International Atomic Energy Agency

INDC(NDS)-300
Distr.: L
TSIR-21

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

REPORT ON THE SECOND INTERNATIONAL ACTIVATION CALCULATION BENCHMARK COMPARISON STUDY

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February 1994

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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ABSTRACT

An activation comparison study was completed under the coordination of the IAEA Nuclear Data Section. It was participated by 11 regionally or internationally available computer codes developed principally for fusion reactor technology applications. A set of benchmark cross section and decay data libraries was established for all participating codes to use. Two calculations were performed for the respective targets, Cr-50 and natural iron, at a specified neutron spectrum at the first wall of a fusion reactor. The irradiation time was set for one year continuously for both cases. The results were compared and discussed.

February 1994

I. Introduction

Under the coordination of the Nuclear Data Section of the International Atomic Energy Agency, a comparison study was completed in 1990 [Ref. 1] on activation calculations for 11 elements using the spectrum produced at the first wall of a fusion reactor. The participants of the comparison study were requested to perform activation calculations using the regionally available activation cross section and decay data libraries, as well as activation calculation computer codes.

The second activation calculation benchmark comparison study was conducted according to the recommendation made at the IAEA Consultants' Meeting on First Results of FENDL-1 Testing and start of FENDL-2, 25-28 June 1990 [Ref. 2]. The procedures of the comparison study adopted were:

(1) Dr. R.A. Forrest (Cuhlam Laboratory, UK sends to NDS/IAEA, limited cross section library, decay library, flux, and irradiation history;

(2) Dr. E.T. Cheng (TSI Research, USA) supplies NDS list of participants;

(3) Dr. A. Pachchenko (NDS, IAEA) sends to participants materials in (1);

(4) Participants send to Cheng results of calculations; and

(5) Cheng reports by the next FENDL meeting.

For the comparison study a small set of 29 nuclides and created data libraries was selected giving the decay data for each nuclide (in ENDF B/5 or 6 format) and a set of cross sections (in 100-group GAMII format). The nuclides are: H-1, H-2, H-3, HE-3, HE-4, TI-48, T1-49, V-49, V-50, V-51, CR-50, CR-51, CR-52, CR-53, CR-54, MN-53, MN-54, MN-55, MN-56, MN-57, FE-54, FE-55, FE-56, FE-57, FE-58, FE-59, CO-59, CO-60, CO-60m. These are shown in Fig.1.

These limited cross section and decay data libraries were selected primarily to test several things:

(1) multiple routes to produce a daughter nuclide;

(2) (n,t) reactions to produce tritium; and

(3) a linear pathway of (n,γ) with no (n,2n) reactions so that an analytic solution for nuclides on the path is possible.

Two runs were requested for the participants to perform:

(1) Irradiation of 1 kg of natural iron (5.8% Fe-54, 91.72% Fe-56, 2.2% Fe-57, 0.28% Fe-58) for 1 year; and

(2) Irradiation of $1x10^{25}$ atoms of Cr-50 atoms for 1 year.

The neutron spectrum flux were those employed by the first comparison study. Appendix 1 gives the detail of the reference neutron spectrum and operating conditions. The participants were requested to give number of atoms of all nuclides in the first run and in the second all non-zero numbers (only 15 nuclides have a non-zero inventory).

II. Activation Calculation Codes

The activation calculation codes included worldwide in the comparison study are:

1. FISPACT - UKAEA/Cuhlam, UK. See R.A. Forrest and D.A.J. Endacott, "FISPACT - User Manual," AERE-M-3654(1988).

2. REAC - Westinghouse/Hanford, U.S.A. See F.M. Mann," REAC*2: Users Manual and Code Description," WHC-EP-0282, Westinghouse Hanford Company, Richland, Washington (1989).

3. ACT4 - JAERI, Japan. See Y. Seki,"THIDA2: An advanced code system for calculation of Transmutations, Activation, Decay Heat and Dose Rate," JAERI 1301, Japan Atomic Energy Research Institute report, (1986).

4. RACC - ANL, U.S.A. See Jungchung Jung," Theory and Use of the Radioactivity Code RACC," ANL/FPP/TM-122, Argonne National Laboratory report (1979).

5. ACAB - Institute of Nuclear Fusion, Polytechnic University of Madrid, Madrid, Spain.

6. DKR - University of Wisconsin, Madison Wisconsin, U.S.A. See D.L. Hendersen and Osman Yasar," DKR-ICF: A Radioactivity and Dose Rate Calculation Code Package," UWFDM-714, Vols. 1 and 2 (1986).

7. FDKR - Southwestern Institute of Physics, China. See Y. Yang, K. Feng and J. Huang, "FDKR: A Radioactivity Calculation Code for Fission, Fusion and Hybrid Reactors," SWIP, China (1988).

8. ACTIVA - Baikov Institute of Metallurgy, USSR Academy of Sciences. Written by V.V. Ivanov, V.P. Kolotov, and V.V. Atrashkevich of BIM, Moscow, Russian Federation.

9. SAM - Research and Development Institute of Power Engineering, Moscow, RF. Results contributed by O. Schchipakin of RDIPE.

10. FRINDA - Kurchatov Institute of Atomic Energy, Moscow, RF. Contributed by A. Kashirskij of KIEA.

11. ANITA - Department of Energy Engineering, University of Genova, Italy. See C. Ponti and S. Stramaccia, "ANITA - Analysis of Neutron Induced Transmutation and Activation," EUR 12622 EN, Joint Research Center, Ispra, Italy (1989).

III. Participants:

1. China

   Computer Code: FDKR
   Kai-ming Feng and Jin-hua Huang, Southwestern Institute of Physics, P.O. Box 432, Chengdu, China 610041

2. Italy

   Computer Code: ANITA
   Nicola Cerullo, DINE, University of Genova, via all 'Opera Pia, 15/A, I-16145 Genova, Italy

3. Japan

   Computer Code: ACT4
   Y. Seki, Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Naka-machi, Naka-gun, Ibaraki-ken, Japan 311-01.

