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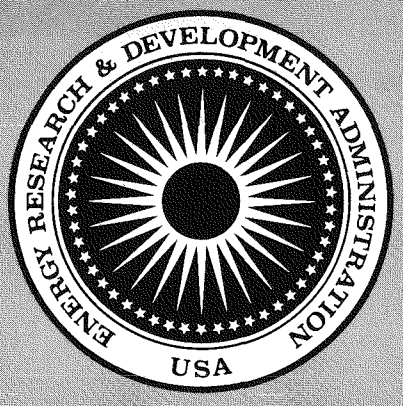

HASL-311

MODIFICATION OF AN ITERATIVE CODE FOR UNFOLDING NEUTRON SPECTRA FROM MULTISPHERE DATA

By
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Date Published—October 1976

Health and Safety Laboratory
Energy Research and Development Administration
New York, New York

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ABSTRACT

The iterative spectral unfolding code, BON, developed at the Health and Safety Laboratory has been rewritten to use recently calculated 31-group response matrices and has been renamed BON31G. Tests were performed to evaluate the effect on the unfolded spectrum of the trial vector used to initiate the iterative process.

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INTRODUCTION

An iterative method, to solve a matrix approximation to a flux integral equation, reported by Scofield and Gold[1,2] was adapted here to the unfolding of neutron spectra from multisphere spectrometer data.[3]

New response matrices for the multisphere arrays have since been developed[4] and have been inserted into the code. A routine for calculating the maximum absorbed dose and dose equivalent, using previously reported data,[5-7] has been added. Tests were performed to evaluate the effect on the unfolded spectrum of the selection of the trial vector used to initiate the iterative process.

A listing of the code appears in the appendix along with a set of input test data and a tabulation of the output.

ITERATIVE UNFOLDING OF MULTISPHERE SPECTROMETER DATA

The multisphere spectrometer, first described by Bramblett et al.[8] consists of an array of neutron counters. The array is composed of a bare thermal neutron detector, one covered with cadmium, and others surrounded by polyethylene moderators of various diameters. Each counter has a different response to neutrons as a function of energy.

The number of counts registered by a given counter is:

$$B(i) \int_{E_a}^{E_b} K(i,E)\ N(E)\ dE \qquad (1)$$

where

$B(i)$ = counts registered by counter i,
$N(E)$ = the incident neutron spectrum,
$K(i,E)$ = the response of counter i as a function of energy E, and
E_a-E_b = the energy range covered by the spectrometer.

Equation (1) in matrix form is:

$$B = N \cdot K \tag{2}$$

where K is a 7×31 transform matrix. Equation (2) is multiplied by the transposed matrix K^T to yield

$$K^T \cdot B = K^T \cdot K \cdot N,$$

or

$$V = KK \cdot N, \tag{3}$$

Since these matrices are ill conditioned, the solution of equation 3 by the inversion of KK is not unique. Applying the physically real constraint that both V and N are non-negative, one may define a vector D with elements

$$d_{ij} = (n_i/v_j)\ \delta_{ij}, \tag{4}$$

where δ_{ij} is the Kronecker delta. Then, equation (3) is rewritten as

$$N = DV, \tag{5}$$

where D cannot be identified with KK^{-1} except when KK is diagonal.

The work of Gold[2] led to an iterative method, that, although it does not converge to an exact solution of equation (5) will yield a physically appropriate one.[3] The recursion formula is:

$$n_j^{(m+1)} = d_{jj}^{(m+1)}\ v_j = \frac{n_j^m \cdot v_j}{\sum_i kk_{ij}\ n_j^m} \tag{6}$$

where

$$v_j = \sum_i kk_{ij} \cdot b_i$$

b_i = i^{th} measurement, and

m = iteration number

The kernel is composed of a few widely spaced and irregularly shaped response functions, so a suggestion of Gold[2] has been adopted and the vector N is smoothed. Awschalom[9] and Stevenson[10] have shown that a modest linear smoothing on alternate iterations yields acceptable results for some, but not all, realistic spectral shapes. The smoothing equations used are:

$$n_1 = (20\, n_1 + n_2)/21$$

$$n_j \cong (n_{j-1} + 20\, n_j + n_{j+1})/22$$

$$n_{31} = (20\, n_{31} + n_{30})/21 \qquad (7)$$

Watkins and Holeman[11] suggested a convergence test for terminating the iterative procedure. After each iteration, the residual is calculated

$$R_m = \sum_{i=1}^{n} \left(B_i - \sum_{j=1}^{31} K_{ij} \cdot N_j^m \cdot \Delta E_j\right)^2 \qquad (8)$$

where

R_m = the residual for the m^{th} iteration,

B_i = measured counts for the i^{th} counter,

K_{ij} = response of the i^{th} counter at energy E_j,

N_j^m = calculated neutron spectra at energy E_j after m iterations,

ΔE_j = energy interval,

m = iteration number, and

n = total number of counters used

The iterative process is terminated either when R_m reaches a minimum or after a total of 1,000 iterations, whichever occurs first.

A perturbation technique as reported by Weinstein[12] was used to estimate propagation of experimental errors in the unfolded spectrum. This technique relies on the assumption that the statistical error in the counts has a normal distribution,

$$p(x) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left\{\frac{x-\mu}{\sigma}\right\}^2} dx[0 < p(x) \leq 1] \qquad (9)$$

where

$p(x)$ = the relative frequency with which observations will fall below a specified value,

x = the perturbed value,

μ = the mean value, i.e., the measured value, and

σ = the standard deviation

Randomly selecting values of $p(x)$, the measured values μ are perturbed 3 times and values of x are calculated. This yields four sets of measurements to be unfolded. Note that for 2 to 20 measurements, an estimate of σ can simply be based on the range, i.e., $\sigma \cong \text{range}/\sqrt{n}$, where n is the number of measurements. Therefore, taking the maximum and minimum values, of the four unfolded spectra, represents an envelope that has a range of 2 σ.

New, 31-group response matrices, covering the energy range from thermal to 400 MeV, have been calculated for 4 × 4 mm, 8 × 8 mm and 12.7 × 12.7 mm right cylindrical ^{6}Li detectors, exposed bare, and surrounded by polyethylene spheres of 2, 3, 5, 8, 10, 12 and 18 inches in diameter.[4]* Using absorption cross

*It has been customary to express the diameters of the polyethylene spheres in inches and this usage has been retained in this report.

sections for cadmium obtained from the KEDAK nuclear data library and provided us by the National Neutron Cross Section Center at Brookhaven National Laboratory, the response of the detector surrounded by 7.6 mm of cadmium, K_{cd}, was calculated from the bare detector response, K_{bare}, using:

$$K_{cd} = K_{bare} \cdot e^{-\sigma T} \tag{10}$$

where

T = the cadmium thickness (atoms/cm^2)

σ = the absorption cross section (cm^2)

The 31-group response matrix for the 1.27 $\times$ 1.27 cm ^{6}Li detector is presented in Table 1.

THE TRIAL VECTOR

To initiate the iterative process of equation (6), an initial value must be chosen for the vector n_j^1. This trial vector is, in reality, a guess at what the unfolded spectra could be. There has been some question about what effect the choice of this vector has on the unfolded spectrum. To study this effect, if any, it was decided to unfold several sets of measurements using five different trial vectors.

$$\begin{aligned}
&1) \quad n_j^1 = \nu_j = \text{(see equation 6)} \\
&2) \quad n_j^1 = 1, \\
&3) \quad n_j^1 = 1/E_j, \\
&4) \quad n_j^1 = E_j, \text{ and} \\
&5) \quad n_j^1 = 10^{10} \cdot z_j
\end{aligned} \tag{11}$$

Trial vector 1 was chosen because it has been routinely used in previous HASL versions of BON. Trial vector 2 was chosen because it has no shape. Number 3 was selected because it has some physical reality (a 1/E spectrum) and number 4 because it is the inverse of number 3. The fifth trial vector was selected because the programmer had no a priori knowledge of what it would be, z_j being a randomly chosen number between zero and one.

Three pseudo-measurements were generated by folding known spectra into the response matrix:

$$B_i = \sum_{j=1}^{31} K_{ij} \cdot N_j \cdot \Delta E_j \qquad (12)$$

The spectra chosen to generate these pseudo-measurements were 1) a cosmic-ray spectrum similar to that reported by Hess,[14] 2) the ^{252}Cf fission spectrum reported by Green,[15] and a mono-energetic 10 MeV source.

The multisphere spectrometer has been used, in the two configurations indicated in Table 2, to measure cosmic ray and accelerator shield-leakage spectra.[3,13] Although discussion in this report is limited to the normal array, all tests were done for both arrays with similar results.

The spectra used to generate the pseudo-measurements are presented in Figure 1 and the resulting measurements in Table 3. The five trial vectors used are presented in Figure 2.

TEST RESULTS

Figure 3 shows the results obtained for the ^{252}Cf data using trial vectors 1 and 3. As can be seen, the results apparently do depend on the trial vector chosen and neither is a very good representation of the ^{252}Cf spectrum.

