12	7.10e-12	3.95e-12	2.58e-12	6.16e-13	1.32e-13	3.74e-14

Fe-58(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	9.91e-11	7.46e-11	8.89e-11	6.22e-11	4.96e-11	3.60e-11	1.81e-11	9.26e-12
-38	5.93e-11	4.76e-11	6.23e-11	3.65e-11	2.94e-11	4.43e-11	2.74e-11	1.43e-11
-20	6.91e-11	5.19e-11	7.06e-11	3.99e-11	3.40e-11	5.40e-11	3.61e-11	1.87e-11
0	7.31e-11	5.05e-11	7.40e-11	3.66e-11	3.27e-11	5.39e-11	3.89e-11	1.98e-11
20	6.18e-11	3.74e-11	6.15e-11	2.44e-11	2.46e-11	4.21e-11	3.29e-11	1.64e-11
38	4.51e-11	2.48e-11	4.56e-11	1.62e-11	1.66e-11	2.83e-11	2.30e-11	1.13e-11
54	5.89e-11	1.82e-11	4.97e-11	1.65e-11	2.17e-11	1.95e-11	1.43e-11	6.82e-12

Co-59(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	4.78e-09	3.34e-09	4.33e-09	2.91e-09	2.72e-09	2.46e-09	1.33e-09	6.92e-10
-38	6.22e-10	6.07e-10	9.20e-10	4.14e-10	5.73e-10	2.70e-09	1.97e-09	1.05e-09
-20	3.77e-10	2.98e-10	5.27e-10	2.29e-10	5.58e-10	3.21e-09	2.56e-09	1.36e-09
0	3.62e-10	2.42e-10	5.27e-10	1.74e-10	5.23e-10	3.20e-09	2.75e-09	1.44e-09
20	3.08e-10	1.57e-10	4.46e-10	9.53e-11	4.02e-10	2.52e-09	2.33e-09	1.20e-09
38	3.32e-10	1.28e-10	5.08e-10	7.69e-11	2.93e-10	1.73e-09	1.65e-09	8.31e-10
54	2.38e-09	3.45e-10	1.91e-09	4.87e-10	1.06e-09	1.30e-09	1.04e-09	5.05e-10

Th-232(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.74e-11	1.48e-11	1.44e-11	1.21e-11	7.11e-12	1.81e-12	3.24e-13	1.15e-13
-38	6.00e-11	4.31e-11	4.38e-11	3.79e-11	2.55e-11	5.15e-12	6.76e-13	2.35e-13
-20	8.77e-11	6.07e-11	6.46e-11	5.22e-11	3.51e-11	7.30e-12	1.01e-12	3.42e-13
0	9.45e-11	6.15e-11	6.87e-11	5.01e-11	3.43e-11	7.19e-12	1.10e-12	3.67e-13
20	7.91e-11	4.77e-11	5.64e-11	3.65e-11	2.56e-11	5.45e-12	9.18e-13	3.01e-13
38	4.93e-11	2.77e-11	3.44e-11	2.15e-11	1.53e-11	3.19e-12	5.73e-13	1.87e-13
54	1.23e-11	7.00e-12	9.71e-12	5.22e-12	3.43e-12	9.54e-13	2.62e-13	8.55e-14

TABLE XVII (cont.)

Th-232(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	3.88e-09	2.85e-09	3.48e-09	2.41e-09	2.01e-09	1.56e-09	8.11e-10	4.18e-10
-38	2.06e-09	1.64e-09	2.17e-09	1.27e-09	1.06e-09	1.87e-09	1.22e-09	6.41e-10
-20	2.42e-09	1.79e-09	2.44e-09	1.40e-09	1.23e-09	2.27e-09	1.60e-09	8.37e-10
0	2.56e-09	1.75e-09	2.57e-09	1.29e-09	1.19e-09	2.27e-09	1.72e-09	8.85e-10
20	2.16e-09	1.29e-09	2.13e-09	8.60e-10	8.93e-10	1.77e-09	1.46e-09	7.36e-10
38	1.56e-09	8.55e-10	1.57e-09	5.65e-10	6.00e-10	1.20e-09	1.02e-09	5.08e-10
54	2.22e-09	6.38e-10	1.85e-09	6.04e-10	8.56e-10	8.43e-10	6.39e-10	3.07e-10

U-233(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.44e-08	1.09e-08	1.28e-08	9.03e-09	6.92e-09	4.65e-09	2.31e-09	1.18e-09
-38	1.43e-08	1.08e-08	1.35e-08	8.62e-09	6.44e-09	6.19e-09	3.57e-09	1.85e-09
-20	1.86e-08	1.34e-08	1.72e-08	1.06e-08	8.05e-09	7.74e-09	4.75e-09	2.44e-09
0	1.99e-08	1.35e-08	1.82e-08	1.01e-08	7.85e-09	7.72e-09	5.12e-09	2.58e-09
20	1.67e-08	1.02e-08	1.51e-08	7.05e-09	5.89e-09	6.00e-09	4.33e-09	2.14e-09
38	1.14e-08	6.52e-09	1.03e-08	4.47e-09	3.79e-09	3.97e-09	3.01e-09	1.47e-09
54	9.06e-09	3.63e-09	7.65e-09	2.98e-09	3.18e-09	2.55e-09	1.84e-09	8.72e-10

U-233(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.72e-09	1.30e-09	1.53e-09	1.07e-09	8.40e-10	5.89e-10	2.97e-10	1.52e-10
-38	1.41e-09	1.08e-09	1.39e-09	8.51e-10	6.54e-10	7.56e-10	4.53e-10	2.35e-10
-20	1.77e-09	1.29e-09	1.71e-09	1.01e-09	7.95e-10	9.35e-10	6.00e-10	3.10e-10
0	1.88e-09	1.29e-09	1.80e-09	9.54e-10	7.73e-10	9.34e-10	6.47e-10	3.28e-10
20	1.59e-09	9.67e-10	1.49e-09	6.53e-10	5.80e-10	7.27e-10	5.47e-10	2.72e-10
38	1.11e-09	6.28e-10	1.05e-09	4.21e-10	3.81e-10	4.85e-10	3.81e-10	1.87e-10
54	1.06e-09	3.91e-10	8.93e-10	3.31e-10	3.79e-10	3.22e-10	2.35e-10	1.12e-10

U-235(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.15e-08	8.63e-09	1.02e-08	7.16e-09	5.59e-09	3.90e-09	1.96e-09	1.00e-09
-38	1.01e-08	7.65e-09	9.68e-09	6.08e-09	4.63e-09	5.05e-09	3.00e-09	1.56e-09
-20	1.29e-08	9.30e-09	1.21e-08	7.37e-09	5.71e-09	6.26e-09	3.98e-09	2.05e-09
0	1.37e-08	9.31e-09	1.28e-08	6.98e-09	5.55e-09	6.25e-09	4.29e-09	2.17e-09
20	1.16e-08	7.03e-09	1.06e-08	4.82e-09	4.17e-09	4.86e-09	3.63e-09	1.80e-09
38	7.93e-09	4.51e-09	7.32e-09	3.07e-09	2.70e-09	3.23e-09	2.53e-09	1.24e-09
54	7.05e-09	2.64e-09	5.94e-09	2.23e-09	2.52e-09	2.13e-09	1.56e-09	7.39e-10

TABLE XVII (cont.)

U-235(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	4.53e-09	3.37e-09	4.05e-09	2.82e-09	2.27e-09	1.68e-09	8.60e-10	4.41e-10
-38	3.00e-09	2.35e-09	3.06e-09	1.83e-09	1.46e-09	2.08e-09	1.30e-09	6.80e-10
-20	3.64e-09	2.69e-09	3.60e-09	2.09e-09	1.73e-09	2.54e-09	1.71e-09	8.91e-10
0	3.86e-09	2.65e-09	3.79e-09	1.95e-09	1.67e-09	2.54e-09	1.85e-09	9.42e-10
20	3.26e-09	1.97e-09	3.15e-09	1.32e-09	1.26e-09	1.98e-09	1.56e-09	7.83e-10
38	2.32e-09	1.30e-09	2.27e-09	8.59e-10	8.37e-10	1.33e-09	1.09e-09	5.39e-10
54	2.69e-09	8.84e-10	2.26e-09	7.87e-10	9.99e-10	9.12e-10	6.80e-10	3.25e-10

U-238(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.47e-11	6.30e-11	6.20e-11	5.14e-11	3.04e-11	8.04e-12	1.55e-12	5.76e-13
-38	2.51e-10	1.80e-10	1.85e-10	1.59e-10	1.07e-10	2.23e-11	3.19e-12	1.16e-12
-20	3.67e-10	2.55e-10	2.73e-10	2.18e-10	1.47e-10	3.16e-11	4.74e-12	1.68e-12
0	3.96e-10	2.58e-10	2.90e-10	2.10e-10	1.44e-10	3.12e-11	5.17e-12	1.80e-12
20	3.31e-10	2.00e-10	2.38e-10	1.53e-10	1.07e-10	2.36e-11	4.32e-12	1.48e-12
38	2.06e-10	1.17e-10	1.45e-10	9.02e-11	6.39e-11	1.39e-11	2.71e-12	9.22e-13
54	5.27e-11	3.00e-11	4.19e-11	2.23e-11	1.47e-11	4.26e-12	1.25e-12	4.28e-13

U-238(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	3.93e-09	2.87e-09	3.53e-09	2.43e-09	2.05e-09	1.63e-09	8.52e-10	4.39e-10
-38	1.90e-09	1.53e-09	2.04e-09	1.17e-09	1.00e-09	1.93e-09	1.28e-09	6.73e-10
-20	2.20e-09	1.63e-09	2.24e-09	1.27e-09	1.15e-09	2.34e-09	1.67e-09	8.78e-10
0	2.32e-09	1.59e-09	2.35e-09	1.17e-09	1.11e-09	2.33e-09	1.80e-09	9.27e-10
20	1.96e-09	1.17e-09	1.95e-09	7.75e-10	8.36e-10	1.82e-09	1.52e-09	7.71e-10
38	1.43e-09	7.77e-10	1.46e-09	5.11e-10	5.64e-10	1.24e-09	1.07e-09	5.33e-10
54	2.21e-09	6.07e-10	1.84e-09	5.89e-10	8.68e-10	8.77e-10	6.70e-10	3.22e-10

Np-237(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.94e-10	6.26e-10	6.85e-10	5.09e-10	3.31e-10	1.39e-10	5.07e-11	2.42e-11
-38	2.00e-09	1.42e-09	1.62e-09	1.22e-09	8.41e-10	2.92e-10	9.37e-11	4.45e-11
-20	2.90e-09	2.00e-09	2.36e-09	1.68e-09	1.16e-09	4.05e-10	1.34e-10	6.28e-11
0	3.13e-09	2.05e-09	2.52e-09	1.64e-09	1.14e-09	4.04e-10	1.46e-10	6.72e-11
20	2.62e-09	1.58e-09	2.07e-09	1.18e-09	8.48e-10	3.08e-10	1.23e-10	5.52e-11
38	1.65e-09	9.45e-10	1.28e-09	7.03e-10	5.09e-10	1.85e-10	7.95e-11	3.55e-11
54	5.65e-10	3.17e-10	4.73e-10	2.33e-10	1.67e-10	7.69e-11	4.11e-11	1.81e-11

TABLE XVII (cont.)

