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THE CORRECTION FACTOR FOR FAST NEUTRON REACTIONS ON SULFUR AND OXYGEN IN THE MANGANOUS-SULFATE-BATH CALIBRATION OF NEUTRON SOURCES

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A Monte Carlo calculation has been made of the correction for neutrons lost to (n,α) and (n,p) reactions with sulfur and oxygen in the manganous sulfate bath calibration of neutron sources. The correction factor is given as a function of initial neutron energy for monoenergetic neutrons in an infinite bath and as a function of manganous sulfate concentration. The correction factors for various published source spectra are also given. The uncertainty in the correction for a given source spectrum due to uncertainties in the source spectrum is much larger than those due to the Monte Carlo calculation or the cross sections.

1. Introduction

The manganous sulfate bath method for the calibration of neutron sources consists of activating a solution of manganous sulfate with a neutron source and inferring the strength of the neutron source from the manganese activity of the bath. Many types of neutron sources emit neutrons with energies greater than the thresholds of interactions such as ^{16}O(n,γ)^{17}O which cause the neutron to disappear before reaching low neutron energies and being captured by the ^{55}Mn(n,γ)^{56}Mn or the ^{1}H(n,γ)^{2}H reactions. It is necessary to know the numbers of neutrons lost to all types or reactions other than ^{55}Mn(n,γ)^{56}Mn to correctly infer the strength of the neutron source by this method.

Here the correction factor for fast neutron losses is given as a function of the initial energy of the neutron from the source. Consequently, the correction, f, for a particular source is given by

$$f = \int_0^\infty c(E)s(E)\,\mathrm{d}E$$

where $c(E)$ is the correction factor as a function of initial neutron energy E, and $s(E)$ is the unit normalized spectrum of the source. A comparison of past calculations and measurements for particular sources to the present calculation applied to various published neutron source spectra is given in table 1.

2. Description of the calculation

2.1. GENERAL CONSIDERATIONS

The calculation is divided into three parts. The first part is the program for the preparation of the cross section data for the neutron tracking part. The second part is the neutron tracking program which computes the correction factor for given initial neutron energies. The third part is the folding program which determines the correction for given neutron source spectra given the correction factor for all initial neutron energies.

The following types of interactions were included in the calculation:

Hydrogen: elastic scattering, [^{1}H(n,γ)^{2}H was neglected since neutrons were not followed below 1 MeV],

Oxygen: elastic scattering, inelastic scattering to the 6.1 MeV state, (n,α), (n,p) and (n,d),

Sulfur: elastic scattering, inelastic scattering to the 2.24 MeV state, (n,α) and (n,p),

Manganese: elastic scattering, inelastic scattering to the 0.9 MeV state and (n,γ).

Experimental angular distributions were used for oxygen elastic scattering, sulfur elastic scattering, and sulfur inelastic scattering; all other elastic and inelastic scatterings were assumed isotropic in the center of mass system. An infinite medium was assumed. Source holder and source materials were neglected.

2.2. THE DATA PREPARATION PROGRAM

This program reads microscopic cross sections for up to 150 data points per interaction type. The cross section points are chosen so that a linear interpolation between points will be an accurate representation of the cross sections and of the microscopic angular distributions. It then computes the macroscopic cross sections for 100 energy bins distributed linearly in energy between two arbitrary input energies. The distribution of energy bins for the program may be varied to almost any distribution which may be described by an analytic function. A linear distribution of energy bins was chosen over the more common logarithmic distribution because of the greater importance of the cross sections near the initial neutron energy in this calculation. The bin sizes were typically 0.035 MeV for initial neutron energies below 6.5 MeV and 0.1 MeV for initial neutron energies above 6.5 MeV. The macroscopic cross sections are the cross

TABLE 1
Comparison of this calculation with other calculations and measurements.