If equation 6 truly converges to a physically appropriate solution, that solution should not depend on the trial vector chosen. The solution obtained with trial vector 1 converged after 145 iterations and that with trial vector 3 after 283 iterations. Possibly, the discrepancy between the two solutions is due not to the difference in the trial vector chosen, but to the

fact that true convergence had not been reached. To test this hypothesis, the convergence test of Watkins and Holeman[11] was removed from the code and the problem recalculated for 1,000 iterations. Figure 4 compares the results obtained, using trial vector 1, after 145 and 1,000 iterations with the true spectrum. It is obvious that the solution obtained after 1,000 iterations is a much better representation of the ^{252}Cf spectrum.

All five trial vectors were retested letting the code run for the full 1,000 iterations. The percent differences of the solutions obtained for trial vectors 2 through 5 from that obtained with trial vector 1 are presented in Table 4. In no case did the percent differences exceed 0.2%, indicating that the iterative process used does not depend on the trial vector chosen. Similar results were obtained for the other test spectra. It was therefore decided to settle on a single trial vector for use in the code. Since trial vector 2, a constant, is the simplest, it was selected.

It was then necessary to test whether 1,000 iterations are sufficient to insure convergence. Table 5 shows the percent differences of the unfolded ^{252}Cf spectrum after 10,000 iterations from the unfolded spectra after 100, 250, 500, 1,000, and 5,000 iterations. As can be seen, the percent differences after 1,000 iterations are less than 0.05% at all energies and even after 500 iterations the agreement is quite good. Again similar results were obtained with the data for the other test spectra. It was, therefore, decided that the code would run for 1,000 iterations and no convergence tests would be used. Figures 5 and 6 present the normal array results for the cosmic ray and monoenergetic spectra after 1,000 iterations using trial vector 2. The agreement between the unfolded spectrum and the cosmic-ray spectrum is quite good, while the unfolded monoenergetic spectrum is quite broad with the peak somewhat shifted.

DOSIMETRY

Using previously reported data,[6-8] values for the maximum absorbed dose and dose equivalent are computed from:

$$D_i = \frac{\int N(E) R_i(E)\, dE}{\int N(E)\, dE} \qquad (13)$$

where

$i = 1$ for maximum absorbed dose,
$= 2$ for maximum dose equivalent,

$N(E)$ = the unfolded spectrum, and

$R_i(E)$ = the appropriate current-to-dose conversion factors.

Table 6 compares these values for the three unfolded spectra with values obtained from the input spectra. The maximum absorbed dose calculated for the unfolded monoenergetic neutron spectrum is nearly double the result obtained for the input spectrum. Care should be taken in using the multisphere spectrometer to obtain dosimetric quantities of interest. Best results are obtained for smooth continuous spectra such as the cosmic-ray neutron spectrum or accelerator shield leakage spectra. Since the resolution of the multisphere spectrometer is poor, results obtained for spectra containing fine structure are less reliable.

CONCLUSIONS

The results reported here show that the unfolded spectrum is not affected by the choice of the trial vector used to initiate the iterative process. It is also shown that the convergence criteria suggested by Watkins and Holeman[11] should not be used and that, at least for the type spectra tested in this report, 1,000 iterations should insure convergence. The multisphere spectrometer system and this unfolding technique perform best for smooth continuous spectra such as would be likely outside thick shields around high energy accelerators. It is less successful for spectra having fine structure. One should, therefore, carefully consider the quality of the results desired, the spectra likely to be encountered, and the availability and feasibility of alternative spectrometric systems, before deciding whether or not to use the multisphere spectrometer.

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TABLE 1

RESPONSE OF THE 1.27 by 1.27 cm ^{6}Li DETECTOR IN MULTISPHERES

ENERGY	COUNTER								
MEV	BARE	CADMIUM	2	3	5	8	10	12	18
2.07E-07	1.86170	0.0	0.78070	0.56810	0.27270	0.07229	0.02739	0.00988	0.00025
5.48E-07	1.71270	0.0	1.63290	1.23790	0.58863	0.15371	0.05791	0.02084	0.00054
1.05E-06	1.60290	0.00131	1.84910	1.48990	0.72351	0.18852	0.07091	0.02551	0.00068
2.25E-06	1.42390	0.49913	1.96740	1.69150	0.84809	0.22133	0.08318	0.02992	0.00081
4.77E-06	1.20960	0.63803	1.98690	1.82290	0.95091	0.24943	0.09371	0.03371	0.00092
1.01E-05	0.98385	0.94906	1.94190	1.90250	1.03880	0.27472	0.10321	0.03713	0.00104
2.14E-05	0.76835	0.03378	1.85420	1.94210	1.11560	0.29833	0.11211	0.04035	0.00114
4.52E-05	0.58118	0.34772	1.73950	1.95020	1.18320	0.32097	0.12070	0.04345	0.00125
9.58E-05	0.42927	0.00226	1.60930	1.93310	1.24290	0.34306	0.12915	0.04651	0.00136
2.03E-04	0.31454	0.00019	1.47230	1.89620	1.29570	0.36502	0.13763	0.04959	0.00147
4.34E-04	0.22750	0.00000	1.33470	1.84390	1.34180	0.38702	0.14625	0.05273	0.00159
9.13E-04	0.15998	0.00007	1.20050	1.77940	1.38140	0.40911	0.15503	0.05594	0.00171
1.92E-03	0.11246	0.05666	1.07280	1.70710	1.41610	0.43196	0.16429	0.05933	0.00183
4.07E-03	0.07998	0.05158	0.95311	1.62990	1.44810	0.45656	0.17444	0.06307	0.00198
8.62E-03	0.06047	0.04001	0.84181	1.55060	1.48130	0.48497	0.18639	0.06750	0.00215
1.82E-02	0.04554	0.03712	0.73752	1.47130	1.52270	0.52170	0.20214	0.07337	0.00237
3.86E-02	0.03472	0.03065	0.63689	1.39120	1.58290	0.57586	0.22594	0.08234	0.00271
8.18E-02	0.02745	0.02489	0.53390	1.30240	1.67560	0.66698	0.26797	0.09854	0.00333
1.67E-01	0.03681	0.03506	0.42943	1.18860	1.79490	0.82257	0.34731	0.13099	0.00466
3.37E-01	0.05642	0.05404	0.32835	1.02510	1.89280	1.07740	0.50486	0.20499	0.00845
6.79E-01	0.01421	0.01373	0.21165	0.79128	1.86850	1.42690	0.79741	0.37993	0.02414
1.39E 00	0.00858	0.00849	0.12550	0.55859	1.74000	1.88970	1.33390	0.80668	0.11141
2.78E 00	0.00572	0.00565	0.06229	0.31238	1.22620	1.80070	1.55340	1.15580	0.31182
5.54E 00	0.00327	0.00325	0.02859	0.15759	0.76214	1.47490	1.52240	1.36010	0.65352
1.12E 01	0.00160	0.00159	0.01180	0.06960	0.39724	0.95633	1.13290	1.16080	0.84621
2.04E 01	0.00074	0.00074	0.00572	0.03345	0.19084	0.47209	0.57504	0.60890	0.49932
3.52E 01	0.00039	0.00039	0.00333	0.01986	0.11650	0.30308	0.38293	0.42152	0.39275
6.09E 01	0.00033	0.00033	0.00230	0.01346	0.08063	0.21868	0.28522	0.32503	0.34113
1.05E 02	0.00046	0.00046	0.00200	0.01081	0.06505	0.18279	0.24516	0.28790	0.33396
1.82E 02	0.00081	0.00081	0.00208	0.00964	0.05818	0.17054	0.23501	0.28335	0.35509
3.16E 02	0.00151	0.00151	0.00263	0.00934	0.05331	0.15879	0.22232	0.27255	0.35990

NOTE: COLUMN HEADINGS INDICATE DETECTOR TYPE OR DIAMETER OF POLYTHYLENE SPHERE EXPRESSED IN INCHES.

TABLE 2

CONFIGURATION OF THE MULTISPHERE SPECTROMETER SYSTEM
AS USED AT HASL

Counter	Normal	Extended	Identification No.
Bare	Yes	Yes	2
Cadmium Covered	Yes	No	3
2" Dia. Polyethylene	Yes	Yes	4
3" " "	Yes	Yes	5
5" " "	Yes	Yes	6
8" " "	Yes	Yes	7
10" " "	No	Yes	8
12" " "	Yes	No	9
18" " "	No	Yes	10

*Identification numbers are the values LL(kk) used by BON31G. Detector number 1 is the cadmium difference (bare detector counts minus cadmium-covered detector counts).