Pu-239(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.02e-08	7.63e-09	9.05e-09	6.34e-09	4.95e-09	3.45e-09	1.74e-09	8.89e-10
-38	9.76e-09	7.32e-09	9.12e-09	5.89e-09	4.43e-09	4.51e-09	2.67e-09	1.39e-09
-20	1.28e-08	9.14e-09	1.16e-08	7.32e-09	5.57e-09	5.61e-09	3.54e-09	1.83e-09
0	1.37e-08	9.22e-09	1.23e-08	7.00e-09	5.43e-09	5.60e-09	3.82e-09	1.93e-09
20	1.15e-08	7.00e-09	1.02e-08	4.89e-09	4.07e-09	4.36e-09	3.23e-09	1.61e-09
38	7.75e-09	4.44e-09	6.93e-09	3.07e-09	2.60e-09	2.89e-09	2.25e-09	1.10e-09
54	6.25e-09	2.41e-09	5.25e-09	2.01e-09	2.23e-09	1.88e-09	1.38e-09	6.55e-10

Pu-239(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	6.07e-09	4.46e-09	5.45e-09	3.77e-09	3.15e-09	2.47e-09	1.28e-09	6.58e-10
-38	2.88e-09	2.34e-09	3.17e-09	1.79e-09	1.54e-09	2.94e-09	1.92e-09	1.01e-09
-20	3.25e-09	2.45e-09	3.46e-09	1.89e-09	1.74e-09	3.56e-09	2.52e-09	1.32e-09
0	3.43e-09	2.37e-09	3.62e-09	1.71e-09	1.67e-09	3.55e-09	2.71e-09	1.39e-09
20	2.90e-09	1.72e-09	3.01e-09	1.11e-09	1.26e-09	2.78e-09	2.29e-09	1.16e-09
38	2.15e-09	1.15e-09	2.28e-09	7.45e-10	8.59e-10	1.88e-09	1.61e-09	7.99e-10
54	3.46e-09	9.51e-10	2.89e-09	9.18e-10	1.34e-09	1.33e-09	1.01e-09	4.83e-10

Pu-240(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	9.31e-10	7.33e-10	8.05e-10	5.96e-10	3.91e-10	1.71e-10	6.59e-11	3.19e-11
-38	2.18e-09	1.55e-09	1.79e-09	1.32e-09	9.16e-10	3.40e-10	1.18e-10	5.67e-11
-20	3.13e-09	2.17e-09	2.57e-09	1.81e-09	1.25e-09	4.66e-10	1.67e-10	7.90e-11
0	3.37e-09	2.22e-09	2.74e-09	1.77e-09	1.23e-09	4.65e-10	1.82e-10	8.44e-11
20	2.83e-09	1.71e-09	2.25e-09	1.27e-09	9.17e-10	3.55e-10	1.52e-10	6.95e-11
38	1.79e-09	1.03e-09	1.41e-09	7.59e-10	5.54e-10	2.16e-10	1.00e-10	4.52e-11
54	6.59e-10	3.63e-10	5.52e-10	2.68e-10	1.97e-10	9.52e-11	5.35e-11	2.38e-11

Pu-240(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	5.82e-09	4.29e-09	5.22e-09	3.61e-09	3.01e-09	2.34e-09	1.21e-09	6.22e-10
-38	3.06e-09	2.45e-09	3.25e-09	1.88e-09	1.58e-09	2.80e-09	1.82e-09	9.55e-10
-20	3.56e-09	2.65e-09	3.64e-09	2.06e-09	1.82e-09	3.39e-09	2.39e-09	1.25e-09
0	3.77e-09	2.59e-09	3.82e-09	1.89e-09	1.76e-09	3.39e-09	2.57e-09	1.32e-09
20	3.18e-09	1.90e-09	3.17e-09	1.26e-09	1.32e-09	2.65e-09	2.17e-09	1.10e-09
38	2.31e-09	1.26e-09	2.36e-09	8.29e-10	8.92e-10	1.79e-09	1.53e-09	7.57e-10
54	3.34e-09	9.62e-10	2.78e-09	9.10e-10	1.29e-09	1.26e-09	9.53e-10	4.57e-10

TABLE XVII (cont.)

Pu-241(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.52e-08	1.14e-08	1.35e-08	9.49e-09	7.44e-09	5.23e-09	2.64e-09	1.35e-09
-38	1.32e-08	1.00e-08	1.27e-08	7.99e-09	6.09e-09	6.74e-09	4.04e-09	2.10e-09
-20	1.69e-08	1.22e-08	1.59e-08	9.68e-09	7.51e-09	8.35e-09	5.34e-09	2.76e-09
0	1.80e-08	1.22e-08	1.68e-08	9.19e-09	7.31e-09	8.34e-09	5.76e-09	2.92e-09
20	1.52e-08	9.25e-09	1.39e-08	6.36e-09	5.49e-09	6.49e-09	4.87e-09	2.43e-09
38	1.04e-08	5.94e-09	9.60e-09	4.05e-09	3.56e-09	4.32e-09	3.40e-09	1.66e-09
54	9.32e-09	3.47e-09	7.84e-09	2.94e-09	3.35e-09	2.85e-09	2.09e-09	9.95e-10

Pu-241(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	3.76e-09	2.80e-09	3.37e-09	2.34e-09	1.89e-09	1.40e-09	7.15e-10	3.67e-10
-38	2.46e-09	1.93e-09	2.52e-09	1.50e-09	1.20e-09	1.73e-09	1.08e-09	5.66e-10
-20	2.98e-09	2.20e-09	2.96e-09	1.71e-09	1.42e-09	2.12e-09	1.43e-09	7.41e-10
0	3.16e-09	2.17e-09	3.11e-09	1.59e-09	1.38e-09	2.11e-09	1.54e-09	7.83e-10
20	2.67e-09	1.61e-09	2.58e-09	1.07e-09	1.03e-09	1.65e-09	1.30e-09	6.51e-10
38	1.90e-09	1.06e-09	1.86e-09	7.01e-10	6.89e-10	1.11e-09	9.10e-10	4.48e-10
54	2.23e-09	7.27e-10	1.87e-09	6.49e-10	8.30e-10	7.60e-10	5.65e-10	2.70e-10

Am-241(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.06e-10	5.62e-10	6.06e-10	4.58e-10	2.98e-10	1.25e-10	4.59e-11	2.20e-11
-38	1.78e-09	1.27e-09	1.41e-09	1.09e-09	7.51e-10	2.55e-10	8.16e-11	3.87e-11
-20	2.57e-09	1.78e-09	2.05e-09	1.50e-09	1.03e-09	3.50e-10	1.15e-10	5.38e-11
0	2.77e-09	1.81e-09	2.19e-09	1.45e-09	1.01e-09	3.48e-10	1.25e-10	5.74e-11
20	2.32e-09	1.40e-09	1.80e-09	1.05e-09	7.54e-10	2.65e-10	1.05e-10	4.73e-11
38	1.46e-09	8.32e-10	1.11e-09	6.24e-10	4.53e-10	1.61e-10	6.91e-11	3.08e-11
54	4.94e-10	2.68e-10	4.09e-10	2.00e-10	1.47e-10	6.88e-11	3.70e-11	1.63e-11

Am-241(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.32e-08	9.88e-09	1.18e-08	8.24e-09	6.59e-09	4.81e-09	2.44e-09	1.25e-09
-38	9.18e-09	7.16e-09	9.32e-09	5.58e-09	4.42e-09	5.99e-09	3.71e-09	1.93e-09
-20	1.12e-08	8.25e-09	1.11e-08	6.43e-09	5.26e-09	7.35e-09	4.89e-09	2.54e-09
0	1.19e-08	8.16e-09	1.17e-08	6.00e-09	5.09e-09	7.34e-09	5.27e-09	2.68e-09
20	1.00e-08	6.08e-09	9.68e-09	4.06e-09	3.83e-09	5.72e-09	4.46e-09	2.23e-09
38	7.11e-09	3.99e-09	6.94e-09	2.65e-09	2.54e-09	3.84e-09	3.12e-09	1.53e-09
54	7.93e-09	2.68e-09	6.67e-09	2.35e-09	2.92e-09	2.61e-09	1.93e-09	9.23e-10

TABLE XVIII
REACTION RATES USING LOS ALAMOS LIBRARY

B-10(N,A)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	2.54e-08	1.1e-08	2.24e-08	1.60e-08	1.28e-08	9.28e-09	3.81e-09	2.40e-09
-38	1.57e-08	1.25e-08	1.62e-08	9.70e-09	7.82e-09	1.15e-08	5.38e-09	3.76e-09
-20	1.89e-08	1.41e-08	1.89e-08	1.10e-08	9.22e-09	1.42e-08	6.94e-09	4.96e-09
0	1.99e-08	1.38e-08	1.98e-08	1.01e-08	8.86e-09	1.41e-08	7.44e-09	5.24e-09
20	1.68e-08	1.01e-08	1.63e-08	6.63e-09	6.60e-09	1.09e-08	6.26e-09	4.33e-09
38	1.20e-08	6.60e-09	1.18e-08	4.32e-09	4.36e-09	7.24e-09	4.43e-09	2.94e-09
54	1.48e-08	4.52e-09	1.21e-08	4.16e-09	5.40e-09	4.86e-09	2.94e-09	1.73e-09

