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SENSITIVITY OF MONTE CARLO CALCULATIONS TO THE NEUTRON CROSS SECTIONS FOR NEUTRON TRANSPORT IN NITROGEN AND IN AIR

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Abstract

The predictions of the SORS Monte Carlo calculations for neutron transport from a 14-MeV neutron source in nitrogen and in air are compared using different libraries for nitrogen. In turn, these libraries are tested against experimental measurements for the integral neutron spectra between 0.5 and 10 mfp at 14 MeV. The measured neutron spectra cover a neutron energy range between 1 eV and 14 MeV. The neutron library for oxygen is checked against measurements for 0.72 mfp at 14 MeV for neutron energies between 30 keV and 14 MeV.

It is found that features of neutron transport at 14 MeV are mainly determined by the neutron cross sections at neutron energies close to the source energy. This is especially so for neutron dose as a function of distance from the source. Neutron fluence as a function of neutron energy at a given distance from the source is, however, more sensitive to the neutron cross sections at energies below 14 MeV. This sensitivity is most pronounced at great distances from the neutron source.

Introduction

Numerous calculations are found in the literature on the problem of neutron transport in air.[1] For example, very extensive and complete calculations have been carried out by Straker,[2,3] who has compared them with some of the well-known and more comprehensive ones. The authors of this paper have performed similar calculations,[4] and these have been compared with Straker's[3] results. The neutron transport calculations presented in Ref. 4 used the neutron cross sections for nitrogen and oxygen, which had been previously tested against the integral measurements for 0.58, 1.06, and 3.0 mfp of nitrogen and 0.72 mfp oxygen. It was shown[4] that the proper treatment of inelastic neutron scattering

*The results presented in this paper were reported at the Seventeenth Annual Meeting of the American Nuclear Society (June 1970).

to discrete levels was necessary for the calculations to reproduce the measurements. Furthermore, it has been found that the neutron transport calculations of dose as a function of distance from the source are sensitive mainly to the neutron cross sections for the higher-energy neutrons.

Oxygen Cross Sections

For oxygen the cross sections at 14 MeV used in the calculations[4] were as follows: σ_{total} = 1678 mbar, σ_{el} = 880 mbar, σ_{n-el} = 798 mbar, $\sigma(n,n')$ = 463 mbar, $\sigma(n,p)$ = 50 mbar and $\sigma(n,\alpha)$ = 285 mbar. As described in detail in Ref. 4, five inelastic levels were considered: a level at 6.10 MeV to account for the doublet at 6.05 and 6.13 MeV; a level at 7.00 MeV to account for the doublet at 6.92 and 7.12 MeV; a level at 8.88 MeV; a level at 9.90 MeV to represent the triplet at 9.59, 9.85, and 10.36 MeV; and a level at 11.10 MeV to account for the triplet at 10.95, 11.08, and 11.26 MeV. The cross section assigned to these five levels was 182 mbar distributed according to the ratio 0.593,

Table 1. Neutron library for oxygen.

Group	$E_{initial}$ (MeV)	E_{av} (MeV)	σ_{total} (mbar)	$\sigma_{elastic}$ (mbar)	σ_{n-e} (mbar)	$\sigma_{(n,n')}$ levels (mbar)	$\sigma_{(n,n')}$ continuum (mbar)	$\sigma_{(r,2n)}$ (mbar)	$\sigma_{(n,x_1)}$[a] (mbar)	$\sigma_{(n,x_2)}$[a] (mbar)
32	1.602	1.696	1859	1859	—	—	—	—	—	—
33	1.791	1.890	2121	2121	—	—	—	—	—	—
34	1.989	2.094	1428	1428	—	—	—	—	—	—
35	2.198	2.308	845	845	—	—	—	—	—	—
36	2.418	2.533	1118	1118	—	—	—	—	—	—
37	2.648	2.768	1293	1293	—	—	—	—	—	—
38	2.889	3.014	1466	1466	—	—	—	—	—	—
39	3.140	3.270	2687	2687	—	—	—	—	—	—
40	3.401	3.537	3258	3258	—	—	—	—	—	—
41	3.673	3.814	3006	2996	10	—	—	—	—	10
42	3.955	4.102	1695	1607	88	—	—	—	—	88
43	4.248	4.400	2191	2134	57	—	—	—	—	57
44	4.551	4.708	1525	1470	55	—	—	—	—	55
45	4.865	5.027	1848	1740	108	—	—	—	—	108
46	5.189	5.356	1087	1076	11	—	—	—	—	11
47	5.524	5.696	1403	1390	13	—	—	—	—	13
48	5.869	6.046	1262	1223	39	—	—	—	—	39
49	6.224	6.407	957	841	116	1	—	—	—	115
50	6.590	6.778	1055	904	151	46	—	—	—	105
51	6.967	7.160	1245	1027	218	93	—	—	—	125
52	7.354	7.552	1208	931	277	195	—	—	—	82
53	7.751	7.955	1072	800	272	205	—	—	—	67
54	8.159	8.368	1231	851	380	325	—	—	—	55
55	8.577	8.792	1222	818	404	329	—	—	—	75
56	9.006	9.226	1168	730	438	330	—	—	—	108
57	9.445	9.670	1298	826	472	295	45	—	—	132
58	9.894	10.12	1358	810	548	335	60	—	1	152
59	10.35	10.59	1282	640	642	390	80	—	3	169
60	10.83	11.07	1563	891	672	390	100	—	10	172
61	11.31	11.55	1684	910	774	390	140	—	52	192
62	11.80	12.18	1655	860	795	390	180	—	60	165
63	12.56	12.94	1611	818	793	372	210	—	45	166
64	13.33	13.50	1600	795	805	290	240	—	60	215
65	13.87	14.14	1659	880	779	239	241	—	59	240
66	14.41	14.50	1678	880	798	182	281	—	50	285

[a] x_1 and x_2 stand for single- and double-charged particles, respectively.

0.361, 0.045, 0.000, and 0.001, respectively. The (n,n') cross section to the continuum accounts for 281 mbar. The tabulation of the oxygen cross sections between 1.6 and 14.5 MeV is given in Table 1; the distribution of the (n,n') cross sections assigned to the inelastic levels as a function of the neutron energy is given in Table 2. For energies below 1.6 MeV, the neutron cross sections were taken from the LRL Neutron Library.[6]

Comparisons between the calculations (carried out with the computer program SORS[7] using the above cross sections) and the measurements of the integral neutron spectra for neutron energies above 1.6 MeV and below 1 MeV are displayed in Figs. 1 and 2, respectively.

Table 2. Probable distribution of the (n,n') cross sections assigned to the levels as function of energy.

E_{lab} (MeV)	Excited levels for oxygen included in SORS (MeV)				
	6.10	7.00	8.88	9.90	11.1
6.48	1	--	—	—	—
7.44	1	—	—	—	—
8.00	0.885	0.115	—	—	—
9.435	0.781	0.219	—	—	—
10.52	0.586	0.329	0.085	—	—
11.79	0.423	0.393	0.184	—	—
12.0	0.406	0.393	0.198	—	0.003
14.0	0.437	0.357	0.183	—	0.023
16.0	0.593	0.361	0.045	—	0.001

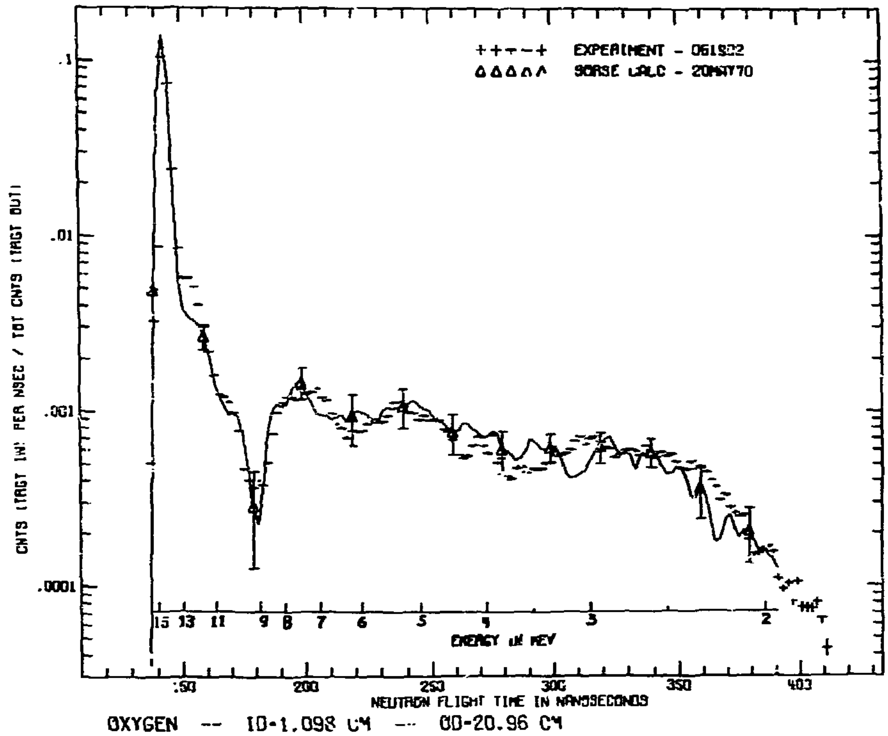


Fig. 1. Comparison between the measured neutron spectrum from 0.72 mfp of liquid oxygen and the predictions of the SORS calculations with the cross sections given in Tables 1 and 2.