TABLE 3

NORMAL ARRAY PSEUDO-MEASUREMENT DISTRIBUTIONS FOR TEST SPECTRA

Detector	Counts Per Neutron		
	Cosmic Ray	^{252}Cf	10 MeV
Bare	2.0367×10^{-1}	1.2300210^{-2}	1.5990×10^{-3}
Cadmium Covered	5.6400×10^{-2}	1.1891×10^{-2}	1.5910×10^{-3}
2" Polyethylene	5.5601×10^{-1}	1.3513×10^{-1}	1.8020×10^{-2}
3" "	9.7567×10^{-1}	5.2169×10^{-1}	6.9600×10^{-2}
5" "	1.3679×10^{0}	1.4620×10^{0}	3.9724×10^{-1}
8" "	9.4572×10^{-1}	1.6127×10^{0}	9.5633×10^{-1}
12" "	3.8312×10^{-1}	8.5370×10^{-1}	1.1608×10^{0}

TABLE 4

PERCENT DIFFERENCES OF THE SPECTRUM OBTAINED WITH TRIAL VECTOR 1 FROM THE SPECTRA OBTAINED WITH THE OTHER TRIAL VECTORS AFTER 1,000 ITERATIONS (^{252}Cf Data)

	TRIAL VECTOR			
E(MEV)	CONSTANT	1/E	E	RANDOM
2.07E-07	-0.014	0.001	-0.045	-0.006
5.48E-07	-0.012	0.000	-0.038	-0.005
1.06E-06	-0.010	0.000	-0.033	-0.005
2.25E-06	-0.008	0.001	-0.028	-0.004
4.77E-06	-0.007	0.000	-0.024	-0.003
1.01E-05	-0.006	0.000	-0.020	-0.003
2.14E-05	-0.005	0.0	-0.018	-0.003
4.52E-05	-0.004	0.0	-0.014	-0.002
9.58E-05	-0.003	0.0	-0.011	-0.002
2.03E-04	-0.003	0.0	-0.009	-0.001
4.34E-04	-0.002	0.000	-0.007	-0.001
9.13E-04	-0.002	0.0	-0.006	-0.001
1.92E-03	-0.001	0.0	-0.004	-0.001
4.07E-03	-0.001	0.0	-0.003	-0.000
8.62E-03	-0.000	0.0	-0.001	0.0
1.82E-02	-0.000	0.0	-0.001	-0.000
3.86E-02	0.0	0.0	-0.000	0.0
8.18E-02	0.000	0.0	0.000	0.0
1.67E-01	0.000	0.0	0.001	0.000
3.37E-01	0.000	0.0	0.001	0.0
6.79E-01	0.0	0.0	0.000	0.0
1.39E 00	0.0	0.0	0.0	0.0
2.78E 00	0.0	0.0	-0.001	0.0
5.54E 00	-0.000	0.0	-0.001	-0.000
1.12E 01	-0.001	0.0	-0.001	-0.001
2.04E 01	0.000	0.0	0.001	0.000
3.52E 01	0.002	0.0	0.007	0.001
6.09E 01	0.006	-0.000	0.020	0.003
1.05E 02	0.014	-0.000	0.043	0.006
1.82E 02	0.024	-0.001	0.079	0.011
3.16E 02	0.035	-0.001	0.114	0.016

TABLE 5

CENT DIFFERENCES OF THE SPECTRUM OBTAINED AFTER 10,000 ITERATIONS FROM THE SPECTRA OBTAINED AFTER FEWER ITERATIONS USING TRIAL VECTOR 2 (^{252}Cf DATA)

	TOTAL NUMBER OF ITERATIONS					
(MEV)	5,000	2,500	1,000	500	250	100
.07E-07	0.0	0.0	-0.013	-0.618	2010.989	*********
.48E-07	0.0	0.0	-0.011	-0.865	1155.973	*********
1.06E-06	0.0	0.0	-0.010	-0.959	691.670	*********
2.25E-06	0.0	0.0	-0.008	-0.961	429.708	86056.563
4.77E-06	0.0	0.0	-0.007	-0.910	269.703	41788.645
1.01E-05	0.0	0.0	-0.006	-0.828	168.816	20881.383
2.14E-05	0.0	0.0	-0.004	-0.730	104.512	10698.223
4.52E-05	0.0	0.0	-0.004	-0.626	63.036	5546.594
9.58E-05	0.0	0.0	-0.003	-0.521	36.703	2913.309
2.03E-04	0.0	0.0	-0.003	-0.423	20.207	1540.719
4.34E-04	0.0	0.0	-0.002	-0.333	10.191	816.356
9.13E-04	0.0	0.0	-0.002	-0.252	4.400	429.881
1.92E-03	0.0	0.0	-0.001	-0.183	1.314	221.901
4.07E-03	0.0	0.0	-0.001	-0.124	-0.101	109.812
8.62E-03	0.0	0.0	-0.000	-0.076	-0.546	50.050
1.82E-02	0.0	0.0	-0.000	-0.037	-0.487	19.377
3.86E-02	0.0	0.0	0.0	-0.008	-0.220	5.053
8.18E-02	0.0	0.0	0.000	0.013	0.073	-0.246
1.67E-01	0.0	0.0	0.000	0.025	0.288	-1.014
3.37E-01	0.0	0.0	0.000	0.028	0.366	-0.155
6.79E-01	0.0	0.0	0.0	0.019	0.266	0.398
1.39E 00	0.0	0.0	0.0	-0.003	-0.040	-0.515
2.78E 00	0.0	0.0	0.0	-0.037	-0.499	-2.690
5.54E 00	0.0	0.0	-0.000	-0.068	-0.908	-4.502
1.12E 01	0.0	0.0	-0.001	-0.063	-0.796	-2.639
2.04E 01	0.0	0.0	0.000	0.039	0.696	7.914
3.52E 01	0.0	0.0	0.002	0.328	4.670	31.272
6.09E 01	0.0	0.0	0.006	0.941	12.760	73.008
1.05E 02	0.0	0.0	0.013	2.070	27.091	140.342
1.82E 02	0.0	0.0	0.023	3.801	48.471	234.889
3.16E 02	0.0	0.0	0.033	5.450	68.529	320.849

TABLE 6

MAXIMUM ABSORBED DOSE IN rad n^{-1} cm^2 AND DOSE EQUIVALENT IN rem n^{-1} cm^2 OBTAINED FOR TEST SPECTRA

	Cosmic Ray		^{252}Cf		10 MeV	
	Input	Unfolded	Input	Unfolded	Input	Unfolded
Normal Array						
Absorbed Dose	2.62×10^{-9}	2.52×10^{-9}	3.59×10^{-9}	4.44×10^{-9}	6.62×10^{-9}	1.19×10^{-8}
Dose Equivalent	1.97×10^{-8}	1.89×10^{-8}	3.10×10^{-8}	3.44×10^{-8}	4.57×10^{-8}	5.83×10^{-8}
Extended Array						
Absorbed Dose	2.62×10^{-9}	2.45×10^{-9}	3.59×10^{-9}	4.01×10^{-9}	6.62×10^{-9}	1.08×10^{-8}
Dose Equivalent	1.97×10^{-8}	3.10×10^{-8}	3.25×10^{-8}	4.57×10^{-8}	5.75×10^{-8}	5.75×10^{-8}
Ratio (Unfolded/Input)						
	Normal	Extended	Normal	Extended	Normal	Extended
Absorbed Dose	0.96	0.94	1.24	1.12	1.80	1.63
Dose Equivalent	0.96	0.94	1.11	1.03	1.28	1.26

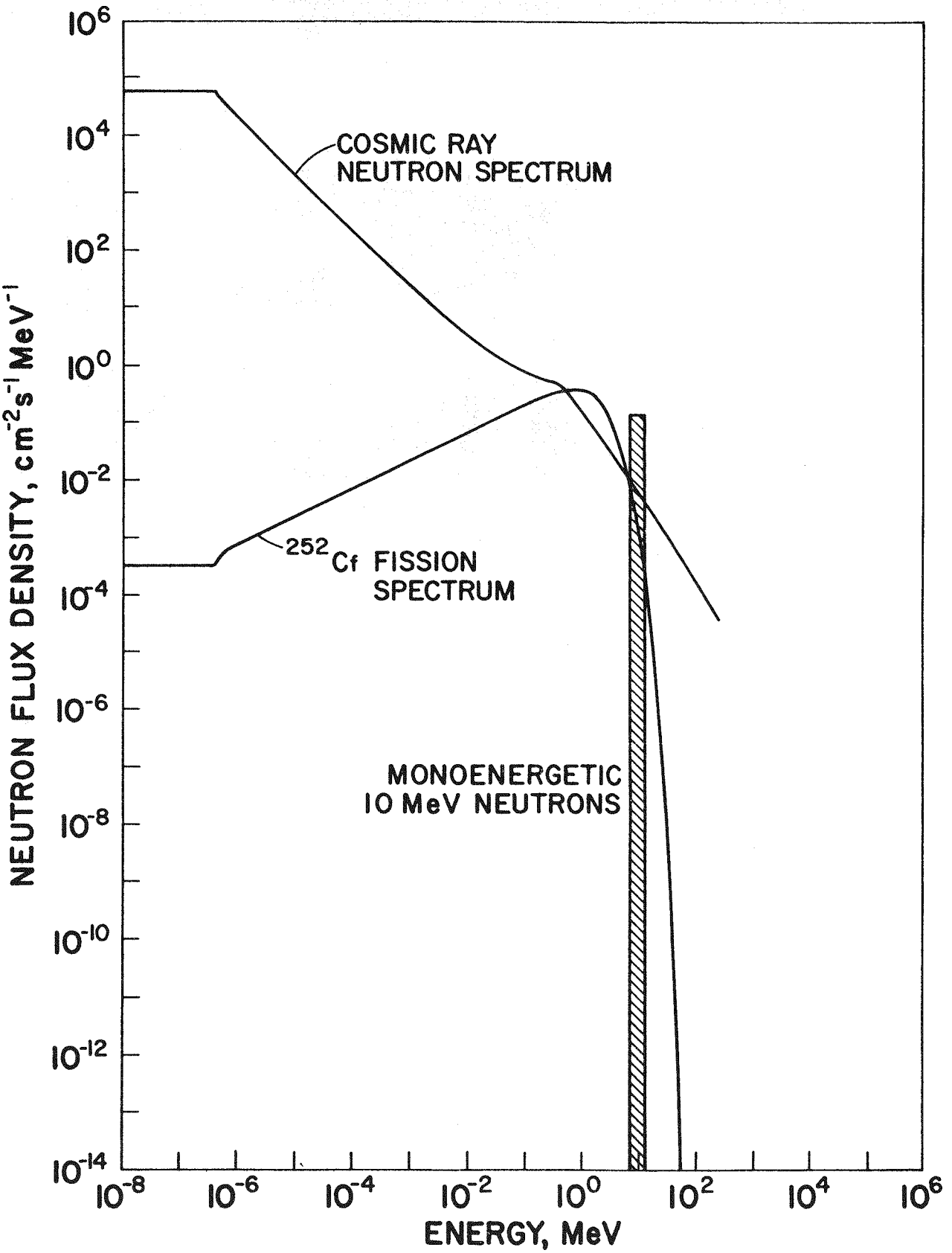

FIGURE 1. Spectra Used to Generate Pseudo-measurements.