4. Spain

   Computer Code: ACAB
   J.M. Perlado, Institute of Nuclear Fusion, Polytechnic University of Madrid, Madrid, Spain

5. UK

   Computer Code: FISPACT
   R. Forrest, AEA Technology, Culham Laboratory, Oxfordshire, OX110RA, United Kingdom

6. USA

   Computer Code: DKR
   Hesham Khater and Mohamed Sawan, Institute of Fusion Technology, University of Wisconsin, Madison, Wisconsin, U.S.A. 53706

Computer Code: RACC
H. Attaya and M.Y. Gohar, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois U.S.A. 60439

Computer Code: REAC
F.M. Mann, Westinghouse Hanford Company, P.O. Box 1970, Richland, WA, USA 99352

7. Russian Federation

Computer Code: FRINDA
A.V. Kashirskij and D.V. Markovskij, Kurchatova Su-Moscow D-182, 123182 RF

Computer Code: ACTIVA
Vitaliy Ivanov, Baikov Institute of Metallurgy, Russian Academy of Sciences, 49 Lenincky Prospect, 117334, Moscow, RF

Computer Code: SAM
O. Schchipakin, Research and Development Institute of Power Engineering, P.O. Box 788, Moscow 101000 RF

Coordination of this comparison study was conducted by Anatoly Pashchenko, Nuclear Data Section International Atomic Energy Agency, P.O. Box 100, A-1400, Vienna, Austria; R. Forrest, AEA Technology, Cuhlam Laboratory, Oxfordshire, OX110RA, United Kingdom; and E.T. Cheng, TSI Research, Inc. 225 Stevens Avenue, Suite 203, Solana Beach, CA USA 92075.

The coordinators also received contributions from Professor Nicola Cerullo (DINE, University of Genova, genova, Italy) and Massimo Zucchetti (Joint Research Center, Ispra, Italy). Cerullo calculated the specified benchmark problems with a code, ADGS-3, developed at the University of Genova. Zucchetti performed similar calculations with the code ANITA. However, the decay data and activation cross section libraries employed for these two sets of calculations are not those provided by R. Forrest. Hence these two contributions were not included in this report because the comparison of such calculations falls outside the scope of the present study.

IV. Analytical Solution for Cr-50 Irradiation

Figure 2 shows the relevant nuclear data for the Cr isotopes. Note that the (n,2n) reactions were deliberately ignored in the test library so that an analytical solution became possible. Table 1 shows the results of the analytic solution and the values given by FISPACT. There is excellent agreement even for Cr-53 and Cr-54, the deficiencies are at the level of rounding errors. Given this agreement for the Cr isotopes it was decided to scale all the data to the FISPACT values.

V. Results of Calculations and Notes

Tables 2 and 3 summarize results of the benchmark comparison calculations. It is noted that:

1. FISPACT results were employed as the reference values because the calculations were carefully benchmarked against analytic solutions for Cr-50 by R. Forrest. The FISPACT results were found to be identified with the analytic results to 6 digits in most cases except the higher-order daughter nuclides. The agreement in the 3rd generation nuclide is to the 5th digit, and 4th generations nuclide to the 4th digit. Section V gives details of the analytical solution of the Cr-50 calculation.

2. R. Forrest suggested that the decay constants in the stable nuclides can be assumed to be 1×10^{-25} if the concentrations of the stable nuclides are not to be printed in the output for some computer codes. K. Feng noted that Forrest's suggestion works well for his FDKR calculations.

3. ACT4 calculations performed by Y. Seki employed the decay data CHAINLIB in his code package, THIDA2. Seki noted that the difference between CHAINLIB and UKDECAY.CHE is negligible. However, Forrest suggested that a large discrepancy in the results is still possible, particularly when there is a 4.3% difference in the half-life for Mn-57.

4. Ti-50 is a nuclide not shown in the reference FISPACT calculations. It is given in both DKR and IRRADIA calculations. Khater explains that this is primarily due to:

Cr-50(n,g) Cr-51(EC) V-51(n,2n) V-50(n,p) Ti-50

reaction chains as far as DKR is concerned. Note that the V-50(n,p)Ti-50 reaction was not present in the distributed library and therefore there is no route for Ti-50 production in the majority of codes.

5. Attaya noted that the natural abundances of the four iron isotopes. Fe-54. Fe-56. Fe-57 and Fe-58. given in the file "IN-CHE.FE" are slightly different from those he used. His abundance numbers are based on the information compiled by the National Nuclear Data Center at Brookhaven National Laboratory. He suggested that it be useful in the future to specify also the atomic densities for all the isotopes. This will avoid any possible differences in the results due to such discrepancies.

VI. Discussion of Results

Table 2 & 3 contain the results of the two calculations for the 11 inventory codes. These results are analyzed in the following sections to answer the questions in the introduction.

1. Production of light nuclides

The light nuclides H-1, H-2, H-3, He-3 and He-4 are produced by reactions such as (n,t) and (n,p), and once formed they will react and decay in the same way as H or He isotopes present in the starting material. Tables 2 and 3 indicate that the following codes are able to calculate production of these light nuclides: FISPACT, IRRADIA, ANITA, REAL and ACAB.

There is excellent agreement between FISPACT, ANITA and ACAB with REAC giving good agreement for H-2, H-3 and He-3, but differing by a factor of 3 for H-1 and a factor of about 12 for He-4. For the Cr irradiation, IRRIDIA differs by a factor of about 70 for H-2 and a factor of about 10 for H-3 and He-3, while giving no result for He-4. For the Fe irradiation IRRADIA differs by a factor of about 40 for H-2 while calculating the amount of the other nuclides to within about 15%.

2. Comparison with analytical calculation for Cr-50 irradiation

Section IV gives the results of the analytical calculation. In order to compare the 11 codes, Fig. 3 shows the ratio of the results for each code to the FISPACT results.

There is good agreement with the analytical values for all the 5 Cr isotopes for the following codes: FISPACT, RACC, ACAB and DKR.

ANITA is 20% low and REAC 40% low by the end of the chain, while ACT4 gives no results for Cr-53 or Cr-54. FDKR gives no result for Cr-54, while SAM and FRINDA only consider the first step reaction producing Cr-51, giving no results for Cr-52, Cr-53 and Cr-54. IRRADIA gives no values for Cr-53 or Cr-54 and the value for Cr-52 is only 4% of the analytical value. Thus only 6 of the 11 inventory codes treat multi-step reactions in any detail.

This comparison consists of a chain with only a few reactions (4). It is known that especially for heavy elements that many multi-step pathways containing 6 - 8 reactions are imported for the production of long lived radionuclides. The detailed trends of the four codes with the best agreement are considered in more detail in Fig. 4.