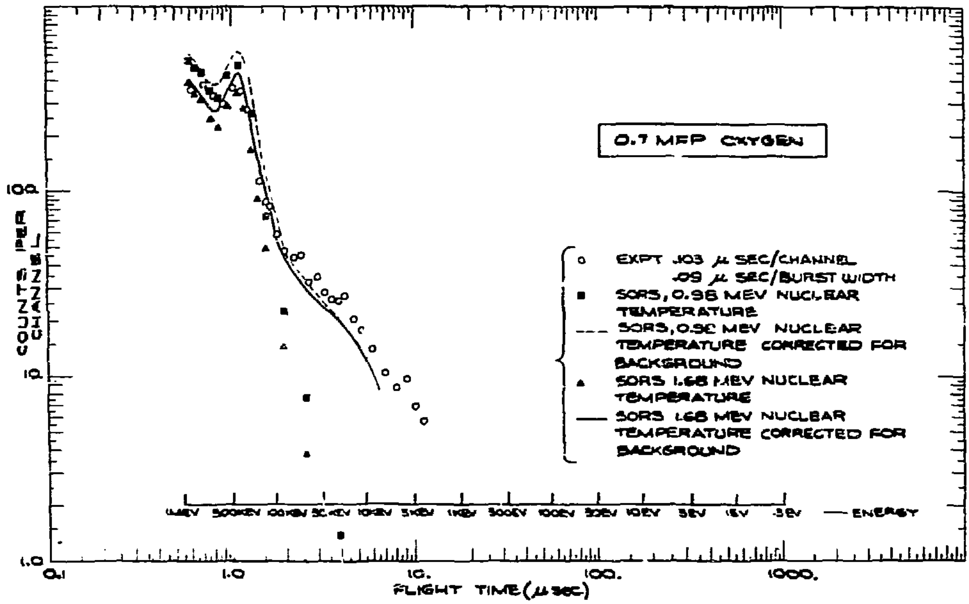


Fig. 2. Comparison between the measured neutron spectrum below 1 MeV from 0.72 mfp of liquid oxygen and the SORS calculations carried out of two nuclear temperatures: 0.98 MeV and 1.68 MeV.

For the low energy measurements[5] ($E_n \leq 1$ MeV), the calculation is in fair agreement down to 30 keV; below this energy the background corrections become very important and are not too well known.

Nitrogen Cross Sections

For nitrogen, SORS calculations were carried out for two different neutron libraries, A and B, which resulted[4] from the impossibility of reconciling the total cross sections[8] with the sum of the elastic[9] and nonelastic[10] cross sections. It should be pointed out that Libraries A and B resulted from two extreme assumptions: in A it was assumed that the measured elastic cross sections were too low, and they were raised accordingly to give the measured values of the total cross sections[8]; for B the assumption was made that the measured inelastic cross sections[10] were too low, and consequently they were increased to agree with the values of σ_{total}.[8] The SORS calculations[4] with Libraries A and B are compared with the measurements for 0.58, 1.06, and 3.0 mfp of liquid nitrogen in Fig. 3. Libraries A and B are tabulated in Tables 3 and 4, respectively. For neutron energies below 1.6 MeV, the neutron cross sections were again obtained from the LRL Neutron Library.[5] The main features of these two libraries are: (a) they

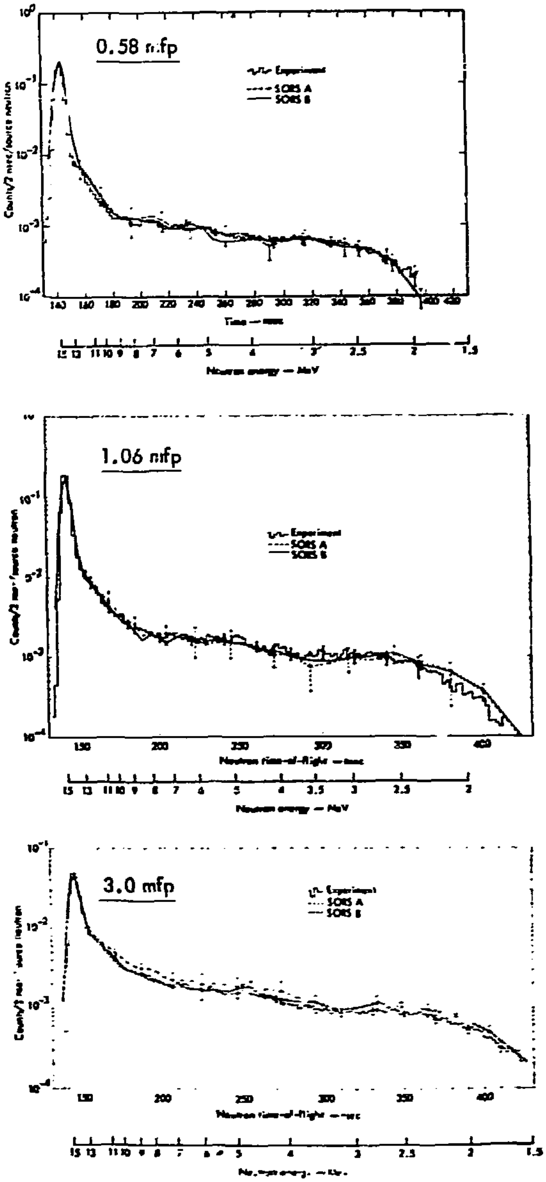


Fig. 3. Comparison between the measured neutron spectra from 0.58, 1.06, and 3.0 mfp of liquid nitrogen and SORS calculations carried out with neutron Libraries A and B, given in Tables 3 and 4.

have the same total cross section[8]; (b) discrepancies as large as 20 to 30% occur for the elastic cross sections and the nonelastic cross sections around 7-MeV neutron energy; and (c) the partial cross sections at 14 MeV (group 66) are very similar. The differences between them are no larger than the quoted 10% errors in the measurements. This last feature of the 14-MeV cross sections is responsible for the close agreement between the two SORS calculations with Libraries A and B. In spite of the closeness of these two calculations, Library B seems to give slightly better overall agreement, particularly with the 3 mfp measurements shown in Fig. 3.

These two libraries were also used by Sauter and Robinson[11] to calculate the neutron transport through liquid ntrogen, where the 14-MeV (d,t) source and neutron detector were both immersed in the nitrogen. These SORS calculations were compared with the measurements carried out by Gulf General Atomic (GGA).[12,13] The calculations carried out with Libraries A and B were normalized to the measurements. Figure 4, taken from Sauter and Robinson's[11] report, compares the SORS predictions with the measurements at a distance of 195.8 cm (approximately 10 mfp) from the neutron source. The numbers in parentheses are the normalization factors. The shapes of the detector-output pulse height spectra obtained with these two calculations as a function of the source-detector distance are quite similar, particularly at the smaller distances. The need for normalization factors of the order of 50% or less at all distances is probably indicative of the source strength uncertainties in the GGA measurements.

Table 3. Neutron Library A for nitrogen.