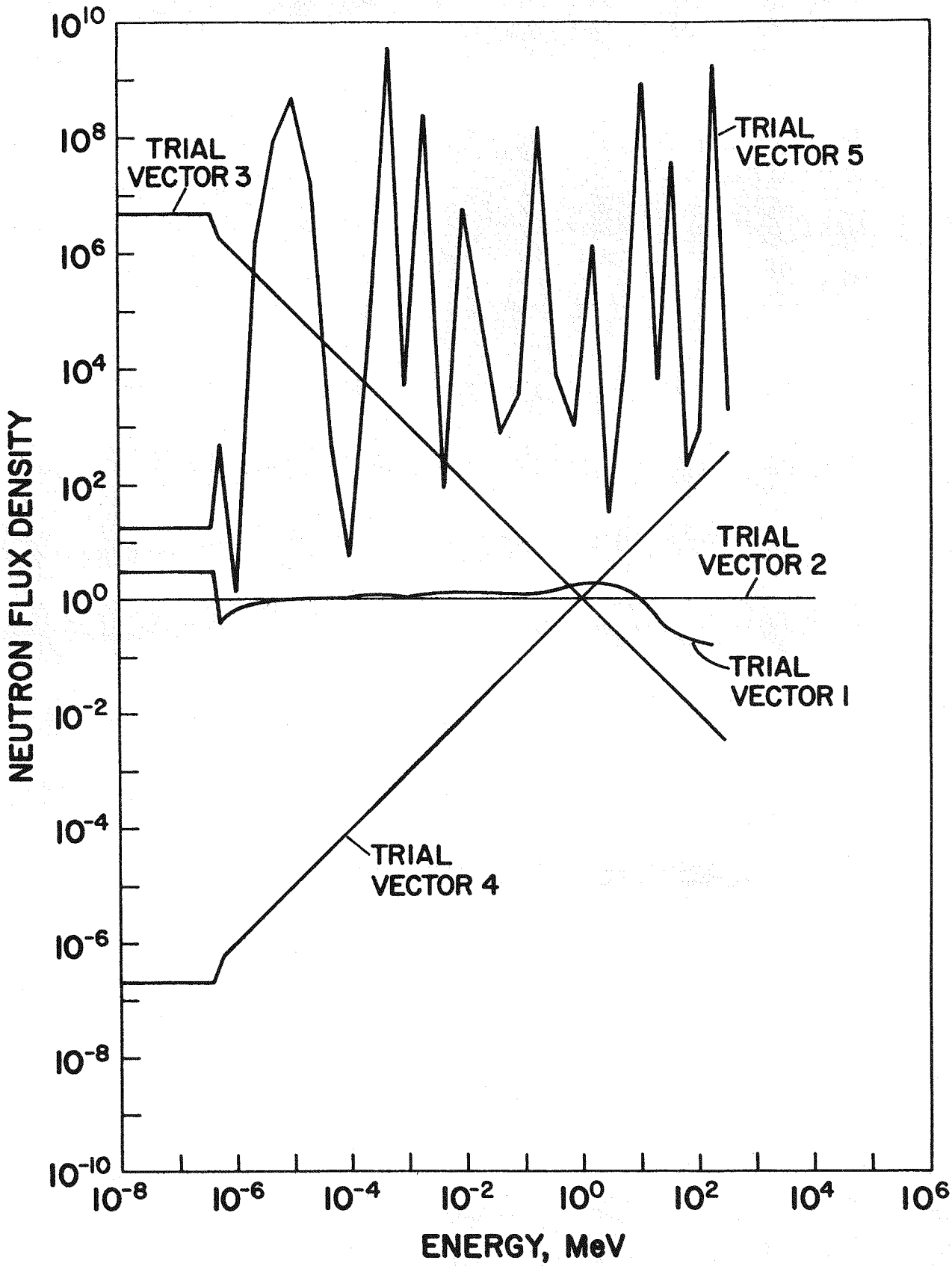

FIGURE 2. Trial Vectors Used to Test BON31G.

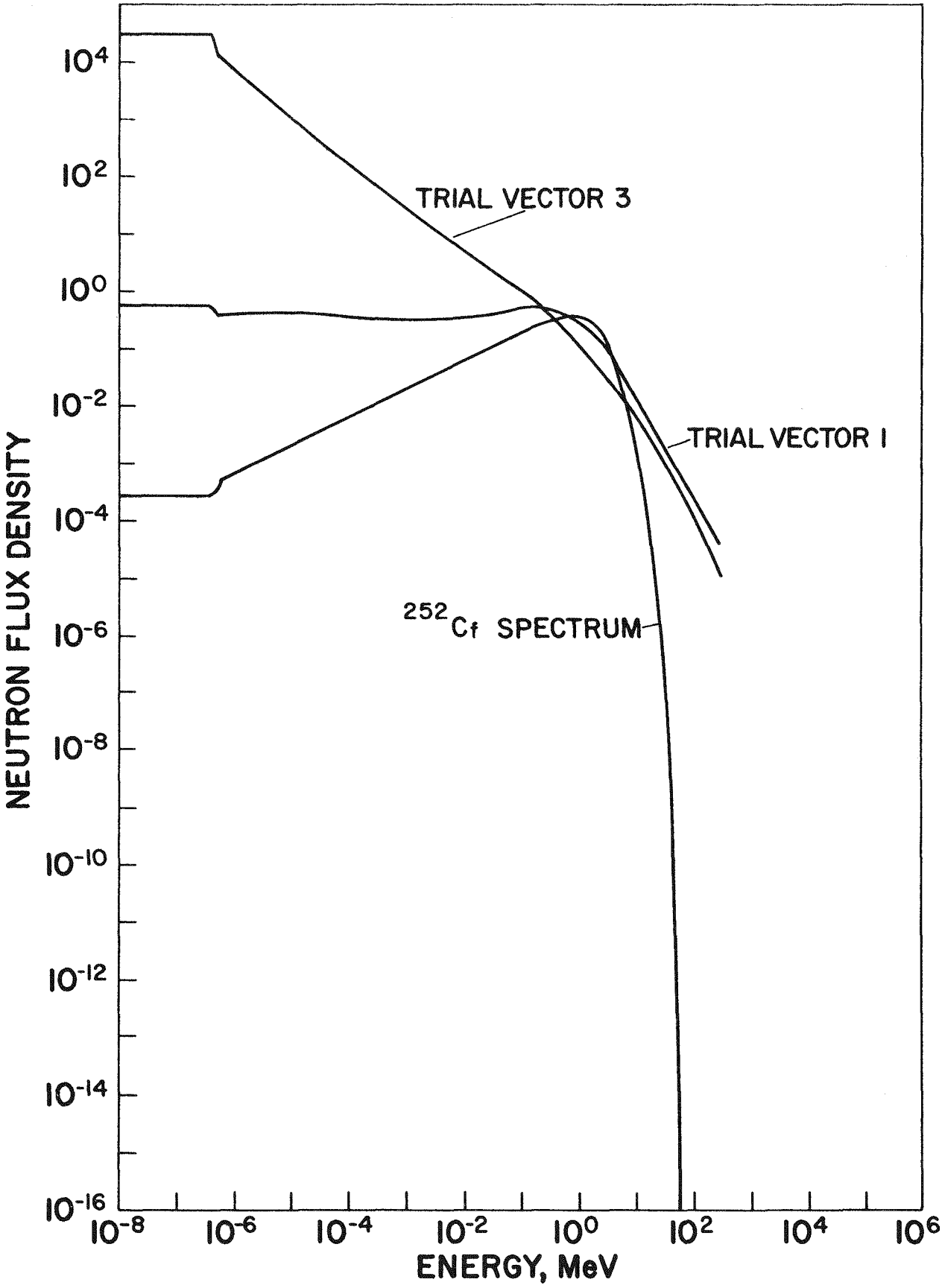

FIGURE 3. Comparison of Unfolded Spectra Obtained with Trial Vectors 1 and 3 with the ^{252}Cf Spectrum used to Generate the Pseudo-measurement.