WATER:		
Po-Be(α,n)	1.0352 ± 0.021	Elliot estimate (1948)1)
	1.0305	This calculation using the spectrum of Medveczky with carrier (1961)2)
	1.0438	This calculation using the spectrum of Medveczky carrier free (1961)2)
	1.0319	This calculation using the spectrum of Murray (1958)3)
Ra-Be(α,n)	1.0244 ± 0.003	de Troyer measurement (1954)4) as amended by Geiger (1959)5)
	1.0309	Huber calculation (1950)6)
	1.0183 ± 0.004	McTaggart calculation (1961)7)
	1.0070 ± 0.013	McTaggart experiment (1961)7)
	1.0172 ± 0.0025	Ryves and Harden experiment (1965)31)
	1.0244	This calculation using the spectrum of Hess (calculation) (1957)8)
	1.0193	This calculation using the spectrum of Hill (experiment) (1947)9) with Hess' lo energy group
	1.0243	This calculation using the spectrum of Geiger experiment with 22% assumed i the low group (1964)10)
	1.0193	This calculation using the spectrum of Geiger experiment with 37% assumed i the low group (1964)10)
	1.0147	This calculation using the spectrum of Geiger experiment with 52% assumed i the low group (1964)10)
	1.0253	This calculation using the spectrum of Medveczky (1961)2)
SATURATED BATH:		
Po-Be(α,n)	1.0288 ± 0.005	McTaggart calculation (1961)7)
	1.0440	This calculation using the spectrum of Medveczky with carrier (1961)2)
	1.0611	This calculation using the spectrum of Medveczky carrier free (1961)2)
	1.0452	This calculation using the spectrum of Murray (1958)3)
Ra-Be(α,n)	1.0348 ± 0.005	McTaggart calculation (1961)7)
	1.0315 ± 0.003	Ryves and Harden experiment (1965)31)
	1.0342	This calculation using the spectrum of Hess (calculation) (1957)8)
	1.0275	This calculation using the spectrum of Hill (experiment) (1947)9) with Hess' lo energy group
	1.0346	This calculation using the spectrum of Geiger experiment with 22% assumed in the low group (1964)10)
	1.0276	This calculation using the spectrum of Geiger experiment with 37% assumed in the low group (1964)10)
	1.0210	This calculation using the spectrum of Geiger experiment with 52% assumed in the low group (1964)10)
	1.0366	This calculation using the spectrum of Medveczky (1961)2)
Fission	1.0054 ± 0.005	McTaggart calculation (1961)7)
	1.0063	This calculation using the spectrum of Watt (1951)11)

sections averaged over the energy bin. The cross sections are then converted to relative interaction probabilities for the energy bins. The relative interaction probabilities give the exact single scattering approximation to the correction factor averaged over the energy bin. Angular distributions are read in at up to 41 angles per distribution and for up to 150 energies per interaction type. The angular distributions are determined for the centers of the energy bins by linear interpolation and the distribution for the center of the energy bin is used for the entire bin. The angular distribution output of the data preparation program is in terms of the cosines of the upper edges of the angular bins of equal probability for up to 40 angular bins. There is one set of cosines for each energy bin.

2.3. THE TRACKING PROGRAM

This program uses the output of the data preparation program as its input for cross sections. For an arbitrary number of energies it reads the initial neutron energy, the number of neutrons to be followed and the maximum number of scatterings through which each neutron is to be tracked. An individual neutron track is terminated if it is lost to an (n,α), (n,p), (n,d) or (n,γ) interaction; if its energy falls below the bottom of the provided cross section information; if its energy falls below an input discard energy; or if it undergoes an input maximum number of scatterings.

In following a neutron, the center of mass scattering angle and the lab scattering angle are determined to the nearest degree; the provided angular distribution linearly interpolated in cosine of the center of mass scattering angle; and the conversion of center of mass to lab system is included in the determination of the new neutron energy.

The program records the neutrons lost to the various interactions and computes the correction factor by which the actual number of neutrons passing below the given discard energy should be multiplied to give the original number of starting neutrons.

2.4. THE FOLDING PROGRAM

This program will read up to 500 points of any correction curve as a function of initial neutron energy and up to 500 points of any source spectrum. The points are chosen so a linear interpolation is an accurate representation of the curves. The spectrum may be in arbitrary units. The program then normalizes the spectrum, multiplies the normalized spectrum by the correction curve at 2000 linearly interpolated points and gives the resultant source correction factor.