Li-6(N,A)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.47e-09	5.64e-09	6.56e-09	4.69e-09	3.67e-09	2.53e-09	1.03e-09	6.46e-10
-38	6.15e-09	4.74e-09	5.92e-09	3.76e-09	2.88e-09	3.28e-09	1.47e-09	1.02e-09
-20	7.83e-09	5.74e-09	7.33e-09	4.54e-09	3.54e-09	4.08e-09	1.91e-09	1.35e-09
0	8.32e-09	5.72e-09	7.72e-09	4.27e-09	3.43e-09	4.06e-09	2.05e-09	1.43e-09
20	6.99e-09	4.26e-09	6.36e-09	2.90e-09	2.55e-09	3.14e-09	1.72e-09	1.18e-09
38	4.78e-09	2.72e-09	4.39e-09	1.84e-09	1.64e-09	2.06e-09	1.21e-09	7.97e-10
54	4.48e-09	1.61e-09	3.66e-09	1.37e-09	1.58e-09	1.33e-09	7.95e-10	4.65e-10

Na-23(N,2N)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.18e-15	1.04e-15	8.97e-16	8.62e-16	4.95e-16	8.36e-17	5.97e-18	1.24e-18
-38	5.17e-15	3.73e-15	3.25e-15	3.37e-15	2.29e-15	3.05e-16	1.34e-17	2.77e-18
-20	7.48e-15	5.17e-15	4.75e-15	4.56e-15	3.11e-15	4.30e-16	2.07e-17	4.02e-18
0	8.03e-15	5.15e-15	5.01e-15	4.30e-15	3.02e-15	4.20e-16	2.24e-17	4.35e-18
20	6.70e-15	3.96e-15	4.10e-15	3.11e-15	2.23e-15	3.15e-16	1.86e-17	3.55e-18
38	4.19e-15	2.27e-15	2.49e-15	1.83e-15	1.33e-15	1.84e-16	1.12e-17	2.21e-18
54	7.97e-16	4.40e-16	5.57e-16	3.40e-16	2.23e-16	4.15e-17	4.79e-18	9.40e-19

Sc-45(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	2.10e-10	1.60e-10	1.82e-10	1.31e-10	9.84e-11	6.24e-11	2.52e-11	1.57e-11
-38	2.21e-10	1.65e-10	2.05e-10	1.31e-10	9.79e-11	8.58e-11	3.67e-11	2.48e-11
-20	2.87e-10	2.07e-10	2.62e-10	1.62e-10	1.22e-10	1.08e-10	4.79e-11	3.30e-11
0	3.05e-10	2.09e-10	2.76e-10	1.55e-10	1.18e-10	1.07e-10	5.15e-11	3.49e-11
20	2.57e-10	1.59e-10	2.28e-10	1.08e-10	8.82e-11	8.28e-11	4.33e-11	2.88e-11
38	1.75e-10	1.02e-10	1.55e-10	6.91e-11	5.67e-11	5.39e-11	3.03e-11	1.94e-11
54	1.33e-10	5.85e-11	1.08e-10	4.62e-11	4.48e-11	3.33e-11	1.96e-11	1.13e-11

TABLE XVIII (cont.)

Ti-46(N,P)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.63e-12	1.43e-12	1.24e-12	1.18e-12	6.82e-13	1.19e-13	9.27e-15	2.17e-15
-38	7.02e-12	5.06e-12	4.45e-12	4.58e-12	3.11e-12	4.25e-13	2.07e-14	4.78e-15
-20	1.02e-11	7.02e-12	6.50e-12	6.19e-12	4.22e-12	5.98e-13	3.17e-14	6.97e-15
0	1.09e-11	7.00e-12	6.85e-12	5.84e-12	4.09e-12	5.84e-13	3.43e-14	7.51e-15
20	9.10e-12	5.38e-12	5.60e-12	4.22e-12	3.03e-12	4.39e-13	2.85e-14	6.13e-15
38	5.69e-12	3.09e-12	3.41e-12	2.48e-12	1.81e-12	2.56e-13	1.73e-14	3.80e-15
54	1.10e-12	6.08e-13	7.74e-13	4.69e-13	3.08e-13	5.91e-14	7.40e-15	1.63e-15

Cr-50(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.46e-10	1.10e-10	1.27e-10	9.06e-11	6.89e-11	4.51e-11	1.81e-11	1.12e-11
-38	1.35e-10	1.00e-10	1.35e-10	7.89e-11	6.20e-11	6.24e-11	2.65e-11	1.78e-11
-20	1.69e-10	1.22e-10	1.68e-10	9.47e-11	7.53e-11	7.84e-11	3.46e-11	2.36e-11
0	1.80e-10	1.23e-10	1.77e-10	9.00e-11	7.27e-11	7.79e-11	3.71e-11	2.50e-11
20	1.51e-10	9.17e-11	1.46e-10	6.14e-11	5.42e-11	6.01e-11	3.12e-11	2.06e-11
38	1.06e-10	6.04e-11	1.01e-10	3.99e-11	3.55e-11	3.92e-11	2.18e-11	1.39e-11
54	9.35e-11	3.92e-11	7.71e-11	3.14e-11	3.15e-11	2.42e-11	1.42e-11	8.16e-12

Mn-55(N,2N)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	5.75e-14	5.04e-14	4.37e-14	4.20e-14	2.41e-14	4.07e-15	2.91e-16	6.03e-17
-38	2.52e-13	1.81e-13	1.58e-13	1.64e-13	1.12e-13	1.49e-14	6.54e-16	1.35e-16
-20	3.64e-13	2.52e-13	2.31e-13	2.22e-13	1.51e-13	2.09e-14	1.01e-15	1.96e-16
0	3.91e-13	2.51e-13	2.44e-13	2.09e-13	1.47e-13	2.04e-14	1.09e-15	2.12e-16
20	3.26e-13	1.93e-13	1.99e-13	1.51e-13	1.09e-13	1.53e-14	9.06e-16	1.73e-16
38	2.04e-13	1.10e-13	1.21e-13	8.90e-14	6.49e-14	8.95e-15	5.46e-16	1.08e-16
54	3.88e-14	2.14e-14	2.71e-14	1.65e-14	1.09e-14	2.02e-15	2.33e-16	4.58e-17

Ni-58(N,P)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.94e-11	1.68e-11	1.54e-11	1.38e-11	8.09e-12	1.82e-12	2.42e-13	8.94e-14
-38	7.22e-11	5.24e-11	4.92e-11	4.68e-11	3.17e-11	5.54e-12	5.11e-13	1.85e-13
-20	1.04e-10	7.30e-11	7.18e-11	6.35e-11	4.32e-11	7.80e-12	7.63e-13	2.70e-13
0	1.12e-10	7.31e-11	7.58e-11	6.03e-11	4.19e-11	7.63e-12	8.27e-13	2.88e-13
20	9.36e-11	5.62e-11	6.19e-11	4.35e-11	3.10e-11	5.73e-12	6.87e-13	2.35e-13
38	5.85e-11	3.25e-11	3.77e-11	2.56e-11	1.85e-11	3.35e-12	4.25e-13	1.46e-13
54	1.33e-11	7.50e-12	9.89e-12	5.66e-12	3.73e-12	9.22e-13	1.90e-13	6.51e-14

TABLE XVIII (cont.)

Fe-54(N,P)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.42e-11	1.23e-11	1.12e-11	1.02e-11	5.93e-12	1.28e-12	1.56e-13	5.30e-14
-38	5.40e-11	3.91e-11	3.64e-11	3.50e-11	2.37e-11	4.00e-12	3.36e-13	1.12e-13
-20	7.81e-11	5.45e-11	5.32e-11	4.75e-11	3.23e-11	5.64e-12	5.04e-13	1.64e-13
0	8.38e-11	5.46e-11	5.62e-11	4.51e-11	3.13e-11	5.52e-12	5.47e-13	1.75e-13
20	7.00e-11	4.19e-11	4.59e-11	3.25e-11	2.31e-11	4.14e-12	4.54e-13	1.43e-13
38	4.37e-11	2.42e-11	2.80e-11	1.91e-11	1.38e-11	2.42e-12	2.79e-13	8.82e-14
54	9.75e-12	5.49e-12	7.20e-12	4.15e-12	2.73e-12	6.48e-13	1.23e-13	3.87e-14

Fe-58(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.27e-10	9.51e-11	1.12e-10	7.95e-11	6.37e-11	4.53e-11	1.84e-11	1.16e-11
-38	6.85e-11	5.56e-11	7.29e-11	4.27e-11	3.52e-11	5.63e-11	2.61e-11	1.81e-11
-20	7.91e-11	6.00e-11	8.17e-11	4.61e-11	4.05e-11	6.92e-11	3.36e-11	2.39e-11
0	8.33e-11	5.80e-11	8.53e-11	4.18e-11	3.87e-11	6.88e-11	3.61e-11	2.53e-11
20	7.02e-11	4.21e-11	7.04e-11	2.72e-11	2.88e-11	5.32e-11	3.04e-11	2.09e-11
38	5.13e-11	2.78e-11	5.21e-11	1.79e-11	1.93e-11	3.53e-11	2.15e-11	1.42e-11
54	7.39e-11	2.15e-11	5.93e-11	1.99e-11	2.66e-11	2.38e-11	1.42e-11	8.33e-12