Group	$E_{initial}$ (MeV)	σ_{total} (mbar)	$\sigma_{elastic}$ (mbar)	σ_{n-e} (mbar)	$\sigma_{(n,n')}$ levels (mbar)	$\sigma_{(n,n')}$ continuum (mbar)	$\sigma_{(n,2n)}$ (mbar)	$\sigma_{(n,x_1)}$[a] (mbar)	$\sigma_{(n,x_2)}$[a] (mbar)
32	1.602	1988	1921	67	—	—	—	22	45
33	1.791	1745	1647	98	—	—	—	13	85
34	1.989	1558	1479	79	—	—	—	20	59
35	2.198	1428	1282	146	—	—	—	36	110
36	2.418	1409	1274	135	—	—	—	30	105
37	2.648	1390	1234	156	—	—	—	21	135
38	2.889	1618	1329	289	2	—	—	42	245
39	3.140	1600	1237	363	4	—	—	34	325
40	3.401	1723	1298	425	6	—	—	47	370
41	3.673	1797	1418	379	10	—	—	59	310
42	3.955	2065	1575	490	15	—	—	75	400
43	4.248	1696	1286	410	18	—	—	52	340
44	4.551	1218	844	374	24	—	—	50	300
45	4.865	1275	920	355	31	—	—	49	275
46	5.189	1459	1197	262	44	—	—	48	170
47	5.524	1382	1106	276	60	—	—	46	170
48	5.869	1421	1119	302	85	—	—	42	175
49	6.224	1307	995	312	112	—	—	40	160
50	6.590	1208	893	315	138	—	—	37	140
51	6.967	1428	1054	374	165	—	—	34	175
52	7.354	1437	1043	394	180	—	—	34	180
53	7.751	1375	959	416	181	—	—	35	200
54	8.159	1220	802	418	182	—	—	36	200
55	8.577	1278	884	394	182	25	—	36	150
56	9.006	1282	878	404	183	45	—	36	140
57	9.445	1363	943	420	183	70	—	37	130
58	9.894	1437	1002	435	183	96	—	36	120
59	10.35	1417	968	449	183	121	—	35	110
60	10.83	1402	940	462	182	149	—	31	100
61	11.31	1468	977	491	180	184	—	27	100
62	11.80	1542	982	560	180	249	—	26	105
63	12.56	1516	961	555	170	280	2	23	80
64	13.33	1526	983	543	142	300	4	22	75
65	13.87	1550	989	561	138	330	6	22	65
66	14.41 14.60	1550	980	570	135	345	8	22	60

[a] x_1 and x_2 stand for single- and double-charged particles, respectively.

Table 4. Neutron Library B for nitrogen.

Group	$E_{initial}$ (MeV)	σ_{total} (mbar)	$\sigma_{elastic}$ (mbar)	σ_{n-e} (mbar)	$\sigma_{(n,n')}$ levels (mbar)	$\sigma_{(n,n')}$ continuum (mbar)	$\sigma_{(n,2n)}$ (mbar)	$\sigma_{(n,x_1)}$[a] (mbar)	$\sigma_{(n,x_2)}$[a] (mbar)
32	1.602	1988	1921	67	—	—	—	22	45
33	1.791	1745	1647	98	—	—	—	13	85
34	1.989	1558	1479	79	—	—	—	20	59
35	2.198	1428	1282	146	—	—	—	36	110
36	2.418	1409	1274	135	—	—	—	30	105
37	2.648	1390	1234	156	—	—	—	21	135
38	2.889	1618	1328	290	3	—	—	42	245
39	3.140	1600	1231	369	10	—	—	34	325
40	3.401	1723	1286	437	20	—	—	47	370
41	3.673	1797	1392	405	36	—	—	59	310
42	3.955	2065	1540	525	50	—	—	75	400
43	4.248	1696	1239	457	65	—	—	52	340
44	4.551	1218	798	420	70	—	—	50	300
45	4.865	1275	863	412	88	—	—	49	275
46	5.189	1459	1125	334	116	—	—	48	170
47	5.524	1382	1020	362	146	—	—	46	170
48	5.869	1421	1026	395	178	—	—	42	175
49	6.224	1307	884	423	220	—	—	40	180
50	6.590	1189	750	439	240	—	—	37	152
51	6.967	1428	870	558	272	—	—	34	252
52	7.354	1437	910	527	242	—	—	34	251
53	7.751	1375	897	478	240	—	—	35	203
54	8.159	1220	782	438	240	—	—	36	162
55	8.577	1278	750	528	240	25	—	36	207
56	9.006	1282	792	490	230	45	—	36	179
57	9.445	1363	836	527	220	70	—	37	200
58	9.894	1437	858	579	210	96	—	36	237
59	10.35	1417	831	586	200	127	—	35	224
60	10.83	1402	787	615	200	166	—	31	218
61	11.31	1468	820	648	180	204	—	27	237
62	11.80	1542	880	660	177	254	1	26	202
63	12.56	1516	920	596	170	280	2	23	121
64	13.33	1525	950	575	142	300	4	22	97
65	13.87	1550	955	595	138	330	6	22	99
66	14.41 14.60	1550	960	590	135	355	8	22	70

[a] x_1 and x_2 stand for single- and double-charge particles, respectively.

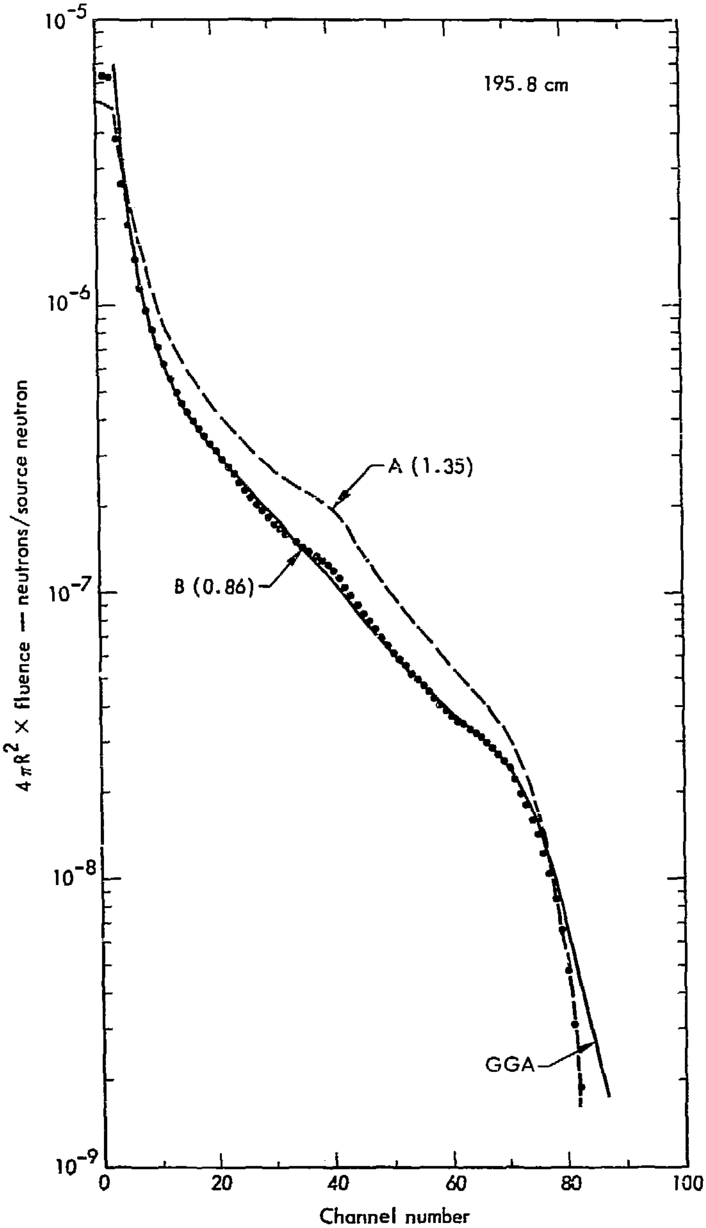


Fig. 4. Comparison between the GGA measurements of the neutron fluence in liquid nitrogen at a distance of 195.8 cm from the 14-MeV source and SORS calculations carried out with Libraries A and B. The numbers in parenthesis are the normalization factors.