2.5. INPUT DATA

The following input cross sections were used:

^{1}H elastic	AWRE[12])
^{16}O elastic	Joanou and Fenech[13])
^{16}O(n,n′) to the 6.1 MeV state	Joanou and Fenech[13])

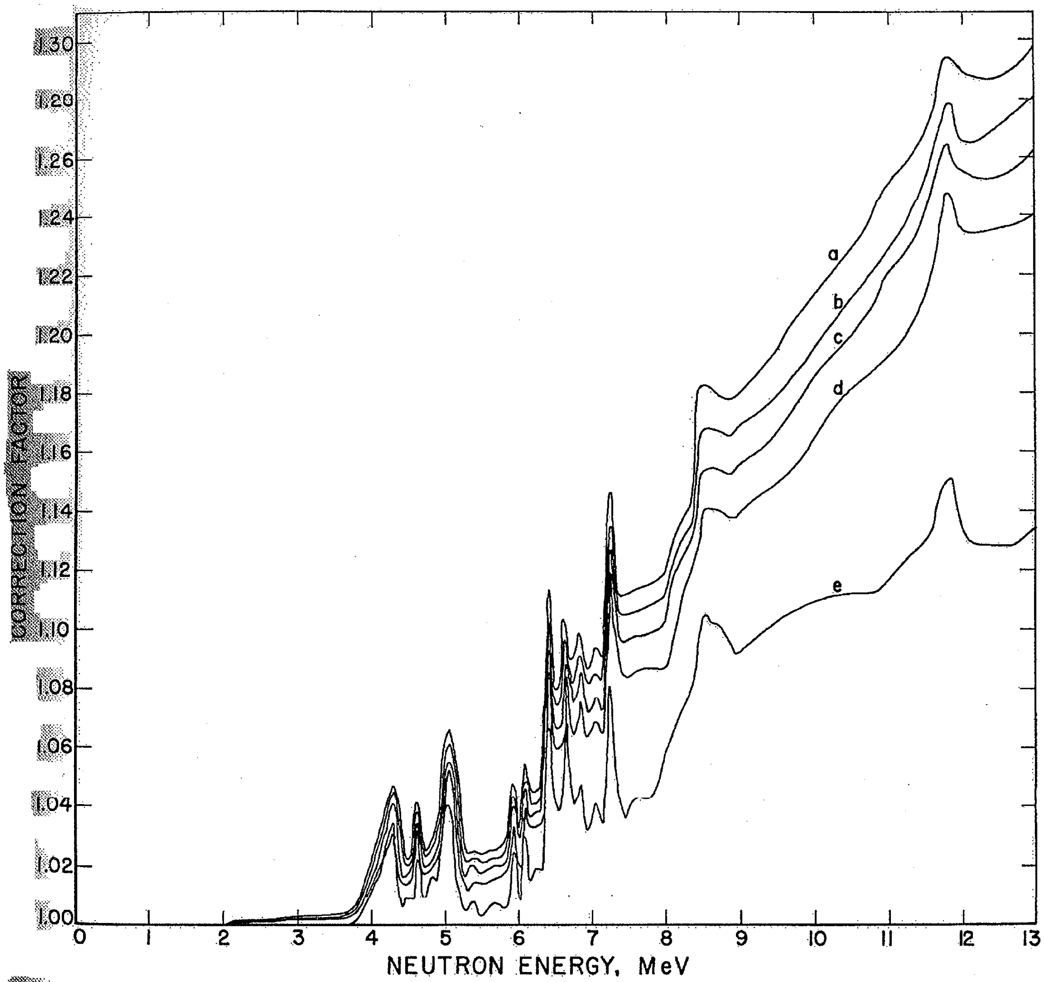

Fig. 1. Fast neutron loss correction factor as a function of initial neutron energy. Monte Carlo results for curve a: 520 g/l $MnSO_4$, curve b: 338 g/l $MnSO_4$, curve c: 237 g/l $MnSO_4$, curve d: 0 g/l $MnSO_4$, curve e: Single scattering results for 237 g/l $MnSO_4$.