Co-59(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	6.48e-09	4.60e-09	5.83e-09	4.01e-09	3.70e-09	3.26e-09	1.39e-09	8.97e-10
-38	8.07e-10	8.25e-10	1.29e-09	5.66e-10	7.67e-10	3.61e-09	1.88e-09	1.38e-09
-20	4.92e-10	4.12e-10	7.87e-10	3.05e-10	7.48e-10	4.31e-09	2.39e-09	1.81e-09
0	4.69e-10	3.26e-10	7.91e-10	2.20e-10	6.97e-10	4.29e-09	2.56e-09	1.91e-09
20	3.97e-10	2.05e-10	6.62e-10	1.13e-10	5.31e-10	3.34e-09	2.16e-09	1.58e-09
38	4.20e-10	1.62e-10	7.14e-10	9.29e-11	3.80e-10	2.26e-09	1.55e-09	1.08e-09
54	3.10e-09	4.38e-10	2.48e-09	6.24e-10	1.37e-09	1.66e-09	1.06e-09	6.40e-10

Th-232(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.86e-11	1.60e-11	1.50e-11	1.31e-11	7.74e-12	1.96e-12	3.03e-13	1.21e-13
-38	6.35e-11	4.62e-11	4.52e-11	4.09e-11	2.77e-11	5.56e-12	6.29e-13	2.46e-13
-20	9.19e-11	6.46e-11	6.59e-11	5.58e-11	3.78e-11	7.83e-12	9.33e-13	3.58e-13
0	9.86e-11	6.50e-11	6.97e-11	5.32e-11	3.67e-11	7.67e-12	1.01e-12	3.83e-13
20	8.23e-11	4.99e-11	5.70e-11	3.83e-11	2.71e-11	5.76e-12	8.40e-13	3.12e-13
38	5.14e-11	2.90e-11	3.48e-11	2.25e-11	1.61e-11	3.36e-12	5.23e-13	1.94e-13
54	1.29e-11	7.32e-12	9.82e-12	5.47e-12	3.61e-12	9.98e-13	2.37e-13	8.75e-14

TABLE XVIII (cont.)

Th-232(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	4.89e-09	3.61e-09	4.33e-09	3.05e-09	2.56e-09	1.97e-09	8.18e-10	5.20e-10
-38	2.32e-09	1.89e-09	2.50e-09	1.45e-09	1.24e-09	2.36e-09	1.14e-09	8.10e-10
-20	2.69e-09	2.02e-09	2.75e-09	1.57e-09	1.43e-09	2.88e-09	1.46e-09	1.07e-09
0	2.83e-09	1.96e-09	2.88e-09	1.43e-09	1.37e-09	2.86e-09	1.57e-09	1.12e-09
20	2.38e-09	1.42e-09	2.38e-09	9.32e-10	1.02e-09	2.22e-09	1.32e-09	9.29e-10
38	1.72e-09	9.33e-10	1.76e-09	6.09e-10	6.79e-10	1.48e-09	9.38e-10	6.32e-10
54	2.70e-09	7.21e-10	2.19e-09	7.01e-10	1.03e-09	1.02e-09	6.28e-10	3.73e-10

U-233(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.69e-08	1.28e-08	1.48e-08	1.06e-08	8.21e-09	5.50e-09	2.22e-09	1.39e-09
-38	1.55e-08	1.18e-08	1.46e-08	9.43e-09	7.13e-09	7.29e-09	3.20e-09	2.20e-09
-20	1.99e-08	1.45e-08	1.83e-08	1.16e-08	8.87e-09	9.12e-09	4.17e-09	2.92e-09
0	2.12e-08	1.45e-08	1.93e-08	1.09e-08	8.59e-09	9.07e-09	4.47e-09	3.08e-09
20	1.78e-08	1.09e-08	1.59e-08	7.48e-09	6.39e-09	6.99e-09	3.76e-09	2.54e-09
38	1.21e-08	5.90e-09	1.09e-08	4.70e-09	4.08e-09	4.57e-09	2.64e-09	1.72e-09
54	1.03e-08	3.88e-09	8.41e-09	3.24e-09	3.58e-09	2.90e-09	1.72e-09	1.00e-09

U-233(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	2.05e-09	1.55e-09	1.80e-09	1.29e-09	1.01e-09	7.07e-10	2.88e-10	1.81e-10
-38	1.54e-09	1.20e-09	1.52e-09	9.42e-10	7.34e-10	9.06e-10	4.11e-10	2.85e-10
-20	1.92e-09	1.42e-09	1.85e-09	1.11e-09	8.88e-10	1.12e-09	5.33e-10	3.77e-10
0	2.04e-09	1.40e-09	1.94e-09	1.04e-09	8.57e-10	1.12e-09	5.72e-10	3.98e-10
20	1.71e-09	1.04e-09	1.60e-09	6.97e-10	6.38e-10	8.63e-10	4.81e-10	3.29e-10
38	1.19e-09	6.71e-10	1.12e-09	4.47e-10	4.15e-10	5.68e-10	3.39e-10	2.23e-10
54	1.22e-09	4.24e-10	1.00e-09	3.66e-10	4.36e-10	3.72e-10	2.23e-10	1.30e-10

U-235(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.37e-08	1.03e-08	1.20e-08	8.58e-09	6.75e-09	4.69e-09	1.91e-09	1.20e-09
-38	1.09e-08	8.44e-09	1.05e-08	6.70e-09	5.17e-09	6.04e-09	2.72e-09	1.89e-09
-20	1.39e-08	1.02e-08	1.30e-08	8.04e-09	6.34e-09	7.51e-09	3.53e-09	2.50e-09
0	1.47e-08	1.01e-08	1.36e-08	7.55e-09	6.13e-09	7.47e-09	3.79e-09	2.64e-09
20	1.24e-08	7.52e-09	1.12e-08	5.13e-09	4.56e-09	5.77e-09	3.19e-09	2.18e-09
38	8.48e-09	4.80e-09	7.79e-09	3.25e-09	2.93e-09	3.79e-09	2.24e-09	1.47e-09
54	8.14e-09	2.85e-09	6.64e-09	2.45e-09	2.89e-09	2.46e-09	1.47e-09	8.62e-10

TABLE XVIII (cont.)

U-235(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	5.56e-09	4.15e-09	4.90e-09	3.48e-09	2.83e-09	2.07e-09	8.53e-10	5.39e-10
-38	3.34e-09	2.66e-09	3.43e-09	2.06e-09	1.67e-09	2.55e-09	1.20e-09	8.43e-10
-20	4.01e-09	3.00e-09	3.98e-09	2.33e-09	1.97e-09	3.14e-09	1.55e-09	1.11e-09
0	4.24e-09	2.94e-09	4.18e-09	2.15e-09	1.89e-09	3.12e-09	1.66e-09	1.17e-09
20	3.57e-09	2.15e-09	3.45e-09	1.42e-09	1.41e-09	2.42e-09	1.40e-09	9.70e-10
38	2.53e-09	1.40e-09	2.49e-09	9.21e-10	9.30e-10	1.60e-09	9.89e-10	6.59e-10
54	3.20e-09	9.79e-10	2.60e-09	8.91e-10	1.18e-09	1.08e-09	6.57e-10	3.87e-10

U-238(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.97e-11	6.81e-11	6.46e-11	5.58e-11	3.32e-11	8.67e-12	1.44e-12	6.00e-13
-38	2.66e-10	1.94e-10	1.91e-10	1.71e-10	1.16e-10	2.41e-11	2.94e-12	1.21e-12
-20	3.85e-10	2.71e-10	2.79e-10	2.34e-10	1.58e-10	3.39e-11	4.33e-12	1.75e-12
0	4.13e-10	2.73e-10	2.95e-10	2.23e-10	1.54e-10	3.33e-11	4.70e-12	1.87e-12
20	3.45e-10	2.09e-10	2.41e-10	1.60e-10	1.14e-10	2.50e-11	3.90e-12	1.53e-12
38	2.15e-10	1.22e-10	1.47e-10	9.43e-11	6.76e-11	1.46e-11	2.44e-12	9.43e-13
54	5.51e-11	3.13e-11	4.23e-11	2.34e-11	1.55e-11	4.44e-12	1.12e-12	4.35e-13

U-238(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	4.98e-09	3.66e-09	4.43e-09	3.11e-09	2.64e-09	2.07e-09	8.63e-10	5.50e-10
-38	2.16e-09	1.78e-09	2.37e-09	1.36e-09	1.18e-09	2.45e-09	1.20e-09	8.54e-10
-20	2.45e-09	1.86e-09	2.55e-09	1.44e-09	1.35e-09	2.98e-09	1.53e-09	1.12e-09
0	2.58e-09	1.79e-09	2.66e-09	1.30e-09	1.29e-09	2.96e-09	1.64e-09	1.19e-09
20	2.17e-09	1.29e-09	2.20e-09	8.43e-10	9.63e-10	2.30e-09	1.38e-09	9.80e-10
38	1.59e-09	8.53e-10	1.65e-09	5.54e-10	6.45e-10	1.53e-09	9.84e-10	6.67e-10
54	2.71e-09	6.90e-10	2.19e-09	6.88e-10	1.05e-09	1.07e-09	6.62e-10	3.94e-10

Np-237(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	8.40e-10	6.72e-10	7.09e-10	5.48e-10	3.56e-10	1.46e-10	4.36e-11	2.46e-11
-38	2.12e-09	1.53e-09	1.67e-09	1.32e-09	9.10e-10	3.10e-10	7.79e-11	4.54e-11
-20	3.04e-09	2.13e-09	2.41e-09	1.80e-09	1.24e-09	4.28e-10	1.10e-10	6.39e-11
0	3.27e-09	2.17e-09	2.56e-09	1.74e-09	1.21e-09	4.23e-10	1.19e-10	6.81e-11
20	2.73e-09	1.65e-09	2.09e-09	1.24e-09	8.97e-10	3.20e-10	9.93e-11	5.57e-11
38	1.72e-09	9.85e-10	1.29e-09	7.35e-10	5.35e-10	1.91e-10	6.47e-11	3.56e-11
54	5.86e-10	3.27e-10	4.74e-10	2.41e-10	1.73e-10	7.80e-11	3.41e-11	1.78e-11

TABLE XVIII (cont.)