Each of these two nitrogen libraries were used with the cross sections for oxygen given in Table 1 to calculate[4] the neutron transport in air. Figure 5, which was taken from Ref. 4, shows the neutron doses as a function of distance calculated with SORS; a 14-MeV point neutron source is assumed in an infinite air medium with a constant density of 1.29 mg/cm^3. Straker's[2] calculation is also shown and is in closer agreement with the one carried out with Library B. Overall, the differences

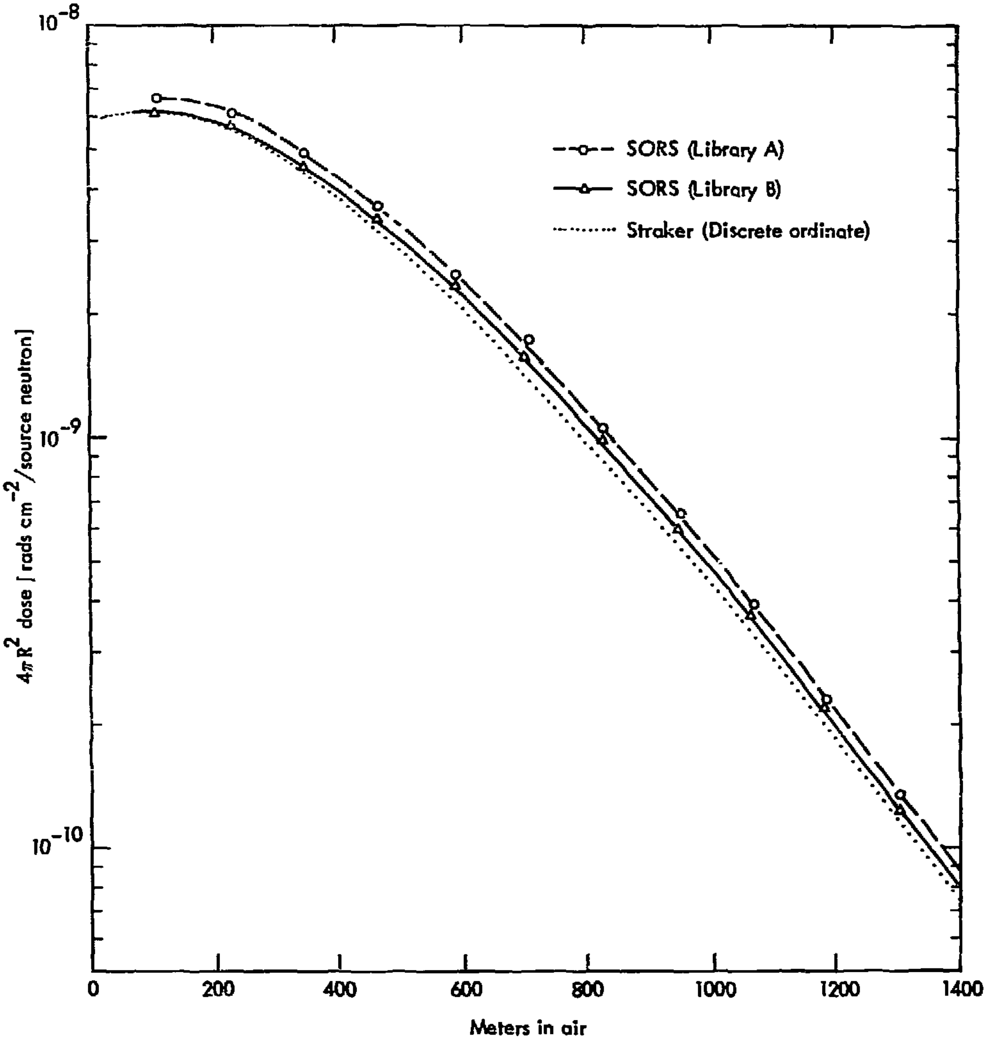


Fig. 5. Comparison of the neutron doses as a function of distance from a 14-MeV neutron source in an infinite air medium with constant density 1.29 mg/cm^3, as predicted by SORS using Libraries A and B and by Straker's[2] calculations using the Discrete Ordinate Method.

between the calculations using Libraries A and B are no larger than 20%.

The neutron fluences in air[4] and in nitrogen[11] for different neutron energies were also calculated with Libraries A and B as a function of distance from the 14-MeV neutron source. In both media the differences between the predictions of A and B are larger for neutron energies between 3 and 11 MeV. Fluences calculated with Library A were higher by as much as 30% for air and as much as 50% for nitrogen at the larger distances.

The preceding discussion summarizes the results of calculations already published in the literature for Libraries A and B. Calculations using Library B gave generally better agreement with the measurements[4,12] and with the dose and fluence calculations carried out by Straker.[2,3]

The low-energy measurements[5] for nitrogen indicated that better agreement could be achieved with the calculations if the (n,n') cross sections to the continuum were lowered. A similar conclusion could be obtained by observing that the calculations are higher between 1.5 and 3 MeV in the high-energy pulse sphere measurements (see Fig. 3).

Harris et al.[14] reported a large (n,α) cross section in nitrogen at 14 MeV by measuring the γ-ray yield. They observed high-energy γ rays, which they attributed to the $^{14}N(n,\alpha)^{11}B$ reaction populating a 5.0-MeV state and a pair of states at 6.7 MeV in ^{11}B, all of which subsequently decayed to the ground state. They[14] estimated that the (n,α) cross sections to these levels could account for as much as 200 mbar and thereby remove a major part of the discrepancy observed in the nitrogen nonelastic cross sections.[10]

The experimental evidence[4,5] for a lower (n,n') cross section to the continuum, the possibility of a larger (n,α) cross section, and the impracticability of having two neutron cross section libraries for nitrogen led to the formulation of Library C. Library C has the following features: (a) the total cross sections are the revised values of Foster and Glascow (July 1969); (b) the elastic cross sections are closer to those in Library B; (c) the (n,n') cross sections to the continuum were decreased as much as 30% at 14 MeV; and (d) the (n,α) cross sections were increased accordingly so that the sum of the partial cross sections would reproduce the total cross sections.

Table 5 shows the cross sections used in Library C between 1.6- and 14.6-MeV neutron energies, and Table 6 gives the probability distribution for the (n,n') cross section to the discrete levels. This distribution among the five levels in nitrogen at 3.95, 5.10, 5.75, 7.07, and 7.95 MeV is the same as that used in Libraries A and B.

SORS calculations with this library for 0.58, 1.06, and 3 mfp of liquid nitrogen are shown in Fig. 6. Also plotted in this figure are the calculations performed earlier[4] with Library B. The predictions of these two calculations, SORS B and SORS C, are very close. However, as expected, Library C yields a much better fit to the neutron spectrum below 3-MeV neutron energy.

The low energy neutron spectra[5] (below 1 MeV) were also calculated using Library C, and Fig. 7 shows a comparison with the measurements. This calculation was performed by representing the level density of the nucleus by an exponential

Table 5. Neutron Library C for nitrogen.

Group	$E_{initial}$ (MeV)	E_{av} (MeV)	σ_{total} (mbar)	$\sigma_{elastic}$ (mbar)	σ_{n-e} (mbar)	$\sigma_{(n,n')}$ level (mbar)	$\sigma_{(n,n')}$ continuum (mbar)	$\sigma_{(n,2n)}$ (mbar)	$\sigma_{(n,x_1)}$[a] (mbar)	$\sigma_{(n,x_2)}$[a] (mbar)
32	1.602	1.696	2096	2027	69	—	—	—	23	46
33	1.791	1.890	1745	1647	98	—	—	—	13	85
34	1.989	2.094	1558	1479	79	—	—	—	20	59
35	2.198	2.308	1428	1282	146	—	—	—	36	110
36	2.418	2.533	1409	1274	135	—	—	—	30	105
37	2.648	2.768	1390	1234	156	—	—	—	21	135
38	2.889	3.014	1598	1325	273	1	—	—	42	230
39	3.140	3.270	1607	1260	347	3	—	—	34	310
40	3.401	3.537	1706	1316	390	5	—	—	45	340
41	3.673	3.814	1787	1419	368	7	—	—	59	302
42	3.955	4.102	2075	1620	455	10	—	—	75	370
43	4.248	4.400	1752	1355	397	25	—	—	52	320
44	4.551	4.708	1258	918	340	30	—	—	50	260
45	4.865	5.027	1256	932	324	40	—	—	49	235
46	5.189	5.356	1467	1211	256	65	—	—	46	145
47	5.524	5.696	1386	1100	286	85	—	—	46	155
48	5.869	6.046	1422	1096	326	110	—	—	50	166
49	6.224	6.407	1314	984	330	130	—	—	40	160
50	6.590	6.778	1207	775	432	180	—	—	70	182
51	6.967	7.160	1384	827	557	225	—	—	80	252
52	7.354	7.552	1440	855	585	240	—	—	85	260
53	7.751	7.955	1380	845	535	230	—	—	85	220
54	8.159	8.368	1230	720	510	230	—	—	70	210
55	8.577	8.792	1268	683	585	240	5	—	80	260
56	9.006	9.226	1299	708	591	240	15	—	76	260
57	9.445	9.670	1356	770	586	220	36	—	70	260
58	9.894	10.12	1420	830	590	220	46	—	64	260
59	10.35	10.59	1379	780	599	210	60	—	65	244
60	10.83	11.07	1360	780	580	199	100	—	40	241
61	11.31	11.55	1437	820	617	184	130	—	56	247
62	11.80	12.18	1532	882	650	177	170	1	56	246
63	12.56	12.94	1566	920	646	170	210	2	43	221
64	13.33	13.60	1547	952	595	142	240	4	22	187
65	13.87	14.14	1558	955	603	138	260	6	22	177
66	14.41	14.50	1550	955	595	135	260	8	22	170