For both FISPACT and DKR there is no clear trend, with excellent agreement with the analytical values. For ACAB after an initial overestimation for Cr-50 and Cr-51, there is an increasing underestimation for Cr-52 through Cr-54. For RACC

there is an increasing overestimation as heavier Cr isotopes are produced. For both ACAB and RACC these errors are very small, even for Cr-54, the trends suggest that if a pathway with 6 or more reactions were considered then the error would be significant but still of little practical importance.

3. Treatment of isomeric states

A single isomeric state (Co-60m) was included in the test library. The following codes treated its production correctly: FISPACT, RACC, ACAB, DKR and ANITA.

The remaining six codes gave no result for Co-60m, however it is impossible to state whether this is a general problem with isomeric states since no values were given for Co-60 either.

In this section, the discussion has been concentrated on the results for the Cr irradiation. However, for both Cr and Fe irradiations, Tables 2 and 3 indicate very substantial differences between the predictive power of the 11 inventory codes. Table 4 shows a summary of the codes for ability to calculate light nuclide production, the comparison with the analytical calculation and the treatment of isomeric states.

VII. Conclusion and Recommendations

From this study four basic criteria can be stated for suitability of an inventory code for fusion applications.

1. Ability of the code to read standard libraries (cross section in 100 or 175 energy group format);

2. Accurate (to within about 5%) prediction of amounts of nuclides in multi-step pathways;

3. Ability to calculate light nuclide (H & He isotopes) production; and

4. Ability to treat isomeric states present in the libraries.

Based on these criteria the codes ACAB and FISPACT are suitable and satisfactory, with ANITA, DKR, RACC and REAC performing less well on at least one criterion. The remaining codes ACT4, FRINDA, ACTIVA, FDKR and SAM appear, at least on the results of the present study, to be inadequate for detailed fusion calculations.

Other criteria not tested in the correct work may need to be considered for the current generation of libraries. These include the ability of the code to use uncertainty data (available only in the EAF-3 library) and produce uncertainty

estimates on radiological responses, e.g. on total activity (currently only FISPACT), and the ability of the code to treat actinide data so that the importance of actinide impurities can be assessed. The importance of sequential changed particle reactions is under investigation and it will become necessary for inventory codes to also use such data libraries.

References:

[1] E.T. Cheng, et al., "International Fusion Activation Calculation Comparison Study," TSI Research report, TSIR-12, January 1991.

[2] IAEA Report, INDC(NDS)-241, November 1990.

Analytical and FISPACT values for ^{50}Cr irradiation

Nuclide	FISPACT value	Analytic value
^{50}Cr	9.90825 1024	9.90825 1024
^{51}Cr	1.69666 1021	1.69666 1021
^{52}Cr	4.37656 1018	4.37656 1018
^{53}Cr	1.19853 1015	1.19852 1015
^{54}Cr	6.29659 1011	6.29661 1011

Table 1
Analytical and FISPACT Values for Cr-50 Irradiation

Table 2 (1 of 2)
Results of Cr-50 Activation Calculations

Initial Quantity: 1.0 E+25
Irradiation: 1 year continuously

Nuclide	FISPACT (91/6/25)	REAC (91/9/14)	ACT4 (90/12/7)	RACC (91/7/31)	ACAB (91/1/3)	DKR (91/2/14)
H-1	7.4720E+22	0.483	-	-	0.999	-
H-2	1.5168E+21	0.993	-	-	0.999	-
H-3	8.6940E+16	0.723	-	-	0.998	-
He-3	1.6479E+15	0.656	-	-	0.998	-
He-4	1.4710E+18	0.779	-	-	0.999	-
Ti-48	5.5482E+19	0.881	0.897	0.612	0.998	1.000
Ti-49	1.1388E+22	0.999	1.005	0.957	0.999	1.000
V-49	2.6309E+22	0.999	0.995	0.960	1.000	1.000
V-50	3.8125E+22	1.000	1.011	1.000	1.000	1.000
V-51	1.4167E+22	0.999	0.980	1.000	0.999	1.000
Cr-50	9.9083E+24	1.000	1.000	1.000	1.000	1.000
Cr-51	1.6967E+21	1.000	1.001	1.000	1.000	1.000
Cr-52	4.3766E+18	0.779	1.115	1.000	1.000	1.000
Cr-53	1.1985E+15	0.712	-	1.000	0.999	1.000
Cr-54	6.2966E+11	0.614	-	1.000	0.998	1.000
Ti-50	-	-	-	-	-	4.115+19

Note: All quantities except that for Ti-50, are given relative to FISPACT calculations.

Table 2 (2 of 2)
Results of Cr-50 Activation Calculations

Initial Quality: 1.0E+25 Cr-50
Irradiation Time: 1 year contiuously

Nuclide	FISPACT (91/6/25)	FDKR (91/7/11)	IRRADIA (91/2/14)	SAM (91/2/5)	FRINDA (91/2/13)	ANITA (91/7/18)
H-1	7.4720+22	-	1.000	-	-	1.000
H-2	1.5168+21	-	7.242+1	-	-	0.999
H-3	8.6940+16	-	0.143	-	-	1.050
He-3	1.6470+15	-	9.116-2	-	-	0.939
He-4	1.4710+18	-	-	-	-	0.889
Ti-48	5.5482+19	0.988	2.176	-	-	0.965
Ti-49	1.1388+22	0.994	0.999	-	-	0.998
V-49	2.6309+22	0.999	0.998	-	1.003	1.000
V-50	3.8125+22	0.996	1.010	-	0.585	0.999
V-51	1.4167+22	0.990	0.983	-	-	0.999
Cr-50	9.9083+24	1.000	1.008	-	-	1.000
Cr-51	1.6967+21	0.993	1.008	1.060	1.009	0.999
Cr-52	4.3766+18	0.989	3.798-2	-	-	0.889
Cr-53	1.1985+15	0.916	-	-	-	0.855
Cr-54	6.2966+11	-	-	-	-	0.801
Ti-50	-	-	1.663+19	-	-	-

Note: All quantities, except that for Ti-50, are given relative to FISPACT calculations