^{16}O(n,α)	Joanou and Fenech[13])
^{16}O(n,d)	Joanou and Fenech[13])
^{55}Mn elastic	BNL 325[14])
^{55}Mn(n,n′) to the 0.9 MeV state	BNL 325[14])
^{55}Mn(n,γ)	BNL 325[14])
S elastic	BNL 325[14])

Sulfur was assumed to be 95.8% ^{32}S and 4.2% ^{34}S

^{32}S (n,p)	EUR 119.e[15])
^{32}S(n,α)	EUR 119.e[15])
^{34}S(n,α)	EUR 119.e[15])

S(n,n′) is determined from the integration of the angular distribution

O elastic angular BNL 400[16])

S elastic angular BNL 400[16])

S inelastic angular BNL 400[16]) to the 2.24 MeV stat

The densities of the manganous sulfate solution a function of MnSO$_4$ concentration were taken from t International Critical Tables of 1928[17]) interpolat to 20°C.

3. Description of results

The graphs of the correction factor as a functi of initial neutron energy and manganous sulfate co centration are given in fig.1. A numerical representati

TABLE 2

Digital representation of the correction factor as a function of initial neutron energy. *A* = the correction factor; *B* = the correspondi initial neutron energy

Concentration 520 gram MnSO$_4$ per liter of solution									
A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
1.0000	0.00	1.0000	2.00	1.0008	2.08	1.0011	2.14	1.0013	2.28
1.0016	2.40	1.0020	2.61	1.0028	2.93	1.0031	3.15	1.0035	3.40
1.0038	3.60	1.0048	3.72	1.0060	3.76	1.0080	3.80	1.0100	3.83
1.0150	3.90	1.0170	3.92	1.0190	3.94	1.0200	3.95	1.0220	4.00
1.0250	4.04	1.0300	4.09	1.0450	4.14	1.0400	4.20	1.0450	4.25
1.0470	4.28	1.0470	4.32	1.0450	4.33	1.0420	4.36	1.0400	4.37
1.0350	4.38	1.0300	4.41	1.0250	4.43	1.0230	4.45	1.0223	4.48
1.0230	4.52	1.0250	4.53	1.0300	4.55	1.0400	4.60	1.0405	4.62
1.0400	4.64	1.0350	4.66	1.0300	4.68	1.0260	4.70	1.0250	4.72
1.0250	4.76	1.0280	4.80	1.0300	4.83	1.0350	4.88	1.0400	4.92
1.0500	4.94	1.0550	4.96	1.0600	4.98	1.0620	5.00	1.0650	5.04
1.0660	5.06	1.0650	5.07	1.0600	5.12	1.0550	5.14	1.0500	5.17
1.0450	5.20	1.0400	5.21	1.0300	5.24	1.0250	5.25	1.0230	5.28
1.0240	5.30	1.0250	5.36	1.0250	5.42	1.0240	5.48	1.0240	5.54
1.0250	5.60	1.0250	5.68	1.0260	5.74	1.0280	5.83	1.0290	5.84
1.0350	5.86	1.0400	5.88	1.0450	5.89	1.0580	5.92	1.0570	5.94
1.0550	5.96	1.0350	5.99	1.0320	6.00	1.0350	6.02	1.0450	6.04
1.0500	6.07	1.0540	6.08	1.0500	6.12	1.0450	6.16	1.0440	6.18
1.0450	6.20	1.0460	6.32	1.1130	6.42	1.0800	6.46	1.0790	6.48
1.0800	6.50	1.0810	6.56	1.1030	6.62	1.0900	6.68	1.0900	6.74
1.0950	6.80	1.0990	6.83	1.0900	6.88	1.0870	6.90	1.0840	6.92
1.087	6.96	1.088	6.98	1.090	7.00	1.093	7.02	1.099	7.03
1.097	7.08	1.091	7.14	1.146	7.24	1.146	7.26	1.130	7.31
1.115	7.34	1.112	7.36	1.111	7.40	1.111	7.44	1.113	7.58
1.114	7.64	1.115	7.78	1.116	7.86	1.118	7.97	1.120	8.00
1.125	8.05	1.130	8.09	1.135	8.18	1.140	8.32	1.142	8.36
1.150	8.17	1.130	8.09	1.135	8.18	1.140	8.32	1.142	8.36
1.150	8.40	1.175	8.42	1.180	8.44	1.183	8.48	1.183	8.60
1.182	8.64	1.180	8.72	1.179	8.76	1.178	8.82	1.178	8.90
1.180	9.01	1.182	9.10	1.185	9.18	1.190	9.35	1.195	9.50
1.200	9.63	1.250	9.76	1.210	9.91	1.215	10.08	1.220	10.23
1.225	10.36	1.230	10.54	1.235	10.68	1.237	10.74	1.240	10.78
1.245	10.86	1.248	10.92	1.250	10.98	1.255	11.16	1.260	11.32
1.265	11.44	1.270	11.54	1.275	11.62	1.278	11.66	1.280	11.68
1.285	11.70	1.290	11.72	1.282	11.74	1.284	11.78	1.294	11.86
1.293	11.91	1.290	12.01	1.289	12.06	1.288	12.14	1.287	12.28
1.287	12.50	1.288	12.58	1.289	12.64	1.294	12.80	1.295	12.92
1.298	13.00								