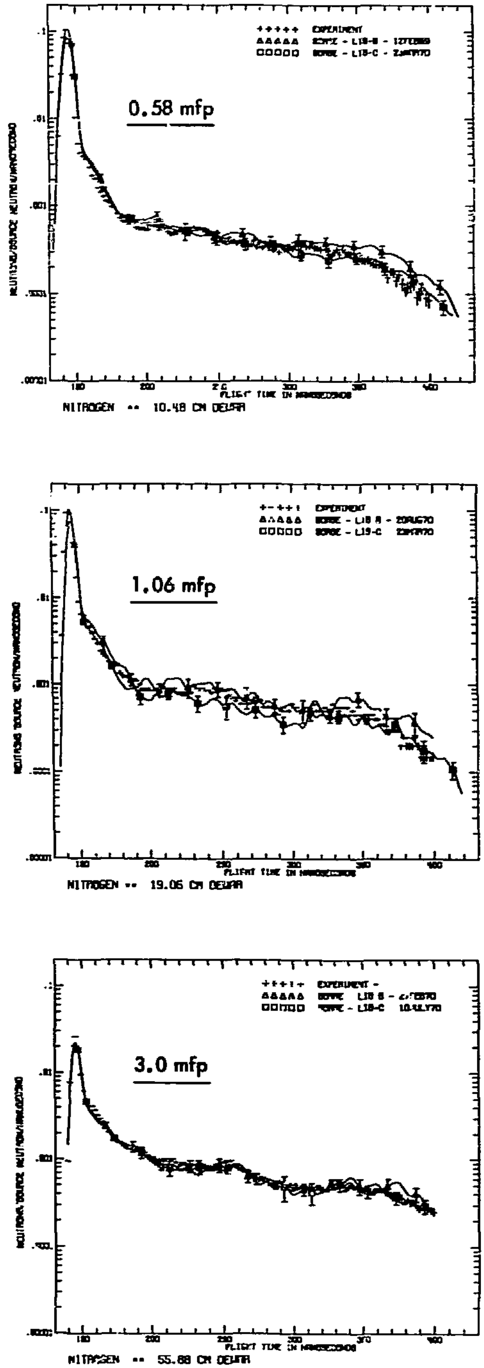
[a] x_1 and x_2 stand for single- and double-charged particles.

Table 6. Probability distribution of the (n,n') as a function of energy (E Division).

E_{lab} (MeV)	Excited levels for nitrogen included in SORS (MeV)				
	3.95	5.10	5.75	7.07	7.95
4.0	1.0	—	—	—	—
6.25	0.90	0.10	—	—	—
7.0	0.604	0.244	0.152	—	—
8.0	0.373	0.245	0.336	0.046	—
10.0	0.300	0.205	0.310	0.127	0.058
12.0	0.265	0.190	0.310	0.157	0.078
14.1	0.254	0.173	0.309	0.178	0.086

function where the nuclear temperature, θ, was a parameter. Agreement with the measurements is good from 1 MeV down to 1 eV neutron energy. The difference between the calculations carried out at temperatures of 1.25 and 1.54 MeV is within the experimental accuracy. Similar calculations[5] were carried out with SORS C to predict the low-energy measurements of GGA.[12] Figure 8 compares GGA measurements with SORS calculations for neutron fluence as a function of mean free paths for 14-MeV neutrons in liquid nitrogen. The calculations were performed for two nuclear temperatures: θ = 0.98 and 1.54 MeV. Agreement with the measurements is fair. The higher temperature gives slightly better agreement at 9.8 mfp.

Some of the high-energy neutron spectra measurements from GGA[12] have



been calculated using Library C.[15] The calculated fluence of neutrons at about 10 mfp in liquid nitrogen is given in Table 7 for Libraries A, B, and C. The values predicted with C are closer to those obtained with B at the higher energies and somewhat in between the predictions of A and B for the lower energies.

Having tested the neutron cross sections of Library C by observing the good agreement between calculation

Table 7. The calculated fluence of neutrons from a point (d,t) source in an infinite medium of liquid nitrogen with neutron Libraries A, B, and C for a distance of 182.8 cm. E_{max} = 15.81 MeV. Fluence is given in $4\pi r^2\phi(r)$ neutrons/source neutron.

Group	E_{min} (MeV)	A ($\times 10^{-3}$)	B ($\times 10^{-3}$)	C ($\times 10^{-3}$)
52	0.136	18.7	17.5	15.0
53	0.261	14.5	14.8	12.3
54	0.429	14.2	11.1	12.8
55	0.638	12.3	11.6	11.1
56	0.889	7.86	7.10	6.78
57	1.18	8.30	6.00	6.73
58	1.72	6.44	4.61	6.70
59	2.55	5.08	3.21	3.72
60	3.55	3.52	2.50	3.08
61	4.73	3.62	1.89	3.44
62	6.07	3.82	1.72	2.03
63	7.57	3.31	1.36	3.01
64	9.24	3.27	2.00	1.78
65	11.1	4.06	1.96	1.97
66	13.1	3.07	2.88	2.24

Fig. 6. Comparison between the measured neutron spectra from 0.58, 1.06, and 3.0 mfp of liquid nitrogen and SORS calculations carried out with neutron Libraries B and C given in Tables 4 and 5.