Pu-239(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.21e-08	9.09e-09	1.06e-08	7.59e-09	5.98e-09	4.17e-09	1.69e-09	1.06e-09
-38	1.05e-08	8.04e-09	9.83e-09	6.46e-09	4.91e-09	5.39e-09	2.42e-09	1.68e-09
-20	1.37e-08	9.92e-09	1.24e-08	7.94e-09	6.13e-09	6.72e-09	3.13e-09	2.22e-09
0	1.45e-08	9.92e-09	1.30e-08	7.52e-09	5.94e-09	6.69e-09	3.37e-09	2.35e-09
20	1.22e-08	7.44e-09	1.07e-08	5.17e-09	4.42e-09	5.16e-09	2.83e-09	1.94e-09
38	8.22e-09	4.69e-09	7.30e-09	3.23e-09	2.81e-09	3.38e-09	1.99e-09	1.31e-09
54	7.16e-09	2.58e-09	5.84e-09	2.20e-09	2.56e-09	2.18e-09	1.30e-09	7.64e-10

Pu-239(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.68e-09	5.67e-09	6.82e-09	4.80e-09	4.03e-09	3.11e-09	1.29e-09	8.21e-10
-38	3.30e-09	2.73e-09	3.70e-09	2.07e-09	1.82e-09	3.71e-09	1.80e-09	1.28e-09
-20	3.68e-09	2.81e-09	3.97e-09	2.16e-09	2.05e-09	4.52e-09	2.31e-09	1.68e-09
0	3.86e-09	2.69e-09	4.14e-09	1.93e-09	1.96e-09	4.50e-09	2.47e-09	1.77e-09
20	3.25e-09	1.91e-09	3.42e-09	1.22e-09	1.46e-09	3.48e-09	2.08e-09	1.47e-09
38	2.42e-09	1.28e-09	2.59e-09	8.14e-10	9.86e-10	2.33e-09	1.48e-09	9.98e-10
54	4.24e-09	1.09e-09	3.44e-09	1.08e-09	1.63e-09	1.61e-09	9.92e-10	5.89e-10

Pu-240(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	9.83e-10	7.86e-10	8.32e-10	6.40e-10	4.19e-10	1.78e-10	5.62e-11	3.22e-11
-38	2.31e-09	1.67e-09	1.84e-09	1.43e-09	9.90e-10	3.59e-10	9.71e-11	5.76e-11
-20	3.29e-09	2.31e-09	2.63e-09	1.94e-09	1.35e-09	4.91e-10	1.36e-10	8.04e-11
0	3.53e-09	2.35e-09	2.79e-09	1.87e-09	1.31e-09	4.86e-10	1.47e-10	8.55e-11
20	2.95e-09	1.79e-09	2.28e-09	1.33e-09	9.70e-10	3.68e-10	1.22e-10	7.00e-11
38	1.86e-09	1.07e-09	1.42e-09	7.93e-10	5.82e-10	2.22e-10	8.05e-11	4.52e-11
54	6.83e-10	3.75e-10	5.56e-10	2.77e-10	2.04e-10	9.56e-11	4.40e-11	2.33e-11

Pu-240(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.32e-09	5.41e-09	6.49e-09	4.58e-09	3.82e-09	2.93e-09	1.22e-09	7.74e-10
-38	3.46e-09	2.83e-09	3.75e-09	2.17e-09	1.85e-09	3.51e-09	1.70e-09	1.20e-09
-20	3.98e-09	3.01e-09	4.12e-09	2.33e-09	2.12e-09	4.29e-09	2.18e-09	1.59e-09
0	4.19e-09	2.91e-09	4.30e-09	2.11e-09	2.03e-09	4.26e-09	2.34e-09	1.67e-09
20	3.53e-09	2.10e-09	3.56e-09	1.37e-09	1.51e-09	3.30e-09	1.97e-09	1.38e-09
38	2.57e-09	1.39e-09	2.65e-09	8.98e-10	1.01e-09	2.20e-09	1.40e-09	9.41e-10
54	4.06e-09	1.09e-09	3.29e-09	1.06e-09	1.55e-09	1.52e-09	9.36e-10	5.55e-10

TABLE XVIII (cont.)

Pu-241(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.81e-08	1.37e-08	1.59e-08	1.14e-08	9.01e-09	6.31e-09	2.57e-09	1.62e-09
-38	1.44e-08	1.11e-08	1.38e-08	8.80e-09	6.79e-09	8.09e-09	3.67e-09	2.55e-09
-20	1.82e-08	1.33e-08	1.70e-08	1.06e-08	8.34e-09	1.00e-08	4.75e-09	3.37e-09
0	1.94e-08	1.33e-08	1.79e-08	9.93e-09	8.06e-09	9.99e-09	5.10e-09	3.56e-09
20	1.62e-08	9.89e-09	1.47e-08	6.75e-09	6.00e-09	7.72e-09	4.28e-09	2.94e-09
38	1.11e-08	6.31e-09	1.02e-08	4.27e-09	3.86e-09	5.07e-09	3.02e-09	1.99e-09
54	1.08e-08	3.75e-09	8.77e-09	3.23e-09	3.85e-09	3.31e-09	1.98e-09	1.16e-09

Pu-241(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	4.62e-09	3.45e-09	4.08e-09	2.89e-09	2.35e-09	1.72e-09	7.10e-10	4.48e-10
-38	2.74e-09	2.18e-09	2.83e-09	1.69e-09	1.38e-09	2.13e-09	1.00e-09	7.01e-10
-20	3.28e-09	2.46e-09	3.27e-09	1.91e-09	1.62e-09	2.61e-09	1.29e-09	9.25e-10
0	3.47e-09	2.40e-09	3.43e-09	1.75e-09	1.56e-09	2.60e-09	1.38e-09	9.76e-10
20	2.92e-09	1.75e-09	2.83e-09	1.16e-09	1.16e-09	2.01e-09	1.16e-09	8.07e-10
38	2.08e-09	1.14e-09	2.05e-09	7.51e-10	7.66e-10	1.33e-09	8.23e-10	5.48e-10
54	2.66e-09	8.05e-10	2.16e-09	7.36e-10	9.79e-10	9.00e-10	5.47e-10	3.22e-10

Am-241(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	7.58e-10	6.12e-10	6.38e-10	5.00e-10	3.27e-10	1.36e-10	4.12e-11	2.36e-11
-38	1.88e-09	1.36e-09	1.46e-09	1.18e-09	8.15e-10	2.75e-10	7.02e-11	4.16e-11
-20	2.69e-09	1.89e-09	2.10e-09	1.61e-09	1.11e-09	3.76e-10	9.75e-11	5.77e-11
0	2.89e-09	1.92e-09	2.22e-09	1.54e-09	1.08e-09	3.72e-10	1.05e-10	6.13e-11
20	2.41e-09	1.46e-09	1.82e-09	1.10e-09	7.98e-10	2.82e-10	8.80e-11	5.03e-11
38	1.52e-09	8.68e-10	1.13e-09	6.52e-10	4.78e-10	1.70e-10	5.82e-11	3.26e-11
54	5.19e-10	2.78e-10	4.16e-10	2.08e-10	1.55e-10	7.20e-11	3.21e-11	1.70e-11

Am-241(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	1.61e-08	1.21e-08	1.42e-08	1.01e-08	8.12e-09	5.87e-09	2.41e-09	1.52e-09
-38	1.02e-08	8.05e-09	1.04e-08	6.26e-09	5.03e-09	7.32e-09	3.41e-09	2.38e-09
-20	1.23e-08	9.18e-09	1.22e-08	7.13e-09	5.96e-09	9.01e-09	4.39e-09	3.14e-09
0	1.30e-08	9.00e-09	1.28e-08	6.59e-09	5.73e-09	8.96e-09	4.72e-09	3.32e-09
20	1.09e-08	6.60e-09	1.05e-08	4.36e-09	4.27e-09	6.93e-09	3.97e-09	2.74e-09
38	7.74e-09	4.30e-09	7.56e-09	2.83e-09	2.81e-09	4.59e-09	2.81e-09	1.86e-09
54	9.36e-09	2.95e-09	7.63e-09	2.65e-09	3.41e-09	3.07e-09	1.86e-09	1.09e-09

TABLE XIX

REACTION RATE RATIOS (TABLE XVII DIVIDED BY TABLE XVIII)

B-10(N,A)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.83	0.83	0.84	0.83	0.82	0.83	1.02	0.83
-38	0.91	0.90	0.91	0.90	0.89	0.83	1.10	0.82
-20	0.92	0.91	0.92	0.91	0.89	0.83	1.15	0.82
0	0.92	0.92	0.92	0.92	0.90	0.83	1.13	0.82
20	0.93	0.93	0.93	0.94	0.91	0.84	1.14	0.82
38	0.93	0.94	0.93	0.95	0.92	0.85	1.12	0.83
54	0.85	0.92	0.88	0.90	0.87	0.86	1.05	0.85

Li-6(N,A)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.86	0.85	0.87	0.85	0.85	0.85	1.05	0.85
-38	0.94	0.92	0.91	0.93	0.92	0.85	1.12	0.84
-20	0.94	0.93	0.95	0.93	0.92	0.85	1.15	0.84
0	0.95	0.94	0.95	0.94	0.93	0.86	1.15	0.84
20	0.95	0.95	0.96	0.96	0.93	0.86	1.16	0.85
38	0.95	0.96	0.96	0.96	0.94	0.87	1.15	0.86
54	0.88	0.94	0.91	0.92	0.89	0.88	1.08	0.87

Na-23(N,2N)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.93	0.96	0.93	0.93	0.94	1.03	0.94
-38	0.95	0.94	0.97	0.94	0.94	0.94	1.02	0.94
-20	0.96	0.95	0.98	0.95	0.95	0.95	1.02	0.94
0	0.96	0.96	0.99	0.96	0.95	0.95	1.03	0.94
20	0.96	0.96	0.99	0.97	0.96	0.96	1.03	0.95
38	0.96	0.96	0.99	0.97	0.96	0.96	1.04	0.95
54	0.96	0.96	0.99	0.96	0.96	0.96	1.04	0.95

Sc-45(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.90	0.90	0.92	0.90	0.89	0.89	1.08	0.89
-38	0.96	0.96	0.97	0.95	0.94	0.89	1.15	0.88
-20	0.96	0.95	0.97	0.95	0.94	0.89	1.18	0.88
0	0.96	0.96	0.97	0.96	0.94	0.89	1.18	0.88
20	0.96	0.97	0.98	0.97	0.95	0.90	1.19	0.88
38	0.97	0.97	0.98	0.98	0.96	0.91	1.18	0.89
54	0.93	0.97	0.96	0.96	0.93	0.92	1.11	0.91

TABLE XIX (cont.)