BLE 2 (continued)

Concentration 338 gram $MnSO_4$ per liter of solution

A	B	A	B	A	B	A	B	A	B
1.0000	0.00	1.0000	2.00	1.0004	2.04	1.0007	2.11	1.0010	2.24
1.0012	2.38	1.0013	2.50	1.0016	2.69	1.0019	2.82	1.0020	2.88
1.0023	3.10	1.0027	3.42	1.0028	3.51	1.0030	3.59	1.0032	3.63
1.0038	3.70	1.0050	3.74	1.0060	3.78	1.0070	3.82	1.0130	3.86
1.015	3.93	1.020	4.01	1.022	4.04	1.026	4.07	1.030	4.14
1.035	4.19	1.040	4.23	1.043	4.28	1.045	4.30	1.044	4.32
1.040	4.35	1.030	4.40	1.025	4.42	1.021	4.44	1.020	4.46
1.021	4.53	1.025	4.55	1.030	4.56	1.035	4.58	1.037	4.60
1.038	4.62	1.037	4.64	1.035	4.66	1.030	4.67	1.025	4.68
1.024	4.70	1.023	4.72	1.023	4.76	1.025	4.79	1.029	4.87
1.035	4.90	1.040	4.93	1.045	4.95	1.055	4.98	1.058	5.00
1.060	5.02	1.061	5.06	1.060	5.08	1.045	5.12	1.040	5.14
1.045	5.16	1.040	5.18	1.035	5.20	1.030	5.22	1.025	5.24
1.023	5.26	1.021	5.28	1.022	5.29	1.023	5.38	1.022	5.44
1.021	5.50	1.021	5.58	1.023	5.66	1.023	5.74	1.024	5.80
1.025	5.83	1.027	5.86	1.030	5.88	1.040	5.90	1.043	5.91
1.044	5.92	1.043	5.94	1.040	5.96	1.030	6.00	1.029	6.01
1.030	6.02	1.035	6.05	1.035	6.07	1.048	6.08	1.048	6.11
1.045	6.14	1.040	6.18	1.040	6.21	1.041	6.28	1.043	6.34
1.103	6.42	1.075	6.48	1.074	6.50	1.075	6.52	1.076	6.54
1.096	6.62	1.090	6.68	1.085	6.70	1.082	6.74	1.084	6.77
1.090	6.82	1.091	6.84	1.090	6.86	1.085	6.90	1.083	6.92
1.081	6.94	1.082	6.98	1.084	7.00	1.085	7.02	1.085	7.08
1.083	7.14	1.136	7.22	1.135	7.26	1.110	7.34	1.107	7.36
1.105	7.40	1.105	7.48	1.107	7.64	1.109	7.86	1.110	7.94
1.111	8.00	1.115	8.03	1.120	8.08	1.125	8.12	1.130	8.22
1.133	8.29	1.135	8.34	1.137	8.38	1.139	8.40	1.160	8.45
1.165	8.48	1.168	8.50	1.168	8.66	1.167	8.76	1.166	8.82
1.165	8.86	1.166	8.93	1.168	8.97	1.170	9.06	1.175	9.32
1.178	9.44	1.180	9.53	1.185	9.70	1.190	9.86	1.195	10.01
1.120	10.15	1.125	10.29	1.210	10.43	1.215	10.60	1.220	10.78
1.223	10.84	1.225	10.88	1.228	10.99	1.230	11.06	1.235	11.18
1.238	11.26	1.240	11.30	1.246	11.42	1.250	11.48	1.255	11.54
1.260	11.60	1.265	11.66	1.267	11.69	1.270	11.71	1.275	11.76
1.277	11.78	1.278	11.82	1.278	11.84	1.277	11.87	1.275	11.89
1.270	11.92	1.267	11.94	1.264	12.00	1.264	12.12	1.265	12.25
1.270	12.45	1.273	12.62	1.275	12.74	1.280	12.98	1.291	13.02