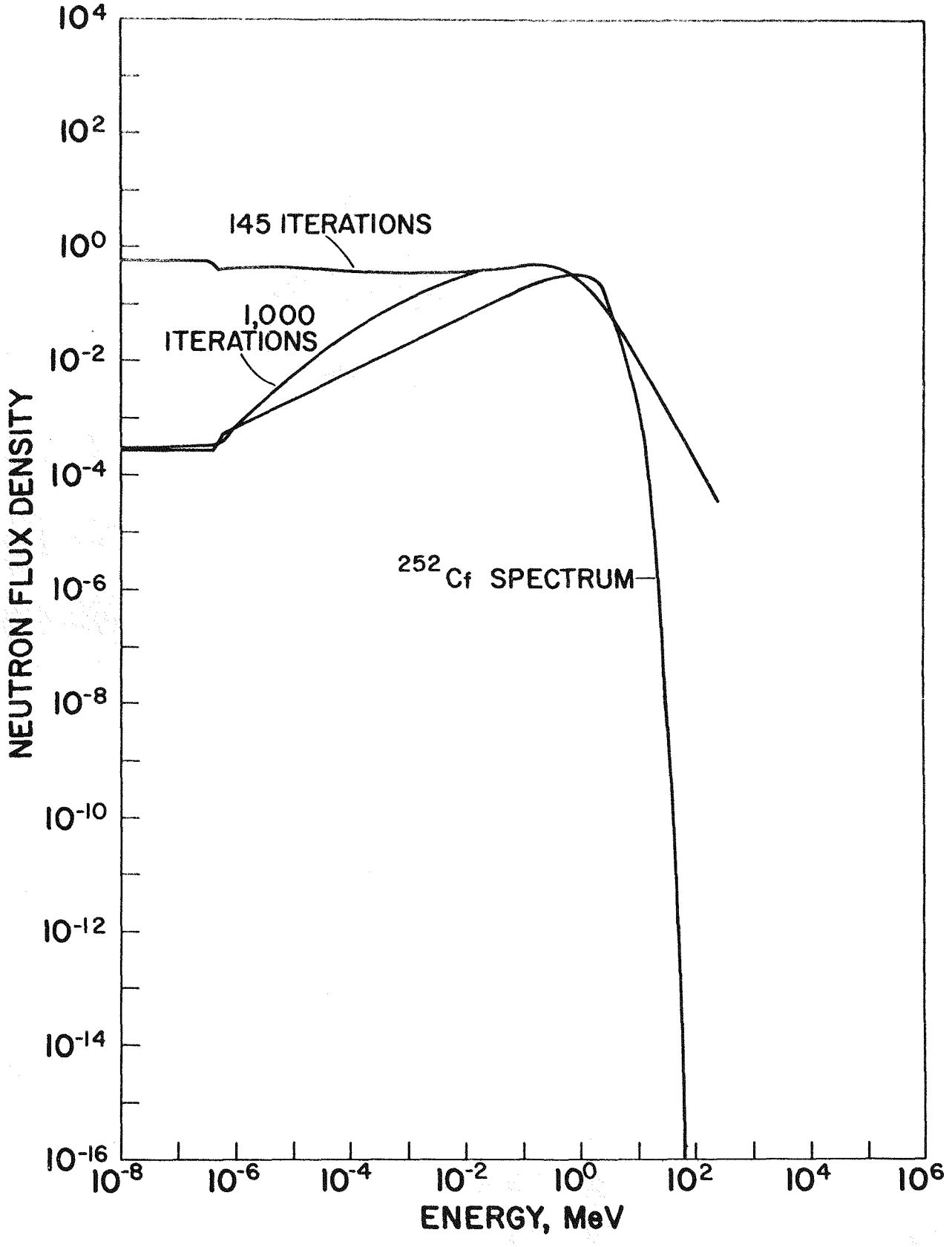

FIGURE 4. Unfolded Spectra after 145 and 1,000 iterations Using Trial Vector 1 with the ^{252}Cf Spectrum.

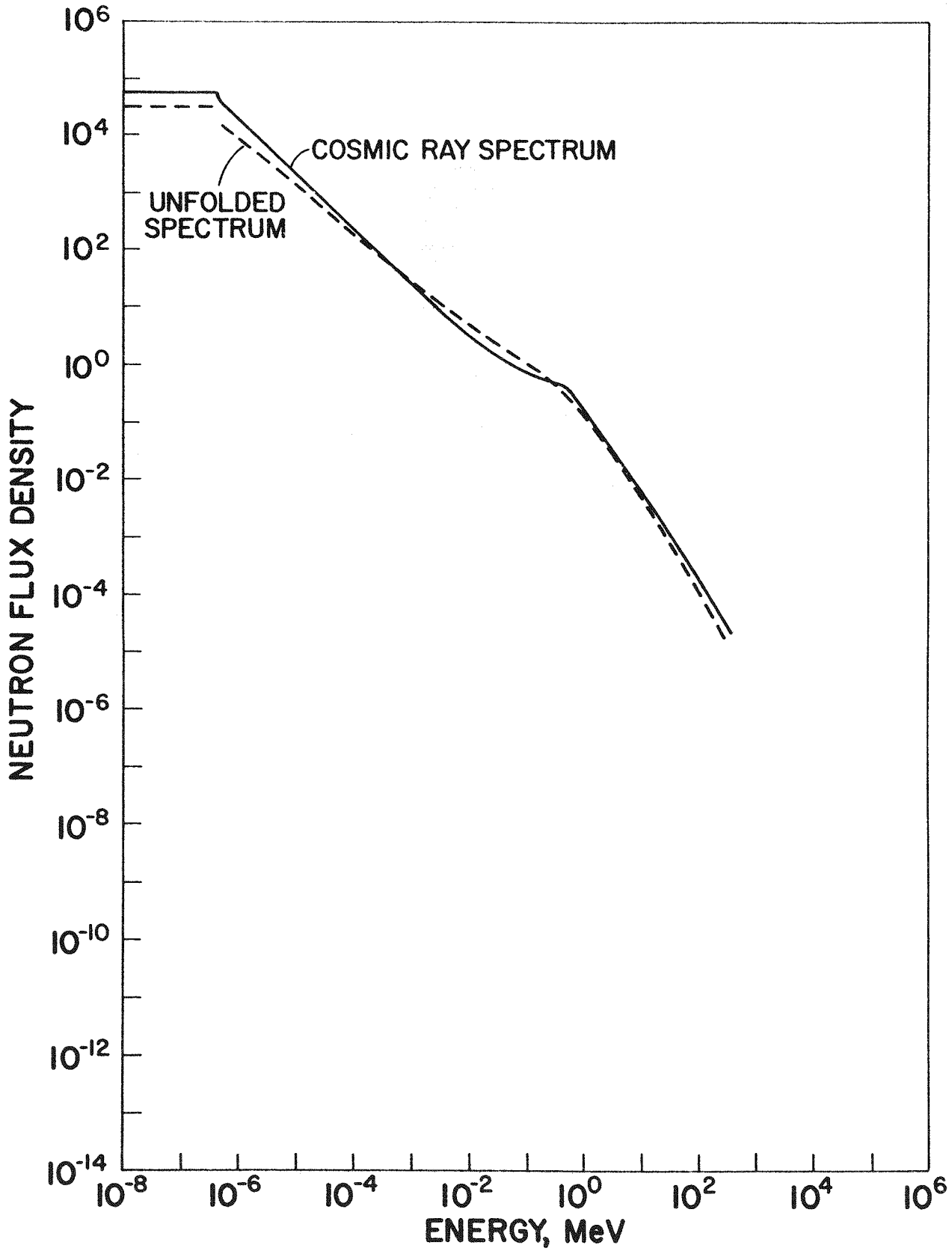

FIGURE 5. Comparison of the Unfolded Spectrum with the Cosmic Ray Spectrum used to Generate the Pseudo-measurement.