Table 3 (1 of 2)
Results of Fe(Nat.) Activation Calculations

Initial Quantity: 1 kg Natural Iron
Irradiation Time: 1 year contiuously

Nuclide	FISPACT (91/6/26)	REAC (91/9/14)	ACT4 (90/12/7)	RACC (91/7/31)	ACAB (91/1/3)	DKR (91/2/14)
H-1	3.4057+22	0.390	-	-	0.998	-
H-2	1.0775+21	0.991	-	-	1.000	-
H-3	4.1580+18	0.983	-	-	0.998	-
He-3	3.6848+17	0.995	-	-	0.998	-
He-4	6.0757+21	0.088	-	-	0.998	-
Ti-48	7.2279+16	0.780	-	1.000	0.998	1.000
Ti-49	1.2406+17	0.895	-	0.997	0.997	0.994
V-49	2.2102+16	0.873	-	0.972	0.997	1.000
V-50	5.0494+18	0.943	-	0.984	0.997	1.000
V-51	6.7837+20	1.001	1.001	0.999	0.998	1.000
Cr-50	7.2099+18	1.001	1.004	1.000	0.998	1.000
Cr-51	8.2794+19	1.002	1.000	1.000	0.999	1.000
Cr-52	5.1715+20	0.994	0.939	0.999	0.998	0.999
Cr-53	4.7682+21	0.987	0.977	0.999	0.998	0.982
Cr-54	1.2876+21	0.992	0.974	0.918	0.998	0.998
Mn-53	5.0038+21	1.000	1.003	0.982	0.998	1.000
Mn-54	2.5656+21	0.996	0.972	0.998	0.998	1.000
Mn-55	1.8048+22	0.994	1.244	0.943	0.998	0.999
Mn-56	6.2759+18	0.998	0.993	0.998	0.999	0.998
Mn-57	8.9639+14	1.000	0.906	1.000	0.999	0.999
Fe-54	6.1518+23	1.002	0.999	1.000	0.999	-
Fe-55	5.1307+22	1.002	1.633	1.000	0.998	0.999
Fe-56	9.8065+24	1.000	0.995	1.000	0.999	-
Fe-57	2.4706+23	1.004	1.009	1.000	0.999	-
Fe-58	3.0114+22	1.003	0.999	1.000	0.999	-
Fe-59	3.0930+18	1.003	0.981	1.000	0.999	0.999
Co-59	1.4319+19	0.156	1.000	1.000	0.998	1.000
Co-60	9.4662+15	-	-	1.000	0.997	1.001
Co-60m	3.3747+11	-	-	1.000	0.998	1.000
Ti-50	-	-	-	-	-	
3.5182+15						

Note: All quantities, except that for Ti-50, are given relative to FISPACT calculations.

Table 3 (2 of 2)
Results of Fe(Nat.) Activation Calculation

Initial Quantity: 1 kg Natural Iron
Irradiation Time: 1 year continously

Nuclide	FISPACT (91/6/26)	FDKR (91/7/11)	IRRADIA (91/2/14)	SAM (91/2/5)	FRINDA (91/2/13)	ANITA (91/7/18)
H-1	3.4057+22	-	1.004	-	-	0.999
H-2	1.0775+21	-	43.54	-	-	0.999
H-3	4.1580+18	-	0.854	-	-	0.995
He-3	3.6848+17	-	1.052	-	-	1.001
He-4	6.0757+21	-	0.997	-	-	0.999
Ti-48	7.2279+16	-	0.848	-	-	0.889
Ti-49	1.2406+17	0.02	1.044	-	-	0.972
V-49	2.2102+16	0.527	1.485	-	-	0.953
V-50	5.0494+18	0.966	0.982	-	-	0.974
V-51	6.7837+20	0.996	1.036	-	-	0.999
Cr-50	7.2099+18	0.998	1.037	-	1.013	0.999
Cr-51	8.2794+19	1.000	1.037	1.053	1.016	0.999
Cr-52	5.1715+20	0.934	0.973	-	0.946	0.998
Cr-53	4.7682+21	0.991	0.998	-	1.004	0.999
Cr-54	1.2876+21	0.973	1.020	-	0.814	0.999
Mn-53	5.0038+21	0.995	1.037	-	1.012	0.999
Mn-54	2.5656+21	0.976	1.023	1.021	0.983	0.998
Mn-55	1.8048+22	0.993	0.620	-	0.622	0.999
Mn-56	6.2759+18	0.987	0.995	1.002	1.006	1.000
Mn-57	8.9639+14	0.994	0.932	0.909	0.961	0.999
Fe-54	6.1518+23	1.000	1.034	-	-	1.000
Fe-55	5.1307+22	0.993	1.000	1.000	1.010	0.999
Fe-56	9.8065+24	0.993	0.995	-	2.32-4	1.000
Fe-57	2.4706+23	0.996	0.980	-	0.051	1.000
Fe-58	3.0114+22	0.992	0.963	-	7.83-3	1.000
Fe-59	3.0930+18	0.991	0.949	0.989	1.002	1.000
Co-59	1.4319+19	0.990	0.452	-	-	0.999
Co-60	9.4662+15	-	-	-	-	0.974
Co-60m	3.3747+11	-	-	-	-	0.975

Note: All quantities are given relative to FISPACT calculations.

Table 4. Abilities of codes

Code	Light Nuclide Production*	Closeness to Analytical Values**	Treatment of Isomeric States***
ACAB	3	3	1
ACT4	0	0	0
ANITA	3	2	1
DKR	0	4	1
FDKR	0	1	0
FISPACT	3	4	1
FRINDA	0	0	0
IRADIA	1	0	0
RACC	0	3	1
REAC	2	2	0
SAM	0	0	0

* 3 - excellent agreement, 0 - no light nuclide production
** 4 - excellent agreement, 0 - 1 or more Cr isotopes have no values
*** 1 - treatment of isomeric, 0 - no treatment