Concentration 237 gram $MnSO_4$ per liter of solution

A	B	A	B	A	B	A	B	A	B
1.0000	0.00	1.0000	2.00	1.0003	2.07	1.0005	2.10	1.0009	2.49
1.0010	2.63	1.0015	2.95	1.0018	3.25	1.0019	3.43	1.0022	3.60
1.0023	3.64	1.0025	3.66	1.0028	3.68	1.0033	3.76	1.0040	3.74
1.005	3.80	1.006	3.82	1.010	3.88	1.014	3.94	1.018	4.02
1.020	4.09	1.023	4.10	1.029	4.15	1.031	4.17	1.033	4.21
1.034	4.23	1.038	4.26	1.040	4.27	1.043	4.30	1.040	4.32
1.030	4.37	1.020	4.39	1.017	4.40	1.016	4.42	1.017	4.49
1.018	4.51	1.019	4.53	1.020	4.55	1.025	4.57	1.034	4.60
1.036	4.62	1.030	4.65	1.021	4.69	1.020	4.70	1.020	4.74
1.027	4.81	1.024	4.86	1.026	4.89	1.028	4.90	1.035	4.94
1.040	4.96	1.045	4.98	1.047	5.00	1.053	5.03	1.055	5.04
1.055	5.08	1.050	5.12	1.045	5.15	1.040	5.16	1.029	5.20
1.025	5.21	1.020	5.24	1.018	5.26	1.017	5.28	1.018	5.31

(Table continued)

TABLE 2 *(continued)*

1.018	5.36	1.021	5.36	1.020	5.40	1.019	5.43	1.017	5.48
1.020	5.63	1.021	5.70	1.020	5.76	1.021	5.81	1.022	5.83
1.023	5.86	1.025	5.88	1.028	5.90	1.039	5.92	1.041	5.94
1.035	5.96	1.026	5.98	1.024	6.00	1.024	6.03	1.030	6.04
1.035	6.05	1.044	6.08	1.046	6.10	1.045	6.11	1.037	6.13
1.036	6.16	1.037	6.20	1.038	6.25	1.038	6.30	1.095	6.42
1.070	6.48	1.066	6.50	1.067	6.58	1.092	6.64	1.090	6.66
1.077	6.72	1.075	6.74	1.077	6.78	1.080	6.80	1.085	6.86
1.084	6.88	1.080	6.89	1.075	6.91	1.073	6.92	1.071	6.94
1.072	6.95	1.073	6.98	1.075	7.02	1.076	7.03	1.077	7.04
1.076	7.08	1.072	7.12	1.073	7.14	1.126	7.24	1.127	7.26
1.126	7.28	1.115	7.32	1.105	7.35	1.100	7.36	1.087	7.38
1.096	7.40	1.096	7.46	1.097	7.52	1.098	7.62	1.098	7.70
1.099	7.80	1.100	7.90	1.101	7.97	1.103	8.00	1.105	8.03
1.110	8.05	1.115	8.10	1.118	8.12	1.120	8.14	1.123	8.20
1.125	8.24	1.129	8.34	1.131	8.38	1.133	8.40	1.135	8.42
1.150	8.45	1.153	8.48	1.154	8.52	1.155	8.58	1.154	8.72
1.152	8.86	1.153	8.91	1.156	8.98	1.157	9.06	1.160	9.22
1.162	9.33	1.165	9.46	1.170	9.60	1.175	9.73	1.180	9.85
1.183	9.93	1.186	10.01	1.190	10.14	1.195	10.31	1.199	10.48
1.205	10.68	1.209	10.80	1.212	10.86	1.215	10.90	1.220	10.98
1.222	11.06	1.225	11.15	1.228	11.26	1.230	11.32	1.233	11.38
1.237	11.45	1.242	11.52	1.247	11.60	1.252	11.64	1.257	11.69
1.261	11.73	1.263	11.75	1.264	11.78	1.265	11.80	1.264	11.84
1.260	11.89	1.257	11.92	1.256	11.94	1.255	12.00	1.244	12.22
1.253	12.48	1.254	12.60	1.255	12.66	1.258	12.80	1.260	12.86
1.265	13.00								