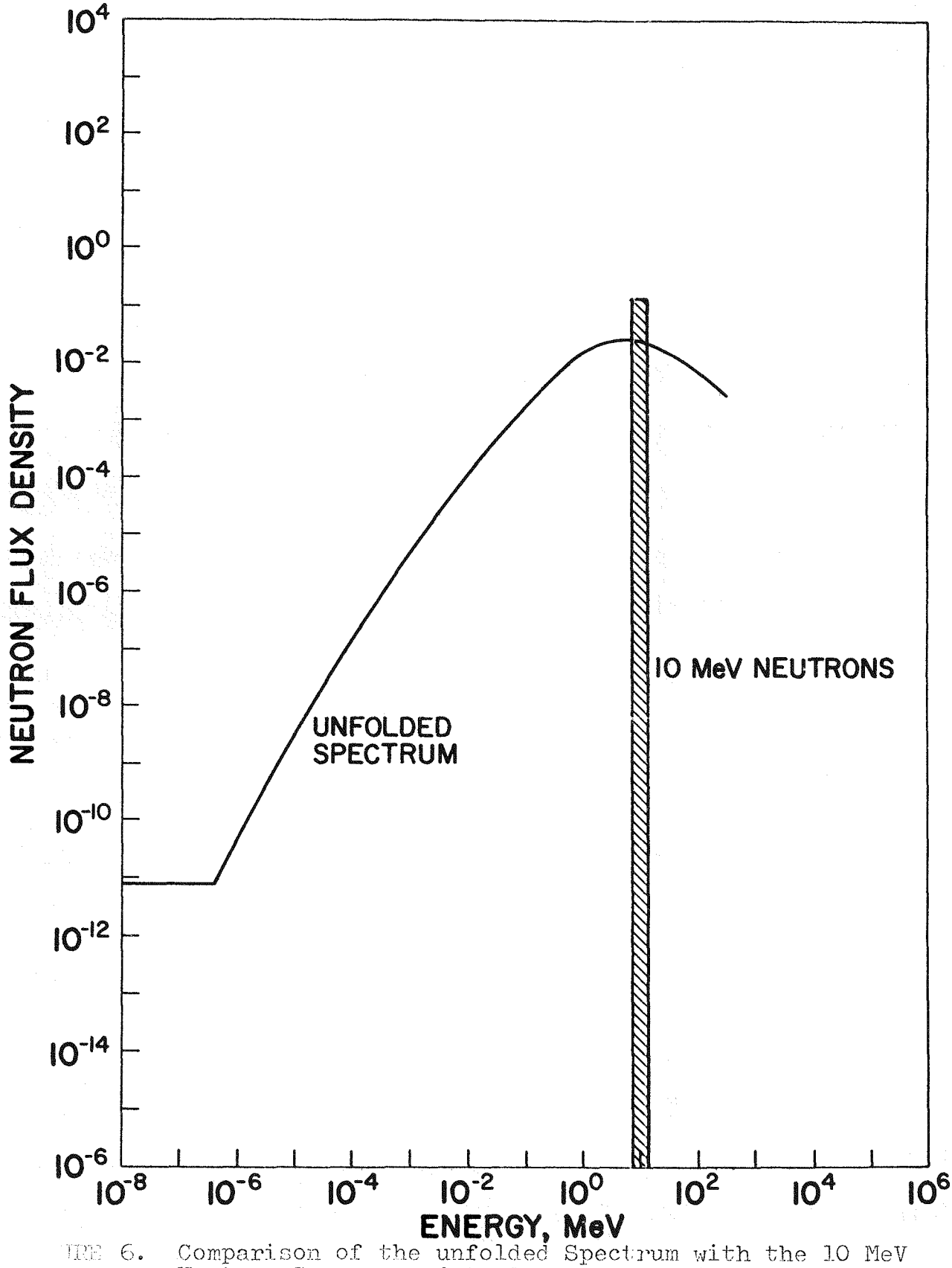

FIG. 6. Comparison of the unfolded Spectrum with the 10 MeV Neutron Source used to Generate the Pseudo-measurement.

APPENDIX

The computer code BON31G, see Tables A-1 to A-5, was written in FORTRAN IV for use with the FTN compiler of the CDC-6600.

The required input for BON31G consists of the response matrix, Table A-6, followed by one or more sets of measurements, Table A-7, separated by end of record, EOR, cards. Each data set consists of a header card containing alphanumeric data describing the measurements. This is followed by a series of data cards each card containing three numbers in format I10, 2F10.0. The first, LL(KK) is the counter identification number, see Table 2, the second BC(KK) is the counts measured and the third, PER(KK) is the percent error in the counts. If PER(KK) is 0.0 or left blank, the code assumes a 10% error in the counts. If the counter identification number, LL(KK), is negative, PER(KK) is taken to be the standard deviation of the counts.

The first page of the output, Table A-8, summarizes the measurement data in four sections corresponding to the actual measurement and the three perturbations used to estimate the two standard deviation envelope of the results. Each section consists of four columns. The first column identifies the detector, the second gives the measured or perturbed counts, the third, the counts recalculated from the spectrum unfolded from the measured or perturbed counts and the fourth is the percent difference between the recalculated and the measured or perturbed counts. The first section also includes a fifth column which lists the values of PER(KK) as a percent of the measured counts.

The second page of the output Table A-9 tabulates the unfolded spectrum as a function of energy, obtained from the measured counts (labelled MEAN in the output), and the maximum and minimum values, obtained from the measured counts and the three perturbations, used to form the spectral envelope. The values of the common logarithms of these data are also presented to facilitate graphical representation of the results. Finally, the mean minimum and maximum values obtained for the dosimetric quantities are presented. It should be noted that the output in Tables A-8 and A-9 includes columns headed COUNTS and (N/CM**2)/MeV. If the input data should be counts per unit time, then these columnar headings would also be per unit time.

TABLE A-1

LISTINT OF THE COMPUTER CODE BON31G

```
      PROGRAM BON31G(INPUT,OUTPUT,PUNCH,TAPE1 = INPUT,TAPE3 = OUTPUT,TAP
     1E2 = PUNCH)
      DIMENSION BK(32,31), AL(10,31), S(4,31), SS(4,31), C(31), PCT(10),
     1 T(31), VECT(31), E(32), DE(31), RAD(31), REM(31), SUM(3,3), O(20)
     2, BC(10), RBC(10), D(10), ER(10), PER(10), LL(10), BALL(10)
      REAL MU(32),DMU(31)
      DATA E/1.E-10,4.14E-7,6.826E-7,1.445E-6,3.059E-6,6.476E-6,1.371E-5
     1,2.902E-5,6.144E-5,1.301E-4,2.754E-4,5.929E-4,1.234E-3,2.613E-3,5.
     2531E-3,1.171E-2,2.479E-2,5.247E-2,0.1111,0.2237,0.4508,0.9072,1.87
     32,3.679,7.408,14.92,25.81,44.65,77.25,133.6,231.2,400.0/
      DATA RAD/5.260E-10,6.088E-10,6.175E-10,6.135E-10,6.070E-10,6.008E-
     110,5.970E-10,5.937E-10,5.892E-10,5.698E-10,5.465E-10,5.251E-10,5.1
     249E-10,5.083E-10,5.039E-10,5.629E-10,6.639E-10,7.847E-10,1.038E-09
     3,1.454E-09,2.244E-09,3.406E-09,4.220E-09,5.778E-09,6.622E-09,9.097
     4E-09,9.610E-09,1.013E-08,1.137E-08,1.490E-08,1.794E-08/
      DATA REM/1.122E-09,1.272E-09,1.296E-09,1.300E-09,1.300E-09,1.297E-
     109,1.269E-09,1.237E-09,1.203E-09,1.157E-09,1.107E-09,1.061E-09,1.0
     237E-09,1.021E-09,1.019E-09,1.554E-09,2.830E-09,5.150E-09,8.827E-09
     3,1.459E-08,2.444E-08,3.354E-08,3.439E-08,4.041E-08,4.572E-08,6.302
     4E-08,7.496E-08,7.382E-08,5.237E-08,5.235E-08,5.877E-08/
      DATA A0/2.515517/,A1/.802853/,A2/.010328/,B1/1.432788/,B2/.189269/
     1,B3/.001308/
      DATA BALL/8HBARE-CAD,8H     BARE,8H CADMIUM,8H  2 INCH,8H  3 INCH,8
     1H  5 INCH,8H  8 INCH,8H 10 INCH,8H 12 INCH,8H 18 INCH/
      ITER = 1000
      ZZ = 123456765432123456768
      CALL SETRN (ZZ)
      DO 10 I = 1,32
   10 MU(I) = ALOG10(E(I))
      DO 20 I = 1,31
      DE(I) = E(I+1)-E(I)
      DMU(I) = MU(I+1)-MU(I)
      E(I) = E(I)+0.5*DE(I)
   20 MU(I) = ALOG10(E(I))
      READ (1,520) AL
      DO 30 I = 1,31
```

TABLE A-2

LISTING OF THE COMPUTER CODE BON31G
(Cont'd)

```
      DO 30 J = 1,10
   30 AL(J,I) = AL(J,I)*DMU(I)
   40 CONTINUE
      READ (1,530) O
      IF (EOF(1)) 410,50
   50 WRITE (3,420) O
      KK = 1
   60 CONTINUE
      READ (1,430) LL(KK),BC(KK),PER(KK)
      IF (EOF(1)) 80,70
   70 KK = KK+1
      GO TO 60
   80 KK = KK-1
      DO 100 I = 1,KK
      IF (LL(I).LT.0) GO TO 90
      IF (PER(I).EQ.0) PER(I) = 10.
      ER(I) = PER(I)*BC(I)/100.
      GO TO 100
   90 ER(I) = PER(I)
      PER(I) = 100.*ER(I)/BC(I)
      LL(I) = -LL(I)
  100 CONTINUE
      DO 110 I = 1,31
      DO 110 J = 1,31
      BK(J,I) = 0.0
      DO 110 M = 1,KK
      L = LL(M)
  110 BK(J,I) = BK(J,I)+AL(L,J)*AL(L,I)
      DO 340 LTP = 1,4
      IT = 1
      IF (LTP.NE.1) GO TO 130
      DO 120 IC = 1,KK
  120 D(IC) = BC(IC)
      GO TO 190
  130 DO 180 IR = 1,KK
```