Ti-46(N,P)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.93	0.96	0.93	0.93	0.94	1.04	0.95
-38	0.95	0.94	0.97	0.94	0.94	0.94	1.03	0.94
-20	0.96	0.95	0.98	0.95	0.95	0.95	1.03	0.94
0	0.96	0.96	0.99	0.96	0.95	0.95	1.03	0.95
20	0.96	0.96	0.99	0.97	0.96	0.96	1.04	0.95
38	0.96	0.97	0.99	0.97	0.96	0.96	1.04	0.95
54	0.96	0.96	0.99	0.96	0.96	0.96	1.05	0.96

Cr-50(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.92	0.93	0.94	0.92	0.91	0.91	1.09	0.90
-38	0.96	0.98	0.97	0.97	0.94	0.90	1.15	0.88
-20	0.96	0.97	0.98	0.96	0.94	0.90	1.17	0.88
0	0.96	0.97	0.98	0.96	0.95	0.90	1.18	0.88
20	0.97	0.98	0.98	0.97	0.95	0.91	1.18	0.88
38	0.97	0.98	0.99	0.98	0.97	0.92	1.17	0.89
54	0.94	0.98	0.97	0.97	0.95	0.94	1.12	0.92

In-55(N,2N)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.93	0.96	0.93	0.93	0.94	1.03	0.94
-38	0.95	0.94	0.97	0.94	0.94	0.94	1.02	0.94
-20	0.96	0.95	0.98	0.95	0.95	0.95	1.02	0.94
0	0.96	0.96	0.99	0.96	0.95	0.95	1.03	0.94
20	0.96	0.96	0.99	0.97	0.96	0.96	1.03	0.95
38	0.96	0.96	0.99	0.97	0.96	0.96	1.04	0.95
54	0.96	0.96	0.99	0.96	0.96	0.96	1.04	0.95

Ni-58(N,P)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.94	0.97	0.93	0.93	0.94	1.08	0.97
-38	0.95	0.94	0.97	0.94	0.94	0.94	1.08	0.96
-20	0.96	0.95	0.98	0.95	0.95	0.95	1.08	0.97
0	0.96	0.96	0.99	0.96	0.95	0.96	1.09	0.97
20	0.97	0.97	1.00	0.97	0.96	0.96	1.09	0.97
38	0.96	0.97	0.99	0.97	0.96	0.97	1.10	0.98
54	0.96	0.97	0.99	0.97	0.96	0.97	1.11	0.99

TABLE XIX (cont.)

Fe-54(N,P)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.94	0.96	0.93	0.93	0.94	1.06	0.95
-38	0.95	0.94	0.97	0.94	0.94	0.94	1.06	0.96
-20	0.96	0.95	0.98	0.95	0.95	0.95	1.06	0.96
0	0.96	0.96	0.99	0.96	0.95	0.96	1.07	0.96
20	0.97	0.97	1.00	0.97	0.96	0.96	1.07	0.97
38	0.96	0.97	0.99	0.97	0.96	0.96	1.08	0.97
54	0.96	0.96	0.99	0.97	0.96	0.97	1.09	0.98
Fe-58(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.79	0.80	0.80	0.79	0.79	0.81	0.99	0.81
-38	0.88	0.87	0.87	0.87	0.85	0.80	1.06	0.80
-20	0.89	0.88	0.88	0.88	0.85	0.79	1.09	0.79
0	0.89	0.89	0.88	0.89	0.86	0.80	1.09	0.79
20	0.89	0.90	0.89	0.91	0.87	0.80	1.10	0.80
38	0.89	0.91	0.89	0.92	0.87	0.82	1.09	0.81
54	0.81	0.85	0.85	0.84	0.82	0.83	1.02	0.83
Co-59(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.75	0.74	0.75	0.74	0.74	0.77	0.97	0.78
-38	0.78	0.75	0.72	0.74	0.76	0.76	1.06	0.77
-20	0.78	0.74	0.68	0.76	0.76	0.76	1.09	0.76
0	0.79	0.76	0.68	0.80	0.76	0.76	1.09	0.77
20	0.79	0.78	0.69	0.86	0.77	0.77	1.10	0.77
38	0.80	0.81	0.72	0.84	0.78	0.78	1.08	0.78
54	0.78	0.80	0.78	0.79	0.79	0.80	1.00	0.80
Th-232(N,F)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.94	0.97	0.94	0.93	0.94	1.08	0.97
-38	0.95	0.94	0.98	0.94	0.94	0.94	1.09	0.96
-20	0.96	0.95	0.99	0.95	0.95	0.95	1.09	0.97
0	0.97	0.96	0.99	0.96	0.95	0.96	1.10	0.97
20	0.97	0.97	1.00	0.97	0.96	0.96	1.11	0.97
38	0.97	0.97	1.00	0.97	0.96	0.97	1.11	0.98
54	0.96	0.97	1.00	0.97	0.97	0.97	1.12	0.99

TABLE XIX (cont.)

Th-232(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.80	0.80	0.81	0.80	0.80	0.81	1.00	0.81
-38	0.90	0.86	0.88	0.89	0.87	0.81	1.08	0.80
-20	0.91	0.90	0.90	0.90	0.88	0.80	1.11	0.80
0	0.92	0.91	0.91	0.92	0.88	0.81	1.11	0.80
20	0.92	0.92	0.91	0.94	0.89	0.81	1.12	0.80
38	0.92	0.93	0.91	0.94	0.90	0.82	1.11	0.81
54	0.83	0.90	0.86	0.87	0.84	0.84	1.03	0.81
U-233(N,F)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.87	0.86	0.88	0.86	0.86	0.86	1.05	0.86
-38	0.94	0.93	0.94	0.93	0.92	0.86	1.13	0.85
-20	0.94	0.93	0.95	0.94	0.92	0.86	1.16	0.85
0	0.95	0.94	0.96	0.94	0.93	0.87	1.16	0.85
20	0.95	0.95	0.96	0.96	0.94	0.87	1.17	0.85
38	0.95	0.96	0.96	0.96	0.94	0.88	1.15	0.86
54	0.89	0.95	0.92	0.93	0.90	0.89	1.08	0.88
U-233(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.85	0.85	0.86	0.85	0.84	0.85	1.04	0.85
-38	0.93	0.92	0.93	0.92	0.91	0.85	1.12	0.84
-20	0.93	0.92	0.94	0.93	0.91	0.85	1.14	0.83
0	0.94	0.93	0.94	0.94	0.92	0.85	1.15	0.84
20	0.94	0.94	0.95	0.95	0.93	0.86	1.15	0.84
38	0.94	0.95	0.95	0.96	0.93	0.87	1.14	0.85
54	0.87	0.93	0.90	0.92	0.88	0.88	1.07	0.87
U-235(N,F)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.85	0.85	0.86	0.85	0.84	0.84	1.04	0.85
-38	0.93	0.92	0.93	0.92	0.91	0.85	1.12	0.84
-20	0.94	0.93	0.94	0.93	0.92	0.85	1.14	0.83
0	0.94	0.94	0.95	0.94	0.92	0.85	1.15	0.83
20	0.95	0.95	0.95	0.96	0.93	0.86	1.15	0.84
38	0.95	0.95	0.95	0.96	0.94	0.87	1.14	0.85
54	0.88	0.94	0.91	0.92	0.88	0.88	1.07	0.87

TABLE XIX (cont.)

U-235(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.83	0.82	0.84	0.82	0.82	0.83	1.02	0.83
-38	0.91	0.90	0.90	0.90	0.89	0.83	1.10	0.82
-20	0.92	0.91	0.92	0.91	0.89	0.82	1.12	0.81
0	0.92	0.92	0.92	0.92	0.90	0.83	1.13	0.81
20	0.93	0.93	0.93	0.94	0.91	0.83	1.13	0.82
38	0.93	0.94	0.92	0.95	0.91	0.84	1.12	0.83
54	0.85	0.91	0.88	0.90	0.86	0.86	1.05	0.85

U-238(N,F)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.94	0.97	0.94	0.93	0.94	1.09	0.97
-38	0.95	0.94	0.98	0.94	0.94	0.94	1.10	0.97
-20	0.96	0.95	0.99	0.95	0.95	0.95	1.11	0.97
0	0.97	0.96	0.99	0.96	0.95	0.96	1.11	0.98
20	0.97	0.97	1.00	0.97	0.96	0.97	1.12	0.98
38	0.97	0.97	1.00	0.97	0.96	0.97	1.12	0.98
54	0.96	0.97	1.00	0.97	0.97	0.97	1.13	1.00

U-238(N,G)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.80	0.80	0.81	0.79	0.79	0.80	1.00	0.81
-38	0.89	0.88	0.87	0.88	0.86	0.80	1.08	0.80
-20	0.91	0.89	0.89	0.90	0.87	0.80	1.11	0.79
0	0.91	0.90	0.90	0.91	0.88	0.80	1.11	0.79
20	0.91	0.92	0.90	0.93	0.88	0.81	1.12	0.80
38	0.91	0.92	0.90	0.94	0.89	0.82	1.10	0.81
54	0.83	0.89	0.85	0.87	0.83	0.83	1.03	0.83

Np-237(N,F)								
z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.95	0.94	0.98	0.94	0.95	0.96	1.17	1.00
-38	0.95	0.94	0.98	0.94	0.94	0.96	1.22	0.99
-20	0.96	0.95	0.99	0.95	0.95	0.96	1.24	1.00
0	0.97	0.96	0.99	0.96	0.96	0.97	1.24	1.00
20	0.97	0.97	1.00	0.97	0.96	0.98	1.25	1.00
38	0.97	0.97	1.00	0.97	0.97	0.99	1.24	1.01
54	0.97	0.98	1.01	0.98	0.98	1.00	1.22	1.03

TABLE XIX (cont.)