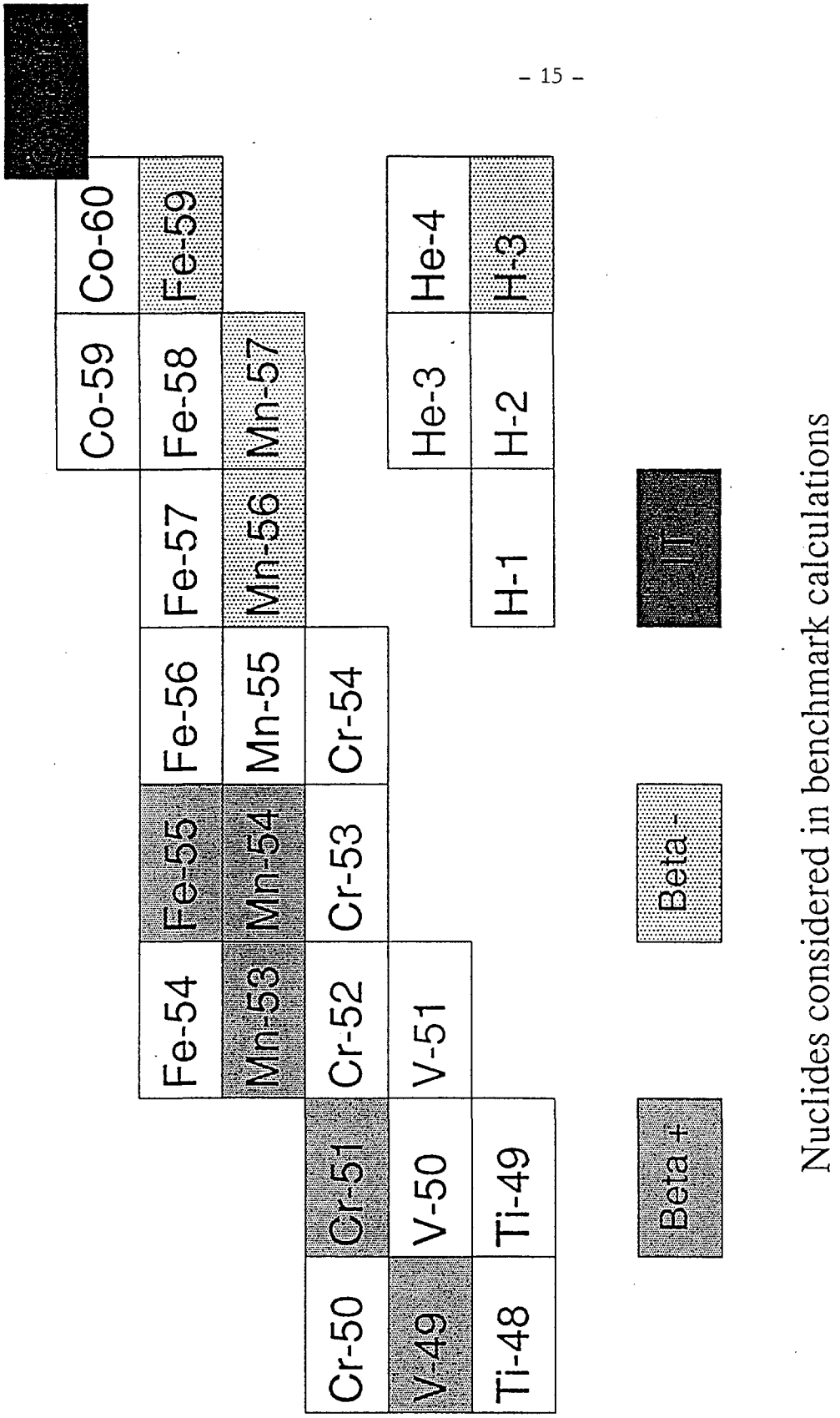

Fig. 1. Nuclides Considered in Benchmark Calculations

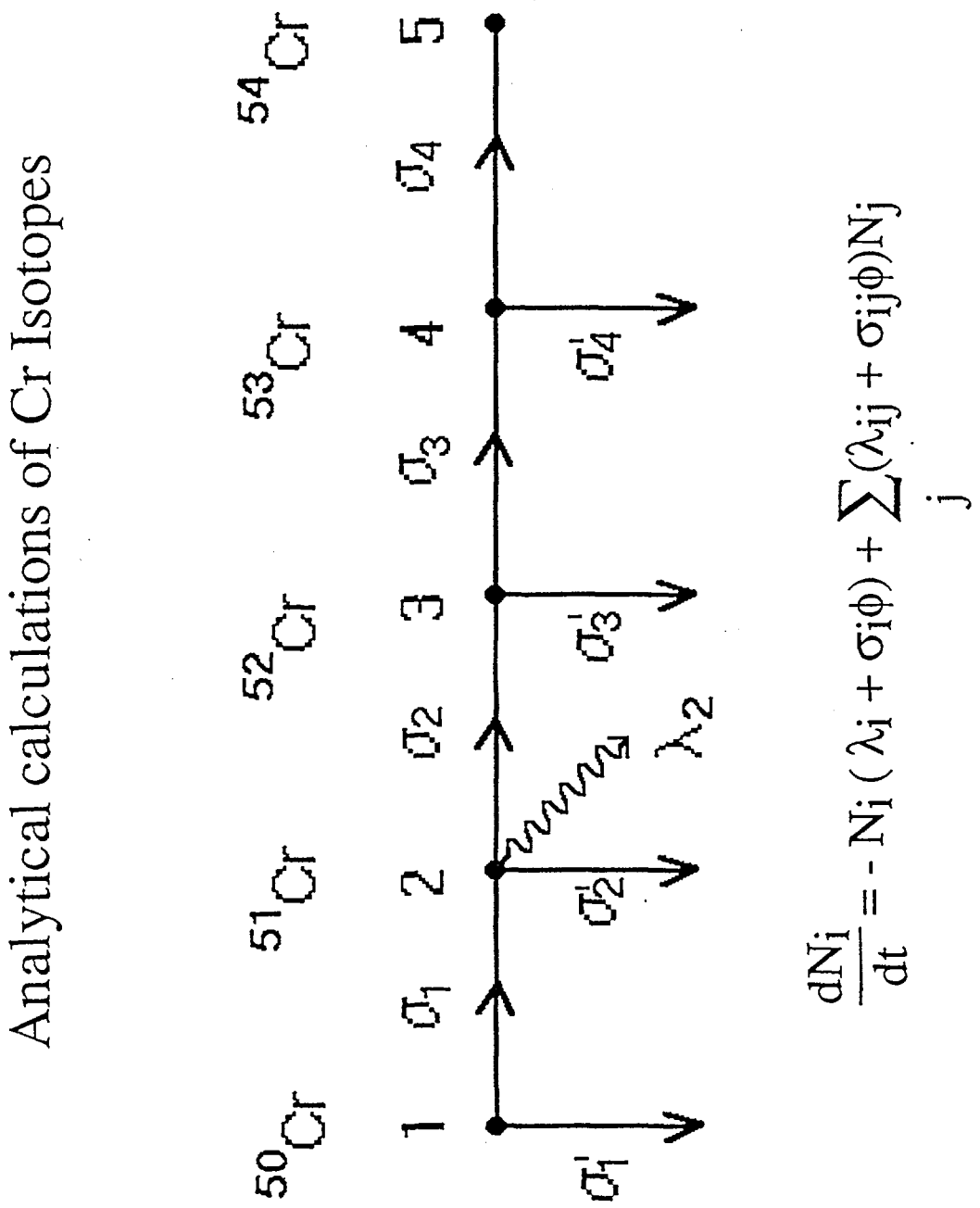

Fig. 2. Analytical Calculations of Cr Isotopes

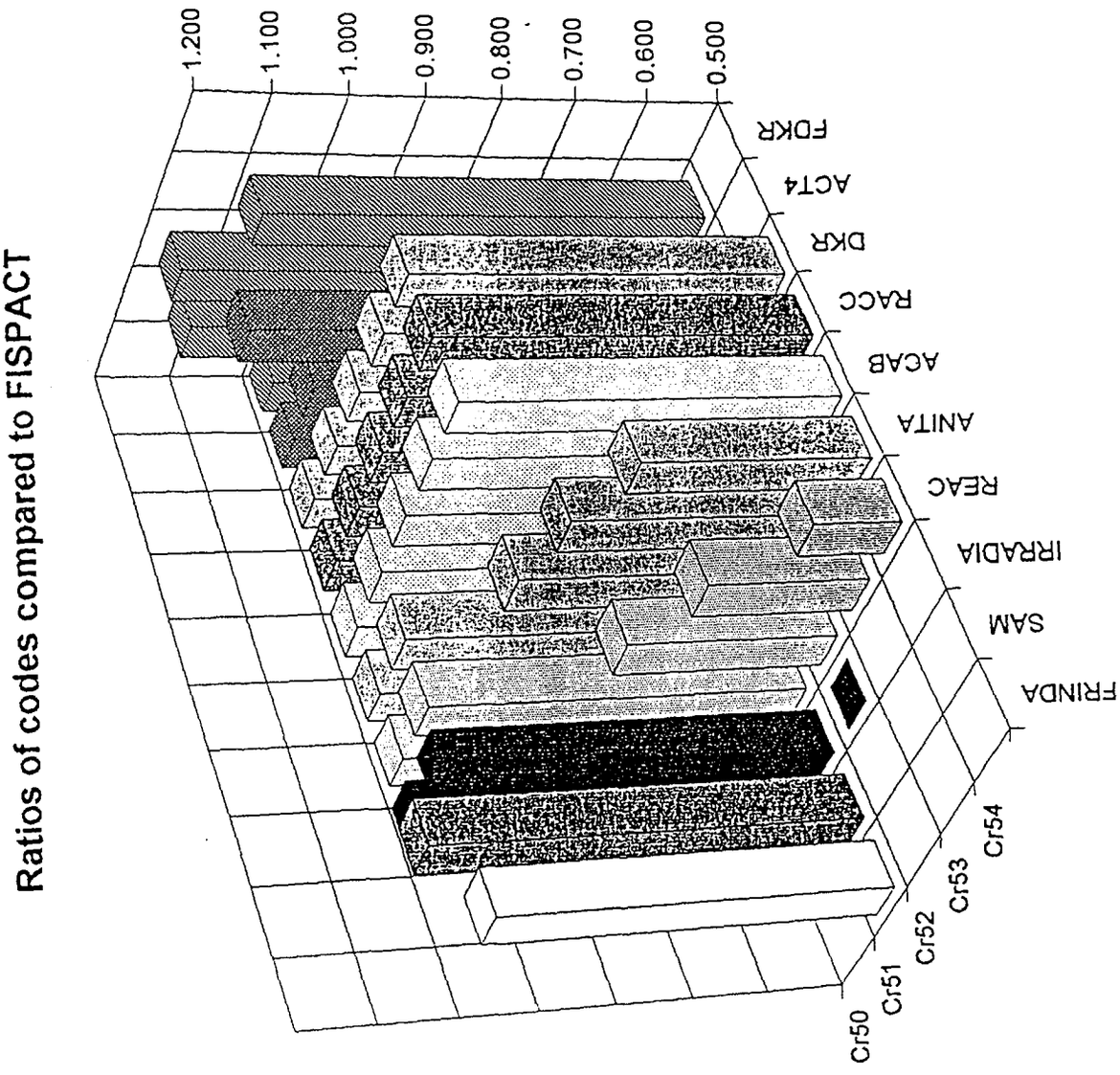

Fig. 3. Ratios of Chromium Isotopes from Codes to FISPACT Results

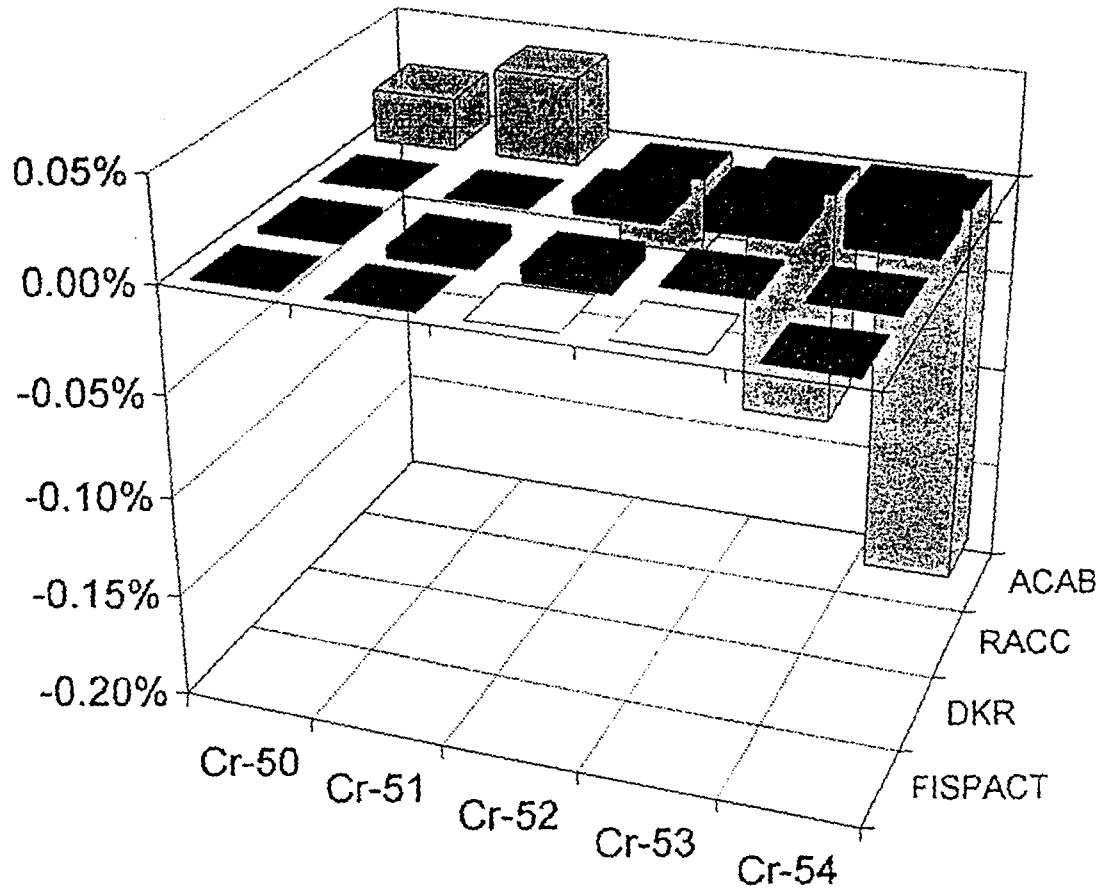

Fig. 4. Percentage Difference from Analytical Solution

APPENDIX 1

A.1 Neutron Fluxes and Spectrum

The neutron fluxes were those calculated from a Li17Pb83 blanket system investigated under the 1984 Blanket Comparison and Selection Study (BCSS) in the United States. In the activation calculation comparison study (ACCS), the first wall flux is used for all calculations.

The blanket system is described below. The plasma and vacuum regions are 0.9 and 0.1 m, respectively. The first wall is made of