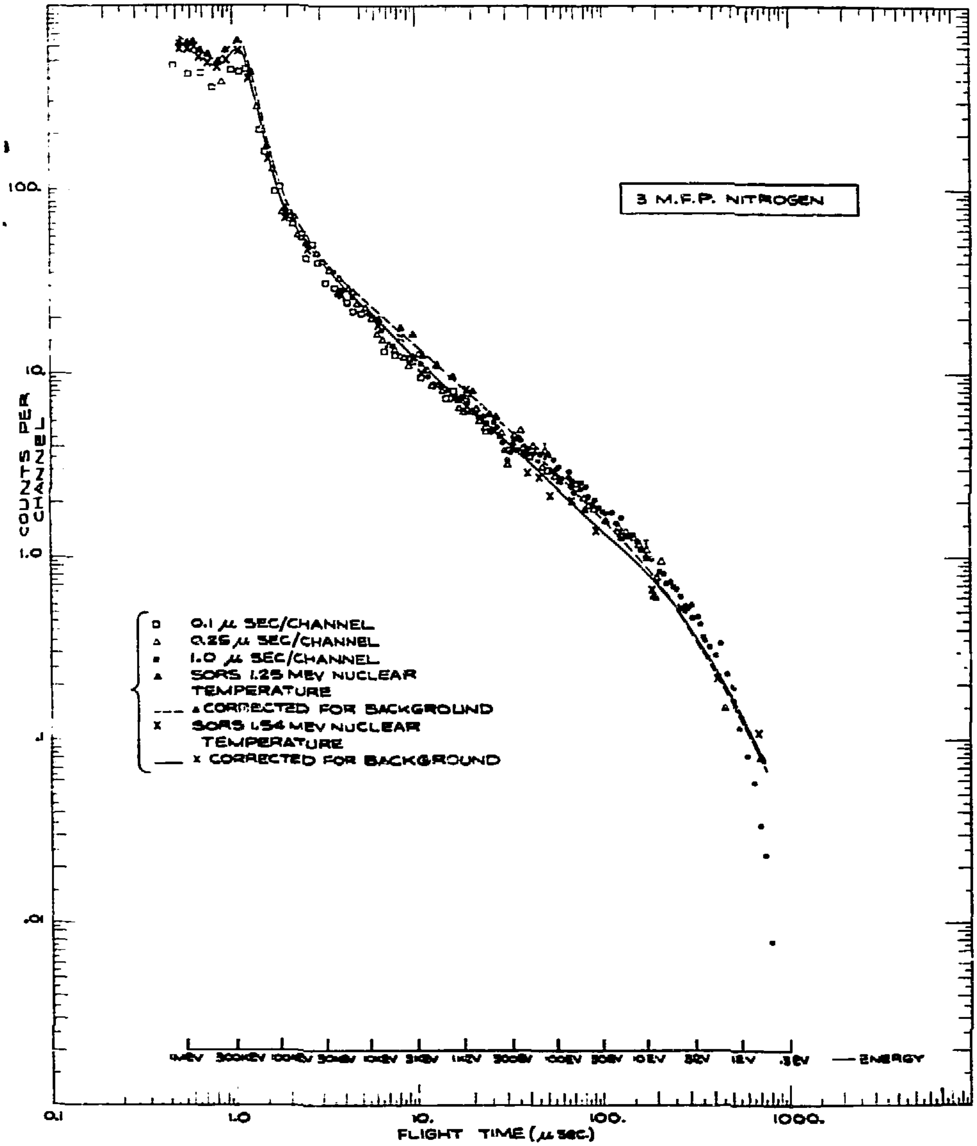


Fig. 7. Comparison between the measured spectrum below 1-MeV neutron energy from 3.0 mfp of liquid nitrogen and SORS calculations carried out with Library C (Table 5) for two nuclear temperatures of 1.25 and 1.54 MeV.

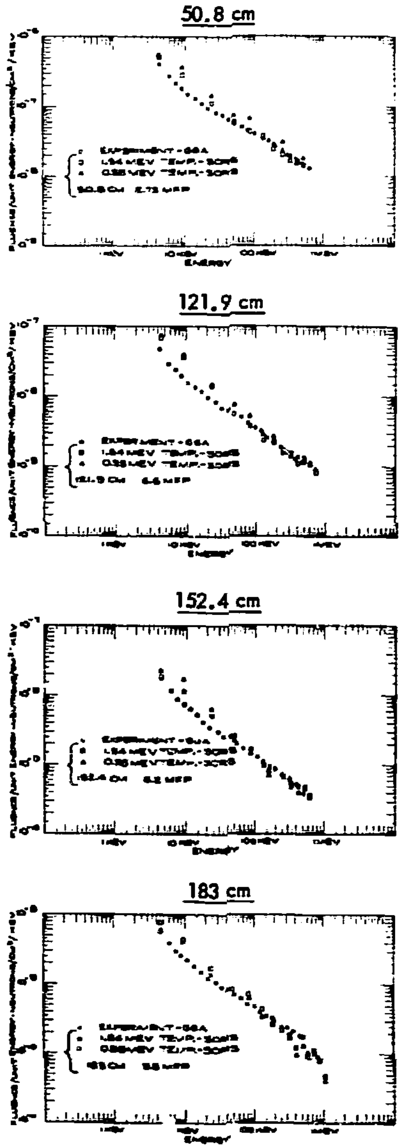


Fig. 8. Comparison between the GGA measurements of the neutron fluences in liquid nitrogen at distances of 50.8, 121.9, 152.4, and 183 cm from the 14-MeV source and SORS calculations carried out with Library C for nuclear temperatures of 0.98 and 1.54 MeV.

and measurements for 1/2 to 10 mfp of liquid nitrogen between 10 keV and 14 MeV, it was interesting to recalculate the air transport problem using Library C.

SORS calculations for air were carried out with the same assumptions that had been made previously, except that the density of air was assumed to be 1.11 mg/cm^3 instead of 1.29 mg/cm^3. This change enabled us to compare our results directly with some recent calculations carried out by Straker.[16] Figure 9 shows the SORS predictions using Library C for nitrogen and the oxygen library shown in Tables 1 and 2. The neutron fluences were calculated as a function of neutron energy at distances of 400 to 1500 m from a 14-MeV neutron source in an infinite homogeneous air medium. Also shown in the figure are Straker's calculations[16] for the two distances. At 400 m the shapes are very similar, although SORS give systematically lower values for the fluences. It is felt that our calculations are to be preferred, since 40 m of air is comparable to 3 mfp and Library C reproduces the low- and high-energy neutron spectra for 3 mfp of liquid nitrogen quite well. At 1500 m the calculated fluences are identical up to 10 MeV. Beyond this energy, SORS predictions are higher by a factor of 2 at 13 MeV and by a factor of 4 at 14 MeV.

The calculated total neutron fluences as a function of distance in an infinite air medium from a 14-MeV (d,t) neutron source are shown in Fig. 10. Straker and Gritzner's[16] calculations are in excellent agreement with the SORS C predictions.

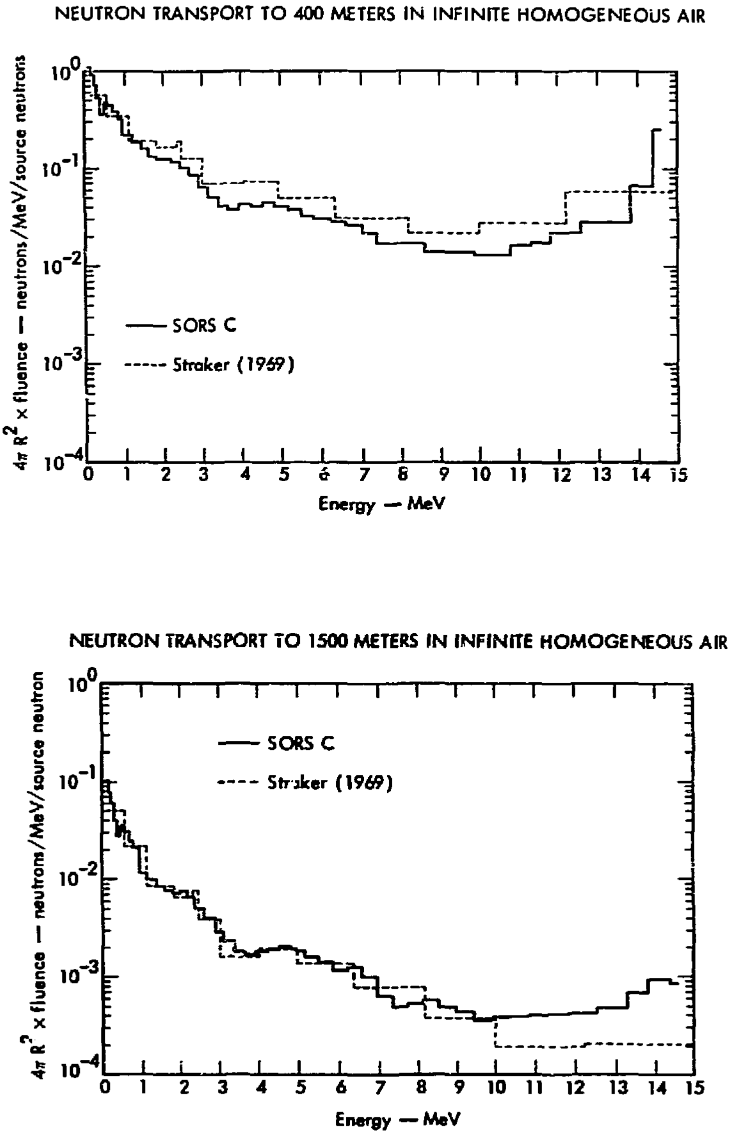


Fig. 9. Comparison of the calculated neutron fluences at 400 and 1500 m from a 14-MeV source in an infinite air medium with constant density 1.11 mg/cm^3 as predicted by SORS using Library C and by Straker's calculations.[16]