TABLE A-3

LISTING OF THE COMPUTER CODE BON31G (Cont'd)

```
      Z = RANNYU(0)
      DZ = 0.5-Z
      IF (DZ) 150,140,160
  140 PERTRB = 0.0
      GO TO 180
  150 SZ = 1.-Z
      A = 1.
      GO TO 170
  160 SZ = Z
      A = -1.
  170 ETA = SQRT(ALOG(1./(SZ*SZ)))
      PERTRB = ETA-(A0+A1*ETA+A2*ETA**2)/(1.+B1*ETA+B2*ETA**2+B3*ETA**3)
  180 D(IR) = BC(IR)+A*PERTRB*ER(IR)
  190 DO 200 I = 1,31
      C(I) = 1.0
      VECT(I) = 0.0
      DO 200 J = 1,KK
      L = LL(J)
  200 VECT(I) = VECT(I)+AL(L,I)*D(J)
      DO 270 N = 1,ITER
      DO 220 J = 1,31
      AX = 0.
      DO 210 M = 1,31
  210 AX = C(M)*BK(J,M)+AX
  220 T(J) = C(J)*VECT(J)/AX
      IF (IT) 230,250,230
  230 DO 240 J = 1,31
  240 C(J) = T(J)
      IT = IT-1
      GO TO 270
  250 DO 260 MAK = 2,30
  260 C(MAK) = (T(MAK-1)+20.*T(MAK)+T(MAK+1))/22.
      C(1) = (20.*T(1)+T(2))/21.
      C(31) = (T(31)*20.+T(30))/21.
      IT = IT+1
  270 CONTINUE
```

TABLE A-4

LISTING OF THE COMPUTER CODE BON31G (Cont'd)

```
      DO 280 J = 1,31
  280 S(LTP,J) = C(J)
      DO 290 M = 1,KK
      RBC(M) = 0.0
      L = LL(M)
      DO 290 J = 1,31
  290 RBC(M) = RBC(M)+AL(L,J)*C(J)
      DO 300 I = 1,KK
  300 PCT(I) = (D(I)-RBC(I))*100./D(I)
      IF (LTP.GT.1) GO TO 320
      WRITE (3,440)
      DO 310 I = 1,KK
      L = LL(I)
  310 WRITE (3,450) BALL(L),D(I),RBC(I),PCT(I),PER(I)
      GO TO 340
  320 WRITE (3,460)
      DO 330 I = 1,KK
      L = LL(I)
  330 WRITE (3,470) BALL(L),D(I),RBC(I),PCT(I)
  340 CONTINUE
      WRITE (3,490) O
      DO 350 I = 1,31
      SS(1,I) = S(1,I)
      SS(2,I) = AMIN1(S(1,I),S(2,I),S(3,I),S(4,I))
  350 SS(3,I) = AMAX1(S(1,I),S(2,I),S(3,I),S(4,I))
      DO 360 J = 1,3
      DO 360 K = 1,31
      SS(J,K) = SS(J,K)/(2.302585093*E(K))
      S(J,K) = 0.
  360 IF (SS(J,K).GT.0.0) S(J,K) = ALOG10(SS(J,K))
      WRITE (3,500)
      DO 370 I = 1,31
      EE = ALOG10(E(I))
  370 WRITE (3,510) E(I),(SS(J,I),J = 1,3),EE,(S(J,I),J = 1,3)
      DO 380 I = 1,3
      DO 380 J = 1,3
```

TABLE A-5

LISTING OF THE COMPUTER CODE BON31G (Cont'd)

```
  380 SUM(I,J) = 0.
      DO 390 I = 1,31
      DO 390 J = 1,3
      X = SS(J,I)*DE(I)
      SUM(1,J) = SUM(1,J)+X
      SUM(2,J) = SUM(2,J)+RAD(I)*X
  390 SUM(3,J) = SUM(3,J)+REM(I)*X
      DO 400 J = 2,3
      DO 400 I = 1,3
  400 SUM(J,I) = SUM(J,I)/SUM(1,I)
      WRITE (3,480) (SUM(2,J),J = 1,3),(SUM(3,J),J = 1,3)
      GO TO 40
  410 CONTINUE
      CALL EXIT
C
  420 FORMAT (1H1,20X,20A4)
  430 FORMAT (I10,2F10.0)
  440 FORMAT (1HO//28X,8HDETECTOR,6X,8HMEASURED,5X,12HRECALCULATED,5X,7H
     1PERCENT,8X,7HPERCENT/43X,6HCOUNTS,9X,6HCOUNTS,7X,10HDIFFERENCE,7X,
     25HERROR)
  450 FORMAT (1H ,26X,A8,1X,1P4E15.4)
  460 FORMAT (1HO/,28X,8HDETECTOR,5X,9HPERTURBED,5X,12HRECALCULATED,6X,7
     1HPERCENT/43X,6HCOUNTS,9X,6HCOUNTS,7X,10HDIFFERENCE)
  470 FORMAT (1H ,26X,A8,1X,1P3E15.4)
  480 FORMAT (1HO/29X,23HMAXIMUM ABSORBED DOSE =,1P3E12.2,17H   RADS/(N/
     1CM**2)/27X,25HMAXIMUM DOSE EQUIVALENT =,3E12.2,17H   REMS/(N/CM**2
     2))
  490 FORMAT (1H1//25X,20A4)
  500 FORMAT (1H ,53X,25HUNFOLDED NEUTRON SPECTRUM//23X,1HE,8X,8(1H-),15
     1H (N/CM**2)/MEV ,8(1H-),8X,1HE,8X,5(1H-),21H LOG10 (N/CM**2)/MEV ,
     26(1H-)/22X,3HMEV,9X,4HMEAN,7X,7HMINIMUM,5X,7HMAXIMUM,4X,8HLETHARGY
     3,6X,4HMEAN,7X,7HMINIMUM,5X,7HMAXIMUM)
  510 FORMAT (1H ,15X,1P8E12.2)
  520 FORMAT (10F8.0)
  530 FORMAT (20A4)
      END
```

TABLE A-6

SAMPLE INPUT FOR BON31G - THE RESPONSE MATRIX (Format 9F8.6)

```
1.8616981.8616980.0     0.7807000.5681000.2727000.0722920.0273890.0098840.000251
1.7127001.7127000.0     1.6328981.2379000.5886300.1537100.0579140.0208440.000543
1.6015871.6029000.0013121.8490981.4899000.7235100.1885200.0709130.0255090.000676
0.9247661.4239000.4991341.9674001.6915000.8480900.2213300.0831840.0299200.000808
0.5715651.2095990.6380341.9868981.8229000.9509100.2494300.0937080.0337090.000925
0.0347850.9838500.9490651.9418981.9024981.0387980.2747200.1032100.0371350.001036
0.7345680.7683500.0337821.8541981.9421001.1156000.2983300.1121100.0403500.001144
0.2334600.5811800.3477201.7394981.9501981.1832000.3209700.1207000.0434550.001251
0.4270060.4292700.0022641.6093001.9331001.2429000.3430600.1291500.0465140.001360
0.3143510.3145400.0001891.4723001.8961981.2956980.3650200.1376300.0495940.001471
0.2274990.2275000.0000011.3347001.8439001.3418000.3870200.1462500.0527290.001587
0.1599060.1599800.0000741.2005001.7794001.3813980.4091100.1550300.0559380.001707
0.0558000.1124600.0566601.0728001.7071001.4161000.4319600.1642900.0593320.001835
0.0283980.0799810.0515830.9531101.6299001.4480980.4565600.1744400.0630730.001977
0.0204550.0604660.0400110.8418101.5505981.4812980.4849700.1863900.0675030.002146
0.0084220.0455380.0371160.7375201.4712981.5226980.5217000.2021400.0733740.002368
0.0040740.0347210.0306470.6368901.3911981.5828980.5758600.2259400.0823410.002707
0.0025580.0274510.0248930.5339001.3024001.6755980.6669800.2679700.0985430.003329
0.0017440.0368090.0350650.4294301.1886001.7949000.8225700.3473100.1309900.004659
0.0023770.0564200.0540430.3283501.0251001.8927981.0773980.5048600.2049900.008454
0.0004750.0142100.0137350.2116500.7912801.8685001.4269000.7974100.3799300.024143
0.0000990.0085850.0084860.1255000.5585901.7400001.8897001.3338990.8066800.111410
0.0000740.0057210.0056470.0622870.3123801.2261981.8006981.5533981.1558000.311820
0.0000150.0032680.0032530.0285930.1575900.7621401.4748981.5224001.3601000.553520
0.0000080.0015990.0015910.0118020.0695980.3972400.9563301.1328981.1608000.846210
0.0     0.0007420.0007420.0057170.0334490.1908400.4720900.5750400.6089000.499320
0.0     0.0003910.0003910.0033300.0198620.1165000.3030800.3829300.4215200.392750
0.0     0.0003320.0003320.0022980.0134590.0806260.2186800.2852200.3250300.341130
0.0     0.0004610.0004610.0019980.0108110.0650460.1827900.2451600.2879000.333960
0.0     0.0008070.0008070.0020850.0096390.0581790.1705400.2350100.2833500.355090
0.0     0.0015100.0015100.0026320.0093410.0533140.1587900.2223200.2725500.359900
```