vanadium alloy (V15Cr5Ti), and is 3 mm thick. It is followed by a Li17Pb83 zone of 0.5 m thick. The compositions in this zone are 7.1% V15Cr5Ti and 73.7% Li17Pb83, all by volume. The Li-6 enrichment is 90%. Finally, there is a manifold zone behind the breeding zone. This is 0.3 m thick, and is composed of 10% V15Cr5Ti, 20% Li17Pb83, and 70% Fe1422 (manganese steel). The blanket model used in the flux calculation is in cylindrical geometry. The boundary condition behind the manifold is vacuum. Calculations were performed using the Monte Carlo code, MCNP, with a continuous energy cross section library based on ENDF/B-V. A total of 10,000 particles were consumed in the calculation. The tritium breeding ratio calculated for this blanket system is 1.434 (0.56%).

The calculated fluxes were grouped into the energy group structures provided for VITAMIN-J (175 groups), IAE/Kurchatov (22 groups), RDIPE (53 groups, JAERI/THIDA (42 groups), GAM-II (100 groups), and REAC2 (55 effective groups) groups structures. The UW and SWIP group structures, 46 and 25 groups, are subsets of the GAM-II group structure. The neutron fluxes were condensed from the calculations. These group fluxes except that given in UW and SWIP group structures are tabulated in the following format: energy boundary, group fluxes, and standard deviations, all in 6e12.3 format. Table A.1 gives the GAM-II group fluxes. Figure A.1 plots the GAM-II spectrum.

The neutron wall loading is specified to be 5 MW/m2. The operating time is one year continuously.

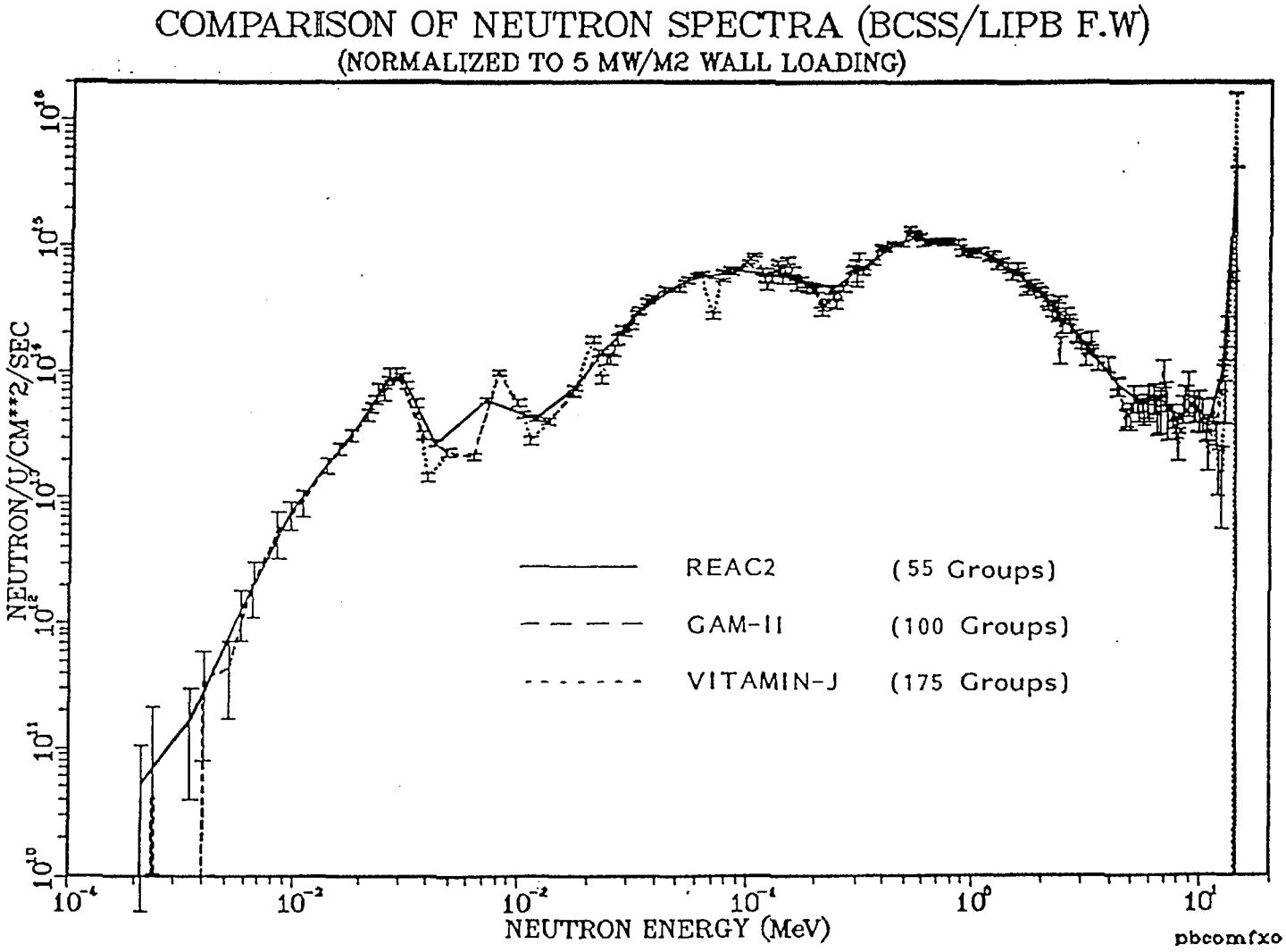

Fig. A.1 Neutron spectra displayed in REAC, GAM-II, and VITAMIN-J group structures (5 MW/m2 wall loading).