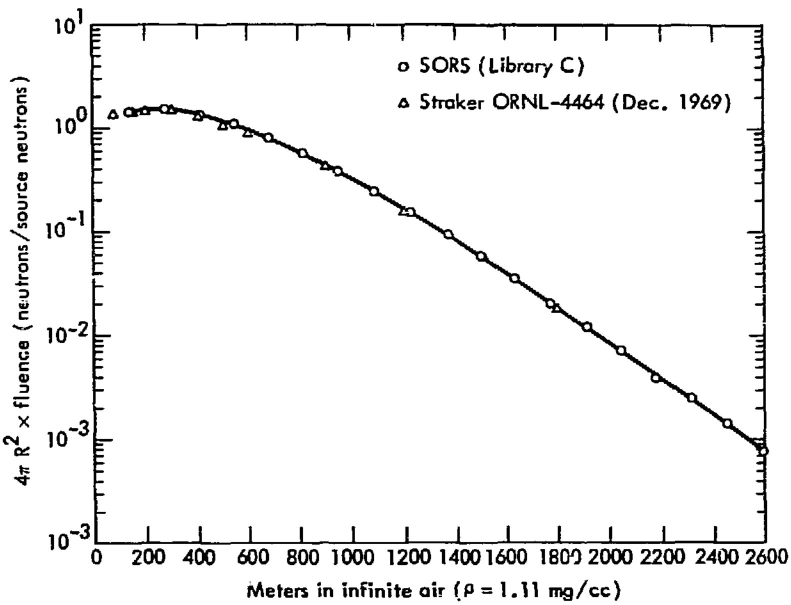


Fig. 10. Comparison of the neutron doses as a function of distance from a 14-MeV source in an infinite air medium with constant density 1.11 mg/cm^3 as predicted by SORS using Library C and by Straker's calculations.[16]

Comparison of the Calculations Using Library C for Nitrogen With Other Evaluations

SORS calculations for neutron transport in liquid nitrogen for a 14-MeV source were carried out with the public SORSND library.[6] Using the program CLYDE, the LRL library was processed into the format of the libraries used in the calculations reported in this paper. Table 8 shows the cross sections for nitrogen between 1.6- and 14.6-MeV neutrons that exist in the LRL library, and Table 6 gives the probability distribution for the (n,n') cross section among the inelastic levels in nitrogen as a function of neutron energy. A comparison of the SORS calculations with this library and library C is shown in Fig. 11 for the integral neutron spectrum above 1.6 MeV for 0.58, 1.06, and 3.0 mfp of liquid nitrogen. Although the statistical errors in the calculations are somewhat large, especially for the 3-mfp case, the predictions of SORS with the LRL library are systematically and significantly higher than the measurements and the predictions using Library C. This effect is attributed to the larger (n,n') cross sections that exist in the public SORS Library.[16]

Finally, a similar comparison was carried out using the nitrogen cross sections evaluated by P. G. Young.[17] Here,

Table 8. *LRL neutron library for nitrogen.*

Group	$E_{initial}$ (MeV)	E_{av} (MeV)	σ_{total} (mbar)	$\sigma_{elastic}$ (mbar)	σ_{n-e} (mbar)	$\sigma_{(n,n')}$ levels (mbar)	$\sigma_{(n,n')}$ continuum (mbar)	$\sigma_{(n,2n)}$ (mbar)	$\sigma_{(n,x_1)}$[a] (mbar)	$\sigma_{(n,x_2)}$[a] (mbar)
32	1.602	1.696	2095	2027	68	—	—	—	23	45
33	1.791	1.890	1816	1721	95	—	—	—	13	82
34	1.989	2.094	1628	1549	79	—	—	—	20	59
35	2.198	2.308	1586	1451	135	—	—	—	36	99
36	2.418	2.533	1390	1263	127	—	—	—	29	98
37	2.648	2.768	1398	1172	226	—	—	—	103	123
38	2.889	3.014	1673	1400	273	—	—	—	42	231
39	3.140	3.270	1667	1322	345	2	—	—	34	309
40	3.401	3.537	1735	1344	391	3	—	—	45	343
41	3.673	3.814	1809	1444	365	5	—	—	59	301
42	3.955	4.102	2117	1664	453	6	—	—	74	373
43	4.248	4.400	1739	1383	356	8	—	—	52	296
44	4.551	4.708	1236	941	295	9	—	—	30	256
45	4.865	5.027	1322	1052	270	12	—	—	24	234
46	5.189	5.356	1454	1265	189	24	—	—	24	141
47	5.524	5.696	1376	1153	223	44	—	—	24	155
48	5.869	6.046	1469	1211	258	68	—	—	24	166
49	6.224	6.407	1342	1067	275	94	—	—	23	158
50	6.590	6.778	1464	1200	264	120	—	—	23	121
51	6.967	7.160	1487	1156	331	141	—	—	23	167
52	7.354	7.552	1410	1066	344	154	—	—	22	168
53	7.751	7.955	1392	1003	389	168	—	—	22	199
54	8.159	8.368	1259	924	335	181	—	—	21	133
55	8.577	8.792	1304	992	312	194	—	—	21	87
56	9.006	9.226	1361	1024	337	223	—	—	21	93
57	9.445	9.670	1440	1064	376	200	67	—	20	89
58	9.894	10.12	1454	1038	416	200	112	—	20	84
59	10.35	10.50	1393	936	457	200	159	—	19	79
60	10.83	11.07	1432	931	501	200	207	—	19	75
61	11.31	11.55	1499	956	543	200	255	—	18	70
62	11.80	12.18	1551	951	600	200	318	—	18	64
63	12.56	12.94	1523	859	664	200	389	2	17	56
64	13.33	13.60	1620	889	731	200	417	3	16	95
65	13.87	14.14	1594	897	697	200	433	4	15	45
66	14.41	14.50	1627	923	704	200	443	5	15	41

[a] x_1 and x_2 stand for single- and double-charged particles.

again, it was necessary to put these cross sections into the proper format through CLYDE. A tabulation of these cross sections is given in Table 9. Furthermore, since Young's evaluation had ten inelastic levels for nitrogen while our format only permits five levels, the (n,n') cross sections to the ten levels were regrouped into five levels at 3.95, 5.10, 5.75, 7.07, and 7.97 MeV; their probability distributions as a function of neutron energy are given in Table 10. The comparison of SORS calculations with Young's evaluation and the C library is shown in Fig. 12. It is seen that the agreement between these two calculations for 0.58, 1.06, and 3.0 mfp of nitrogen is excellent. This is probably due to the close agreement of the neutron elastic and inelastic cross sections at the higher neutron energies (groups 64, 65, 66). The total absorption cross sections, mainly through the (n,p) and (n,α) channels, are identical in the two libraries. However, the (n,p) cross sections in Young's library are much larger at the higher energies, which in turn results in lower (n,α) cross sections than those quoted in Library C. The greatest discrepancies between these two libraries occur for neutron energies

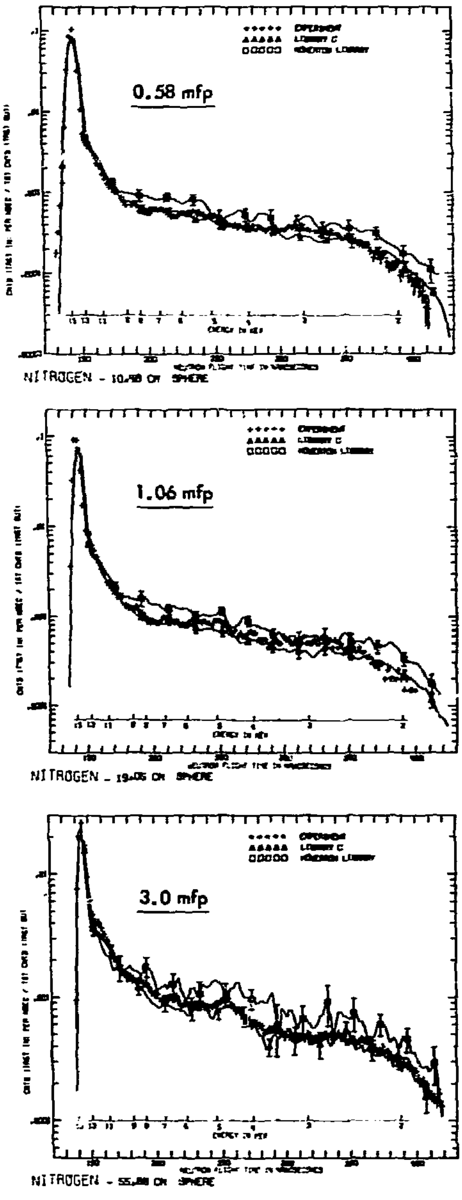


Fig. 11. Comparison between the measured neutron spectra from 0.58, 1.06, and 3.0 mfp of liquid nitrogen and SORS calculations carried out with Library C and the LRL Library given in Tables 5 and 9, respectively.