TABLE A-7

SAMPLE INPUT FOR BON31G (Cont'd) - HEADER CARDS (FORMAT 20A4) AND DATA (FORMAT I10, 2F10.0), EACH SET SEPARATED BY AN END OF RECORDS, EOR

```
          31 GROUP HESS - O BRIEN COSMIC RAY NEUTRON SPECTRUM
         22.0367E-01
         35.6404E-02
         45.5601E-01
         59.7567E-01
         61.3679E 00
         79.4572E-01
         93.8312E-01
EOR
31 GROUP 252-CALIFORNIUM FISSION NEUTRON SPECTRUM AFTER GREEN
         21.2303E-02
         31.1891E-02
         41.3513E-01
         55.2169E-01
         61.4620E 00
         71.6127E 00
         98.5370E-01
EOR
                        MONOENERGETIC 10 MEV NEUTRONS
         21.5990E-03
         31.5910E-03
         41.1802E-02
         56.9598E-02
         63.9724E-01
         79.5633E-01
         91.1608E 00
EOR
EOF
```

TABLE A-8

OUTPUT OF BON?1G - DETECTOR DATA

31 GROUP 252-CALIFORNIUM FISSION NEUTRON SPECTRUM AFTER GREEN TEMP IS 1.39

DETECTOR	MEASURED COUNTS	RECALCULATED COUNTS	PERCENT DIFFERENCE	PERCENT ERROR
BARE	1.2303E-02	1.5408E-02	-2.5235E+01	1.0000E+01
CADMIUM	1.1891E-02	1.4695E-02	-2.3581E+01	1.0000E+01
2 INCH	1.3513E-01	1.6513E-01	-2.2201E+01	1.0000E+01
3 INCH	5.2169E-01	5.7689E-01	-1.0582E+01	1.0000E+01
5 INCH	1.4620E+00	1.4598E+00	1.5181E-01	1.0000E+01
8 INCH	1.6127E+00	1.5539E+00	3.6491E+00	1.0000E+01
12 INCH	8.5370E-01	9.0211E-01	-5.6707E+00	1.0000E+01

DETECTOR	PERTURBED COUNTS	RECALCULATED COUNTS	PERCENT DIFFERENCE
BARE	1.0649E-02	1.5037E-02	-4.1205E+01
CADMIUM	1.3153E-02	1.4097E-02	-7.1827E+00
2 INCH	1.3128E-01	1.6400E-01	-2.4925E+01
3 INCH	5.4739E-01	5.5330E-01	-1.0801E+00
5 INCH	1.3603E+00	1.3809E+00	-1.5129E+00
8 INCH	1.5667E+00	1.5164E+00	3.2083E+00
12 INCH	9.2674E-01	9.5765E-01	-3.3354E+00

DETECTOR	PERTURBED COUNTS	RECALCULATED COUNTS	PERCENT DIFFERENCE
BARE	1.2074E-02	1.8809E-02	-5.5771E+01
CADMIUM	1.3293E-02	1.7789E-02	-3.3816E+01
2 INCH	1.1657E-01	2.0166E-01	-7.2990E+01
3 INCH	5.3247E-01	6.4683E-01	-2.1479E+01
5 INCH	1.5813E+00	1.4522E+00	8.1632E+00
8 INCH	1.3211E+00	1.4018E+00	-6.1095E+00
12 INCH	8.3563E-01	8.0783E-01	3.3273E+00

DETECTOR	PERTURBED COUNTS	RECALCULATED COUNTS	PERCENT DIFFERENCE
BARE	1.3600E-02	1.5199E-02	-1.1757E+01
CADMIUM	1.1753E-02	9.3375E-03	2.0550E+01
2 INCH	1.4086E-01	1.0633E-01	2.4514E+01
3 INCH	4.4409E-01	4.1956E-01	5.5246E+00
5 INCH	1.0745E+00	1.2687E+00	-1.8076E+01
8 INCH	1.8381E+00	1.5780E+00	1.4153E+01
12 INCH	8.5909E-01	1.0157E+00	-1.8233E+01

TABLE A-9

OUTPUT OF BON31G (Cont'd) - UNFOLDED SPECTRUM, TWO SIGMA ENVELOPE AND DOSIMETRIC QUANTITIES

31 GROUP 252-CALIFORNIUM FISSION NEUTRON SPECTRUM AFTER GREEN TEMP IS 1.39
UNFOLDED NEUTRON SPECTRUM

E	(N/CM**2)/MEV			E	LOG10 (N/CM**2)/MEV		
MEV	MEAN	MINIMUM	MAXIMUM	LETHARGY	MEAN	MINIMUM	MAXIMUM
2.07E-07	2.90E-04	5.14E-06	1.53E+03	-6.68E+00	-3.54E+00	-5.29E+00	3.19E+00
5.48E-07	3.90E-04	1.22E-05	5.25E+02	-6.26E+00	-3.41E+00	-4.91E+00	2.72E+00
1.06E-06	8.59E-04	4.40E-05	2.07E+02	-5.97E+00	-3.07E+00	-4.36E+00	2.32E+00
2.25E-06	1.71E-03	1.39E-04	6.54E+01	-5.65E+00	-2.77E+00	-3.86E+00	1.82E+00
4.77E-06	3.32E-03	4.20E-04	1.82E+01	-5.32E+00	-2.48E+00	-3.38E+00	1.26E+00
1.01E-05	6.24E-03	1.20E-03	4.55E+00	-5.00E+00	-2.20E+00	-2.92E+00	6.58E-01
2.14E-05	1.13E-02	3.20E-03	1.02E+00	-4.67E+00	-1.95E+00	-2.49E+00	1.02E-02
4.52E-05	1.98E-02	7.95E-03	2.58E-01	-4.34E+00	-1.70E+00	-2.10E+00	-5.88E-01
9.58E-05	3.31E-02	1.84E-02	3.27E-01	-4.02E+00	-1.48E+00	-1.73E+00	-4.85E-01
2.03E-04	5.32E-02	1.37E-02	4.00E-01	-3.69E+00	-1.27E+00	-1.86E+00	-3.98E-01
4.34E-04	8.11E-02	9.02E-03	4.65E-01	-3.36E+00	-1.09E+00	-2.04E+00	-3.33E-01
9.13E-04	1.20E-01	1.03E-02	5.30E-01	-3.04E+00	-9.19E-01	-1.99E+00	-2.76E-01
1.92E-03	1.71E-01	1.38E-02	5.83E-01	-2.72E+00	-7.67E-01	-1.86E+00	-2.34E-01
4.07E-03	2.31E-01	1.93E-02	6.15E-01	-2.39E+00	-6.36E-01	-1.71E+00	-2.11E-01
8.62E-03	2.98E-01	2.79E-02	6.27E-01	-2.06E+00	-5.26E-01	-1.55E+00	-2.03E-01
1.83E-02	3.65E-01	4.12E-02	6.97E-01	-1.74E+00	-4.38E-01	-1.38E+00	-1.57E-01
3.86E-02	4.23E-01	6.18E-02	8.09E-01	-1.41E+00	-3.74E-01	-1.21E+00	-9.22E-02
8.18E-02	4.57E-01	9.27E-02	8.25E-01	-1.09E+00	-3.40E-01	-1.03E+00	-8.34E-02
1.67E-01	4.68E-01	1.41E-01	7.41E-01	-7.76E-01	-3.29E-01	-8.52E-01	-1.30E-01
3.37E-01	4.32E-01	2.01E-01	5.54E-01	-4.72E-01	-3.65E-01	-6.96E-01	-2.56E-01
6.79E-01	3.37E-01	2.44E-01	3.37E-01	-1.68E-01	-4.72E-01	-6.12E-01	-4.72E-01
1.39E+00	2.09E-01	1.61E-01	2.18E-01	1.43E-01	-6.81E-01	-7.93E-01	-6.61E-01
2.78E+00	1.04E-01	7.01E-02	1.33E-01	4.43E-01	-9.84E-01	-1.15E+00	-8.76E-01
5.54E+00	4.18E-02	2.95E-02	5.48E-02	7.44E-01	-1.38E+00	-1.53E+00	-1.26E+00
1.12E+01	1.43E-02	1.27E-02	1.82E-02	1.05E+00	-1.84E+00	-1.90E+00	-1.74E+00
2.04E+01	5.13E-03	5.03E-03	7.81E-03	1.31E+00	-2.29E+00	-2.30E+00	-2.11E+00
3.52E+01	1.84E-03	1.45E-03	3.45E-03	1.55E+00	-2.74E+00	-2.84E+00	-2.46E+00
6.10E+01	6.32E-04	3.84E-04	1.96E-03	1.78E+00	-3.20E+00	-3.42E+00	-2.71E+00
1.05E+02	2.14E-04	9.57E-05	1.13E-03	2.02E+00	-3.67E+00	-4.02E+00	-2.95E+00
1.82E+02	7.57E-05	2.36E-05	6.59E-04	2.26E+00	-4.12E+00	-4.63E+00	-3.18E+00
3.16E+02	3.17E-05	7.15E-06	3.82E-04	2.50E+00	-4.50E+00	-5.15E+00	-3.42E+00

MAXIMUM ABSORBED DOSE =	4.48E-09	4.79E-09	5.80E-09	RADS/(N/CM**2)
MAXIMUM DOSE EQUIVALENT =	3.36E-08	3.66E-08	3.53E-08	REMS/(N/CM**2)