Pu-239(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.85	0.85	0.86	0.85	0.84	0.84	1.04	0.85
-38	0.94	0.92	0.94	0.93	0.92	0.85	1.12	0.84
-20	0.95	0.94	0.95	0.94	0.92	0.85	1.14	0.83
0	0.95	0.94	0.96	0.95	0.93	0.85	1.15	0.84
20	0.95	0.95	0.96	0.96	0.94	0.86	1.16	0.84
38	0.95	0.96	0.96	0.97	0.94	0.87	1.14	0.85
54	0.88	0.94	0.91	0.93	0.89	0.88	1.07	0.87

Pu-239(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.80	0.80	0.81	0.80	0.79	0.81	1.00	0.81
-38	0.89	0.87	0.87	0.87	0.86	0.81	1.08	0.80
-20	0.90	0.89	0.89	0.89	0.86	0.80	1.11	0.80
0	0.90	0.89	0.89	0.90	0.87	0.80	1.11	0.80
20	0.91	0.91	0.89	0.93	0.88	0.81	1.12	0.80
38	0.90	0.92	0.89	0.93	0.89	0.82	1.10	0.81
54	0.83	0.89	0.85	0.87	0.84	0.84	1.03	0.83

Pu-240(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.96	0.94	0.98	0.94	0.95	0.97	1.19	1.00
-38	0.95	0.94	0.98	0.94	0.94	0.96	1.23	1.00
-20	0.96	0.95	0.99	0.95	0.95	0.97	1.25	1.00
0	0.97	0.96	0.99	0.96	0.96	0.97	1.25	1.00
20	0.97	0.97	1.00	0.97	0.96	0.98	1.26	1.00
38	0.97	0.97	1.00	0.97	0.97	0.99	1.26	1.01
54	0.97	0.98	1.00	0.98	0.98	1.01	1.23	1.03

Pu-240(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.81	0.80	0.82	0.80	0.80	0.81	1.01	0.82
-38	0.90	0.88	0.88	0.88	0.87	0.81	1.08	0.80
-20	0.91	0.90	0.90	0.90	0.87	0.81	1.11	0.80
0	0.91	0.90	0.90	0.91	0.88	0.81	1.11	0.80
20	0.92	0.92	0.91	0.93	0.89	0.81	1.12	0.80
38	0.91	0.92	0.90	0.94	0.90	0.83	1.11	0.81
54	0.83	0.90	0.86	0.87	0.84	0.84	1.03	0.83

TABLE XIX (cont.)

Pu-241(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.85	0.85	0.86	0.85	0.84	0.84	1.04	0.85
-38	0.93	0.92	0.93	0.92	0.91	0.85	1.11	0.84
-20	0.94	0.93	0.95	0.93	0.92	0.85	1.14	0.83
0	0.94	0.94	0.95	0.94	0.92	0.85	1.15	0.83
20	0.95	0.95	0.95	0.96	0.93	0.86	1.15	0.84
38	0.95	0.95	0.95	0.96	0.94	0.87	1.14	0.85
54	0.88	0.94	0.90	0.92	0.88	0.87	1.07	0.87

Pu-241(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.83	0.82	0.84	0.82	0.82	0.83	1.02	0.83
-38	0.91	0.90	0.90	0.90	0.89	0.83	1.10	0.82
-20	0.92	0.91	0.92	0.91	0.89	0.82	1.12	0.81
0	0.92	0.92	0.92	0.92	0.90	0.83	1.13	0.81
20	0.93	0.93	0.93	0.94	0.91	0.83	1.13	0.82
38	0.93	0.94	0.92	0.95	0.91	0.84	1.12	0.83
54	0.85	0.91	0.88	0.89	0.86	0.86	1.05	0.85

Am-241(N,F)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.94	0.93	0.96	0.93	0.93	0.94	1.13	0.94
-38	0.95	0.94	0.98	0.94	0.94	0.94	1.18	0.94
-20	0.96	0.95	0.99	0.95	0.95	0.95	1.20	0.95
0	0.97	0.96	0.99	0.96	0.95	0.95	1.20	0.95
20	0.97	0.97	1.00	0.97	0.96	0.96	1.21	0.95
38	0.97	0.97	1.00	0.97	0.97	0.97	1.20	0.96
54	0.96	0.97	0.99	0.97	0.96	0.97	1.16	0.97

Am-241(N,G)

z(cm)	2101	2402	3404	2503	2603	2704	3811	2909
-54	0.83	0.83	0.84	0.83	0.82	0.83	1.03	0.84
-38	0.92	0.90	0.91	0.91	0.89	0.83	1.10	0.82
-20	0.92	0.91	0.92	0.92	0.90	0.83	1.13	0.82
0	0.93	0.92	0.93	0.93	0.90	0.83	1.13	0.82
20	0.93	0.94	0.93	0.95	0.91	0.84	1.14	0.82
38	0.93	0.94	0.93	0.95	0.92	0.85	1.13	0.84
54	0.86	0.92	0.88	0.90	0.87	0.86	1.05	0.85

TABLE XX

BOC AND EOC FUELED CHARACTERIZER DENSITIES FOR HPC 8-DAY RUN

	2101		2401		2503		2603	
	BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
Pu-239	0.0013000	0.0012900	0.0013190	0.0013120	0.0016050	0.0015980	0.0016160	0.0016100
Pu-240	0.0001760	0.0001782	0.0001780	0.0001795	0.0002160	0.0002173	0.0002180	0.0002193
Pu-241	0.0000190	0.0000192	0.0000190	0.0000191	0.0000240	0.0000241	0.0000240	0.0000241
Pu-242	0.0000030	0.0000030	0.0000030	0.0000030	0.0000040	0.0000040	0.0000040	0.0000040
Am-241	0.0000060	0.0000060	0.0000060	0.0000060	0.0000070	0.0000070	0.0000070	0.0000070
U-235	0.0000370	0.0000366	0.0000370	0.0000367	0.0000350	0.0000348	0.0000360	0.0000358
U-238	0.0053290	0.0053210	0.0053400	0.0053350	0.0050030	0.0049990	0.0050610	0.0050580
F.P.	0.0000000	0.0000130	0.0000000	0.0000089	0.0000000	0.0000080	0.0000000	0.0000064
Act.	0.0000000	0.0000028	0.0000000	0.0000019	0.0000000	0.0000013	0.0000000	0.0000011

B. The Cycle 1 Depletion Experiment

The Cycle 1 depletion calculations were run in three parts, as indicated in the benchmark specifications:

- (1) Beginning-of-life (BOL) to beginning of Cycle 1A (BOC-1A), in which different assemblies received different exposures followed by 120 days of shutdown;
- (2) BOC-1A to EOC-1A (34.1d exposure followed by 94d shutdown);
- (3) BOC-1B to EOC-1B (101.9d exposure).

To obtain the starting model for FFTF Cycle-1A depletion (BOC-1A), a six-time step DANDE run was made to estimate explicit nuclide, fission-product lump, and individual fission-product densities. The explicit-nuclide and aggregate fission-product densities are transferred between the core neutronics and depletion modules via ZNATDN, the standard file¹ for explicit nuclide densities; the individual nonexplicit nuclide chain densities, however, remain in the depletion module and are updated in each time step.

The six time steps used in the approach to BOC-1A were selected mainly from Fig. 6 of the benchmark specifications¹³ and included irradiation times of 10, 15, 19, 24, and 32.4 full-power days, followed by a shutdown time of 120 days, which was estimated from Table 1 of the benchmark specifications. Note that Assembly No. 2607 (Fig. 6 of the benchmark specifications), which actually received 23.6 full power days, was assumed to have received 24.

The mid-core plan of the model used in the approach to BOC-1A is shown in Fig. 4 above. The exposure each assembly received is indicated by a letter of the alphabet, with the exception of those receiving 32.4 full-power days to

which no letter is assigned. Otherwise, those with a final letter "A" received 24 days; those with "B," 19 days; those with "C," 15 days; those with "D," 10 days; and those with "E," 0 days. This exposure scheme is discussed in more detail in Sec. III above and outlined in Table VII. The compositions of all other regions, above and below core, were as specified for the HPC calculations. Note that for this part of the calculation, no replacement or change in position was made for any of the assemblies, as indicated in Table A-1 of the benchmark specifications; thus, each remained in the position shown in Fig. 4 during the entire calculation for the approach to the conditions of BOC-1A. The control assembly bank was, however, positioned as indicated on p. 10 of the benchmark specifications. The reference k_{eff} at the end of this series of calculations was 0.98358. Details are shown in Table XXI.

Results for the Cycle 1 diffusion, three-dimensional, depletion calculations (DIF3D in the core calculational module of DANDE) are shown in Table XXII. Cycle 1A was run in two time steps, 17 and 17.1 days, respectively, and Cycle 1B was run in four 16.95-day time steps. A shutdown period of 94 days was assumed between EOC-1A and BOC-1B. The control assembly bank was proportionately withdrawn for intermediate time steps. The reactivity gain between sub-cycles was the sum of 0.0005 in k_{eff} for the 94-day cooling time and 0.0013 for the additional 1.3-cm control rod bank withdrawal. The final k_{eff} of 0.98353 for EOC-1B compared with 0.98358 for BOC-1A indicates the calculated reactivity loss/control bank worth to be essentially "in balance." The discrepancy amounts to only about 0.02¢/full-power day. Detailed results for Cycles 1A and 1B are shown in Tables XXIII-XXVII.

For comparison purposes, a series of two-dimensional depletion calculations was run for Cycles 1A and 1B. Core mid-plane geometry and nuclide densities were used in the two-dimensional model, and the "extrapolation distance" of the DIF3D card type 12 for representing buckling was varied to give a k_{eff} approximately equal that for the three-dimensional BOC-1A model. The resulting buckling was $4.395 \times 10^{-4}/\text{cm}^2$. Note that, as the beginning time for the Cycle-1 was taken as zero for the two-dimensional runs, the individual nuclide chains in the depletion module were all initialized; whereas the first CINDER-3 run for the three-dimensional problems was a continuation of the approach to Cycle-1 depletion. All explicit nuclide densities, including those for the fission product burnup, however, were taken from the three-dimensional BOC-1A problem.