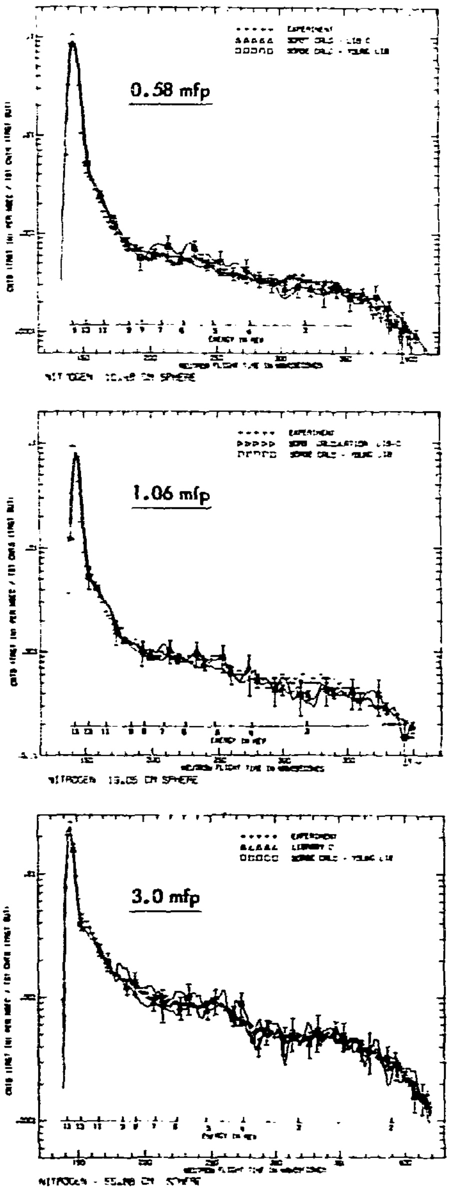


Fig. 12. Comparison between the measured spectra from 0.58, 1.06, and 3.0 mfp of liquid nitrogen and SORS calculations carried out with Library C and the Young-Foster library[17] given in Tables 5 and 10, respectively.

Table 9. Young and Foster neutron library for nitrogen.

Group	$E_{initial}$ (MeV)	E_{av} (MeV)	σ_{total} (mbar)	$\sigma_{elastic}$ (mbar)	σ_{n-e} (mbar)	$\sigma_{(n,n')}$ levels (mbar)	$\sigma_{(n,n')}$ continuum (mbar)	$\sigma_{(n,2n)}$ (mbar)	$\sigma_{(n,x_1)}$[a] (mbar)	$\sigma_{(n,x_2)}$[a] (mbar)
32	1.602	1.696	2112	2025	87	—	—	—	20	67
33	1.791	1.890	1761	1690	71	—	—	—	11	60
34	1.989	2.094	1559	1452	107	—	—	—	17	90
35	2.198	2.308	1551	1422	129	—	—	—	36	93
36	2.416	2.533	1461	1304	157	—	—	—	29	128
37	2.648	2.768	1494	1159	335	1	—	—	105	229
38	2.889	3.014	1726	1378	348	1	—	—	39	398
39	3.140	3.270	1673	1294	379	2	—	—	32	345
40	3.401	3.537	1702	1351	351	3	—	—	44	304
41	3.673	3.814	1850	1409	441	5	—	—	55	381
42	3.955	4.102	2085	1648	437	6	—	—	75	356
43	4.248	4.400	1704	1358	346	9	—	—	49	288
44	4.551	4.708	1268	991	277	17	—	—	39	221
45	4.865	5.027	1191	951	240	26	—	—	36	178
46	5.189	5.356	1459	1231	228	38	—	—	36	154
47	5.524	5.696	1366	1125	241	60	—	—	38	143
48	5.869	6.046	1419	1148	271	86	—	—	43	142
49	6.224	6.407	1356	1053	303	121	—	—	50	132
50	6.590	6.778	1218	875	343	152	—	—	55	136
51	6.967	7.160	1396	1010	386	179	—	—	57	150
52	7.354	7.552	1484	1067	417	195	—	—	57	165
53	7.751	7.955	1481	1054	427	201	—	—	54	172
54	8.159	8.368	1242	841	401	190	1	—	53	157
55	8.577	8.792	1279	905	374	184	2	—	53	135
56	9.006	9.226	1274	901	373	184	11	—	57	121
57	9.445	9.670	1323	931	392	183	28	—	67	114
58	9.894	10.12	1418	994	424	183	46	—	85	110
59	10.35	10.59	1407	942	465	183	70	—	104	108
60	10.83	11.07	1369	871	498	182	94	—	117	105
61	11.31	11.55	1426	902	524	179	118	1	124	107
62	11.80	12.18	1545	983	562	176	155	2	130	99
63	12.56	12.94	1583	968	615	173	211	4	131	96
64	13.33	13.60	1590	960	630	170	232	5	128	95
65	13.87	14.14	1593	960	633	167	243	6	123	94
66	14.41	14.50	1593	960	633	164	250	7	118	94

[a] x_1 and x_2 stand for single- and double-charged particles.

Table 10. Probability distribution of the (n,n') as a function of energy (Phillip Young).

E_{lab} (MeV)	Excited levels (MeV) 3.95	5.10	5.75	7.07	7.95
4.0	1.00				
6.25	0.76	0.24			
7.0	0.565	0.266	0.169		
8.0	0.386	0.235	0.293	0.086	
10.0	0.219	0.117	0.310	0.173	0.181
12.0	0.148	0.124	0.292	0.231	0.205
14.1	0.127	0.157	0.280	0.295	0.141

between 7 and 11 MeV. Young's elastic cross sections are higher by as much as 30% at 8.5 MeV, resulting in a lower nonelastic cross section in this energy interval. Young's cross sections between 7 and 11 MeV are quite similar to those given in Library A.

Conclusions

Comparisons of calculations with measurements have shown that nitrogen Library C for neutron cross sections between 1.6 and 14.6 MeV is definitely preferred over Libraries A and B and should be used in future SORS calculations.

Furthermore, one can conclude that many features of neutron transport in nitrogen and in air from a 14-MeV neutron source are determined primarily by the magnitude of the neutron cross sections at energies around 14 MeV. This is especially true for the calculation of neutron dose as a function of distance from the source. However, the neutron fluence as a function of neutron energy for a given distance is more sensitive to the value of the neutron cross sections at lower energies. Calculations of the fluences using Libraries A and B differ between 20 and 50% in liquid nitrogen, the difference being worse at larger distances from the source. For air the differences are on the order of 30% or less.

It has been shown here that all the available neutron libraries for N, such as Libraries A, B, and C, the ENDF/B library used by Straker in his calculations, and the latest evaluation of the ENDF/B library carried out by Young and Foster at Los Alamos (LASL),[17] give very similar results when neutron transport in air is being calculated. However, it must be pointed out that the differences between these libraries could become important when one is interested in the calculation of γ-ray transport in air. For example, Young and Foster's evaluation and Library A, which are very similar, have higher elastic cross sections than Libraries B or C; this will be reflected in a lower production of γ rays. On the other hand, if the characteristics of γ-ray transport at distances are mainly decided by the features of the high-energy neutron cross sections, then the differences between the values for the absorption channels (n,p), (n,d), or (n,α) in the libraries also become important. Library C, with its large (n,α) cross section, will predict harder γ rays ($E_0 \approx 6$ MeV) than will Young-Foster's library, where the (n,p) cross section is high and the γ rays are much softer. This discrepancy could be resolved by remeasuring the (n,p) and (n,α) cross sections in N at higher energies.

Acknowledgments

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