Table A.1 (Harwell, GAM-II 100 Group Structure)

Group Neutron Fluxes in GAM-II 100 Group Structure
(Normalized to 5 MW/m2 Wall Loading)

Group	Upper Energy (MeV)	Group Flux (n/cm2/s)	Deviation
1	4.140e-07	0.	0.
2	5.316e-07	0.	0.
3	6.826e-07	0.	0.
4	8.764e-07	0.	0.
5	1.125e-06	0.	0.
6	1.445e-06	0.	0.
7	1.855e-06	0.	0.
8	2.382e-06	0.	0.
9	3.059e-06	0.	0.
10	3.928e-06	0.	0.
11	5.043e-06	0.	0.
12	6.476e-06	0.	0.
13	8.315e-06	0.	0.
14	1.068e-05	0.	0.
15	1.371e-05	0.	0.
16	1.760e-05	0.	0.
17	2.260e-05	0.	0.
18	2.902e-05	0.	0.
19	3.727e-05	0.	0.
20	4.785e-05	0.	0.
21	6.144e-05	0.	0.
22	7.889e-05	0.	0.
23	1.013e-04	0.	0.
24	1.301e-04	0.	0.
25	1.670e-04	0.	0.
26	2.144e-04	0.	0.
27	2.754e-04	2.657e+10	9.999e-01
28	3.536e-04	0.	0.
29	4.540e-04	8.528e+10	7.664e-01
30	5.829e-04	1.115e+11	6.097e-01
31	7.485e-04	5.235e+11	4.752e-01
32	9.611e-04	1.372e+12	4.091e-01
33	1.234e-03	2.329e+12	2.509e-01
34	1.585e-03	4.545e+12	1.462e-01
35	2.037e-03	7.795e+12	1.077e-01
36	2.613e-03	1.501e+13	7.980e-02
37	3.355e-03	2.235e+13	6.430e-02
38	4.307e-03	7.812e+12	7.180e-02
39	5.531e-03	5.728e+12	7.540e-02
40	7.102e-03	5.334e+12	7.560e-02
41	9.119e-03	2.446e+13	5.680e-02
42	1.171e-02	1.141e+13	6.150e-02

Group	Upper Energy (MeV)	Group Flux (n/cm2/s)	Deviation
43	1.503e-02	1.004e+13	6.460e-02
44	1.931e-02	1.690e+13	6.100e-02
45	2.479e-02	3.501e+13	5.140e-02
46	3.183e-02	5.011e+13	4.790e-02
47	4.087e-02	8.860e+13	4.090e-02
48	5.248e-02	1.107e+14	4.060e-02
49	6.738e-02	1.434e+14	3.710e-02
50	8.652e-02	1.308e+14	3.400e-02
51	1.111e-01	1.847e+14	3.190e-02
52	1.228e-01	5.387e+13	4.100e-02
53	1.357e-01	6.345e+13	3.970e-02
54	1.500e-01	6.445e+13	3.990e-02
55	1.657e-01	5.449e+13	4.360e-02
56	1.832e-01	4.910e+13	4.800e-02
57	2.024e-01	4.445e+13	5.100e-02
58	2.237e-01	3.213e+13	6.250e-02
59	2.472e-01	3.926e+13	6.000e-02
60	2.732e-01	4.511e+13	5.220e-02
61	3.020e-01	6.550e+13	5.300e-02
62	3.337e-01	6.051e+13	4.660e-02
63	3.688e-01	7.309e+13	4.820e-02
64	4.076e-01	9.404e+13	4.320e-02
65	4.505e-01	1.009e+14	4.090e-02
66	4.979e-01	1.019e+14	3.950e-02
67	5.502e-01	1.280e+14	3.900e-02
68	6.081e-01	1.099e+14	3.960e-02
69	6.721e-01	1.071e+14	4.100e-02
70	7.427e-01	1.055e+14	4.240e-02
71	8.209e-01	1.061e+14	4.110e-02
72	9.072e-01	9.512e+13	4.490e-02
73	1.003e+00	8.805e+13	4.590e-02
74	1.108e+00	8.986e+13	4.930e-02
75	1.225e+00	8.004e+13	5.060e-02
76	1.353e+00	6.972e+13	5.050e-02
77	1.496e+00	6.207e+13	5.170e-02
78	1.653e+00	6.118e+13	5.650e-02
79	1.827e+00	4.570e+13	6.190e-02
80	2.019e+00	4.330e+13	5.920e-02
81	2.231e+00	3.274e+13	7.490e-02
82	2.466e+00	2.712e+13	7.470e-02
83	2.725e+00	2.498e+13	8.410e-02
84	3.012e+00	1.807e+13	9.010e-02
85	3.329e+00	1.515e+13	9.750e-02
86	3.679e+00	1.144e+13	1.261e-01
87	4.066e+00	1.126e+13	1.425e-01
88	4.493e+00	7.568e+12	1.629e-01
89	4.966e+00	4.305e+12	1.633e-01
90	5.488e+00	5.478e+12	1.616e-01

Group	Upper Energy (MeV)	Group Flux (n/cm2/s)	Deviation
91	6.065e+00	5.329e+12	2.055e-01
92	6.703e+00	5.387e+12	1.753e-01
93	7.408e+00	6.737e+12	1.959e-01
94	8.187e+00	3.468e+12	1.624e-01
95	9.048e+00	6.073e+12	2.385e-01
96	1.000e+01	4.983e+12	2.167e-01
97	1.105e+01	3.402e+12	2.142e-01
98	1.221e+01	3.238e+12	2.042e-01
99	1.350e+01	1.372e+13	1.300e-01
100	1.492e+01	4.175e+14	1.110e-02