TABLE XXI
APPROACH TO CYCLE-1A

<u>Exposure Time (Days)</u>	<u>Cooling Time (Days)</u>	<u>Rod Position (cm Withdrawn)</u>	<u>k-effective</u>
0.0	0.0	49.3	0.99898
8.4	0.0	43.2	0.99056
5.0	0.0	43.2	0.98964
4.0	0.0	43.2	0.98844
5.0	0.0	43.9	0.98768
10.0	0.0	42.6	0.98335
0.0	120.0	42.6	0.98358

TABLE XXII
CYCLE-1 RESULTS, 3-DIMENSIONAL CALCULATIONS

<u>Total Exposure (days)</u>	<u>Cooling Time (Days)</u>	<u>Rod Position (cm Withdrawn)</u>	<u>k-eff</u>	<u>Comment</u>
0.0	0.0	42.6	0.98358	BOC-1A
34.1	0.0	53.0	0.98344	EOC-1A
34.1	94.0	54.4	0.98527	BOC-1B
101.9	0.0	81.3	0.98353	EOC-1B

TABLE XXIII
AVERAGE ATOM DENSITIES FOR CYCLE-1A
(Atoms/cm³ x 10²⁴)

<u>Nucleus</u>	<u>DE1-2</u>		<u>DE1-6</u>	
	<u>BOC</u>	<u>EOC</u>	<u>BOC</u>	<u>EOC</u>
²³⁵ U	0.000038	0.000036	0.000036	0.000035
²³⁸ U	0.005579	0.005546	0.005248	0.005225
²³⁹ Pu	0.001365	0.001333	0.001660	0.001626
²⁴⁰ Pu	0.000193	0.000202	0.000235	0.000243
²⁴¹ Pu	0.000020	0.000021	0.000025	0.000026
²⁴¹ Am	0.000006	0.000006	0.000007	0.000007
¹⁴⁷ Nd	0.000000	0.000000	0.000000	0.000000
¹⁴⁸ Nd	0.000000	0.000000	0.000000	0.000000
FP	0.000030	0.000082	0.000045	0.000093

TABLE XXIV
AVERAGE ATOM DENSITIES FOR CYCLE-1B
(Atoms/cm³ x 10²⁴)

Nucleus	DE1-2		DE1-6	
	BOC	EOC	BOC	EOC
²³⁵ U	0.000036	0.000033	0.000035	0.000032
²³⁸ U	0.005546	0.005480	0.005225	0.005177
²³⁹ Pu	0.001336	0.001279	0.001628	0.001563
²⁴⁰ Pu	0.000202	0.000221	0.000243	0.000257
²⁴¹ Pu	0.000021	0.000023	0.000025	0.000027
²⁴¹ Am	0.000006	0.000006	0.000008	0.000007
¹⁴⁷ Nd	0.000000	0.1642-7	0.000000	0.1560-7
¹⁴⁸ Nd	0.000000	0.3320-7	0.000000	0.2401-7
FP	0.000082	0.000185	0.000093	0.000189

TABLE XXV
POWER DENSITY BY ZONE AT END OF CYCLE
(kw/cm³)

Zone	Average Power Density	Peak Power Density	Peak Power Location (z-plane)
DE11R	5.559E+02	7.162E+02	1.205E+02
DE1-2	5.557E+02	7.164+02	1.205E+02
DE1-3	4.721E+02	6.723E+02	1.205E+02
DE1-4	4.381E+02	6.037E+02	1.205E+02
DE1-5	5.257E+02	7.238E+02	1.205E+02
DE1-6	5.297E+02	7.256E+02	1.205E+02

TABLE XXVI
AVERAGE BURNUP
(MWD/T)

<u>Zone</u>	<u>BOC-1A</u>	<u>EOC-1A/BOC-1B</u>	<u>EOC-1B</u>
DE11R	6.871E+03	1.405E+04	2.806E+04
DE1-2	4.070E+03	1.131E+04	2.537E+04
DE1-3	3.319E+03	9.175E+03	2.090E+04
DE1-4	5.218E+03	1.069E+04	2.158E+04
DE1-5	6.471E+03	1.324E+04	2.643E+04
DE1-6	6.232E+03	1.275E+04	2.587E+04

TABLE XXVII
DETAILED FUEL COMPOSITION AT EOC

	Average Atom Density (atom/barn-cm)	
	<u>DE1-2</u>	<u>DE1-6</u>
²³⁴ U	2.118E-09	2.251E-09
²³⁵ U	3.316E-05	3.244E-05
²³⁶ U	1.334E-06	1.011E-06
²³⁸ U	5.480E-03	5.177E-03
²³⁸ Pu	2.140E-07	2.231E-07
²³⁹ Pu	1.279E-03	1.563E-03
²⁴⁰ Pu	2.206E-04	2.573E-04
²⁴¹ Pu	2.277E-05	2.692E-05
²⁴² Pu	3.516E-06	4.469E-06
²⁴¹ Am	6.043E-06	7.320E-06
^{242m} Am	3.168E-13	1.383E-13
²⁴³ Am	9.477E-08	1.016E-07
²⁴² Cm	3.425E-07	3.957E-07
²⁴³ Cm	3.186E-10	2.087E-10
²⁴⁴ Cm	3.264E-09	2.737E-09

The two-dimensional depletion results are shown in Table XXVIII. Note that the reactivity loss for the first time step shown in the table is less than the average. As indicated above, this is due to the fact that depletion, i.e., density changes for the chain nuclides before Cycle 1, was not accounted for in the CINDER chain structure for the two-dimensional runs. On the other hand, the cooling time between Cycles 1A and 1B causes a somewhat larger than average value for reactivity loss to be given for the first time step in Cycle 1B. The overall Cycle 1 reactivity loss of 10.1¢/full-power day for the two-dimensional calculations is about 6% lower than the 10.7¢/full-power day calculated for the HPC experiment in three dimensions given above.

The two-dimensional reactivity loss is consistent with calculated control rod withdrawal distance, however. Figure 8 shows the worth of the control assembly bank as calculated using the 1/3 core HPC model described above. (A few calculated points are shown using the BOC-1A full core model for comparison.) Reading a k_{eff} value of 0.99670 from the graph for a rod position of 42.6 cm, the initial withdrawn position for Cycle 1, and adding the two-dimensional calculated reactivity loss of 0.03263 for Cycle 1 result in a graph value of 1.02933 for k_{eff} . Again, from Fig. 8, this is equivalent to a rod withdrawn position of 81.0 cm, which compares favorably with the experimental 81.3 number given in the benchmark specifications. Additional two- and three-dimensional Cycle 1 depletion comparisons are given in Tables XXIX-XXXI.

Two-dimensional transport depletion calculations using the TWOHEX code were begun, but time/funding limitations did not permit completion. The first run of the series, BOC-1A, using the two-dimensional DIF3D buckling gave a k_{eff} of 0.99201, indicating a transport/diffusion "correction" of 0.0086 $\Delta k/k$. No experimental or calculational results from other laboratories for the FFTF Cycle 1 depletion experiments have been published to date. Hopefully these will be available in the near future for comparison with our results.

TABLE XXVIII
CYCLE-1 DEPLETIONS,
2-DIMENSIONAL RESULTS

Total Exposure (days)	Cooling Time (days)	k_{eff}	Reactivity Loss (Cents/FPD)
0.0	0.0	0.98355	9.3
17.0	0.0	0.97853	10.2
34.0	0.0	0.97296	--
34.0	94.0	0.97350	11.5
51.05	0.0	0.96729	10.2
68.0	0.0	0.96181	10.1
84.95	0.0	0.95636	10.2
101.0	0.0	0.95092	10.1
Cycle-1 Reactivity Loss			10.1

Note: $\beta_{eff} = 0.00318$ used in cents/FPD calculations.

Fig. 8. FFTF Control Bank Worth (no depletion).

TABLE XXIX
AVERAGE ATOM DENSITIES FOR CYCLE-1 DEPLETION,
2-DIMENSIONAL RESULTS

Nucleus	DE1-2		DE1-6	
	Density	2-D/3-D	Density	2-D/3-D
²³⁵ U	0.000033	0.993	0.000033	1.008
²³⁸ U	0.005474	0.999	0.005179	1.000
²³⁹ Pu	0.001274	0.996	0.001565	1.001
²⁴⁰ Pu	0.000221	1.000	0.000255	0.990
²⁴¹ Pu	0.000023	0.993	0.000026	0.981
²⁴¹ Am	0.000006	0.961	0.000007	0.965
FP*	0.000165	1.065	0.000142	0.986

*3-D results = EOC-1B minus BOC-1A.

TABLE XXX
POWER DENSITY AT END OF CYCLE,
2-DIMENSIONAL RESULTS

Zone	Average	2-D/3-D	Peak	2-D/3-D
	Power Density		Power Density	
DE1-1R	591.6	1.064	743.5	1.045
DE1-2	602.8	1.085	750.2	1.047
DE1-3	487.8	1.033	664.5	0.987
DE1-4	451.9	1.031	605.2	1.002
DE1-5	567.1	1.079	738.1	1.020
DE1-6	519.6	0.981	719.4	0.991

TABLE XXXI
AVERAGE BURNUP (EOC),
2-DIMENSIONAL RESULTS

Zone	MWD/T	2-D/3-D*
DE1-1R	2.239E+4	1.057
DE1-2	2.279E+4	1.078
DE1-3	1.812E+4	1.031
DE1-4	1.686E+4	1.031
DE1-5	2.132E+4	1.068
DE1-6	1.951E+4	0.993

*3-D results = EOC-1B minus BOC-1A.

SUMMARY

We have described the structure, operation, and validation of DANDE, a modular code system designed for reactor core neutronics and depletion analysis. The modules consist of standard data processing, core neutronics, and depletion codes, which are linked by standard files and which access standard data libraries, mainly based on ENDF/B-V.

To assist the user in applying DANDE, we have included detailed examples of input to each of the modules. These samples are nontrivial, but are rather detailed in that all were actually used in the FFTF validation calculations of the code system. Such a series of extensive calculations illustrates the accuracy, flexibility and speed with which DANDE can be applied in both fast and thermal reactor core design.

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