Concentration 0 gram $MnSO_4$ per liter of solution

A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
1.0000	0.00	1.0000	3.67	1.0003	3.70	1.0007	3.75	1.0009	3.78
1.003	3.83	1.004	3.88	1.005	3.90	1.007	3.94	1.010	3.98
1.013	4.02	1.015	4.06	1.017	4.10	1.019	4.14	1.021	4.16
1.027	4.18	1.030	4.23	1.034	4.28	1.035	4.30	1.025	4.33
1.020	4.35	1.017	4.37	1.015	4.38	1.014	4.42	1.014	4.48
1.015	4.51	1.017	4.55	1.020	4.58	1.030	4.62	1.020	4.66
1.017	4.68	1.016	4.72	1.017	4.78	1.020	4.83	1.023	4.90
1.025	4.92	1.030	4.96	1.040	5.00	1.050	5.04	1.053	5.06
1.050	5.08	1.040	5.12	1.030	5.16	1.025	5.19	1.020	5.20
1.018	5.21	1.013	5.28	1.017	5.30	1.018	5.34	1.020	5.40
1.019	5.48	1.020	5.60	1.021	5.66	1.022	5.78	1.023	5.82
1.020	5.86	1.025	5.92	1.034	5.94	1.025	5.96	1.021	5.98
1.020	6.00	1.020	6.04	1.022	6.06	1.039	6.10	1.035	6.12
1.034	6.13	1.033	6.14	1.033	6.22	1.034	6.30	1.028	6.34
1.086	6.42	1.062	6.46	1.060	6.48	1.059	6.52	1.060	6.60
1.065	6.63	1.075	6.64	1.084	6.66	1.075	6.68	1.070	6.70
1.068	6.72	1.064	6.76	1.070	6.81	1.075	6.84	1.067	6.88
1.065	6.90	1.063	6.92	1.064	6.96	1.067	7.01	1.068	7.02
1.069	7.06	1.064	7.14	1.066	7.18	1.119	7.26	1.100	7.32
1.095	7.34	1.090	7.38	1.088	7.40	1.087	7.42	1.086	7.46
1.086	7.58	1.087	7.68	1.087	7.86	1.087	8.00	1.089	8.04
1.091	8.08	1.095	8.10	1.100	8.16	1.105	8.18	1.110	8.23
1.115	8.28	1.118	8.33	1.120	8.36	1.122	8.40	1.125	8.46
1.139	8.50	1.141	8.56	1.141	8.62	1.140	8.74	1.138	8.84
1.137	8.90	1.138	8.96	1.145	9.26	1.150	9.54	1.153	9.66
1.155	9.74	1.159	9.88	1.163	10.00	1.170	10.16	1.175	10.24
1.180	10.48	1.185	10.66	1.190	10.90	1.192	11.00	1.198	11.20
1.200	11.26	1.205	11.36	1.210	11.46	1.215	11.56	1.217	11.60
1.223	11.66	1.228	11.69	1.235	11.72	1.240	11.76	1.245	11.78
1.248	11.80	1.248	11.84	1.240	11.91	1.235	11.96	1.234	12.00
1.234	12.16	1.235	12.28	1.236	12.38	1.237	12.50	1.237	12.76
1.236	13.00								

of the correction factors is given in table 2. A large number of different initial neutron energies for each concentration could not be run due to the expense of calculation. The correction curve for all initial neutron energies and for the four bath concentrations were determined from the Monte Carlo results (the Monte Carlo program gives the correction factor for a given initial neutron energy and a given bath concentration) in the following fashion:

The data preparation program provided the exact single scattering approximation to the correction factor as a function of energy. This is a representation of the cross section magnitudes and competition as a function of energy. The Monte Carlo program was run at 41 different initial neutron energies for the 237 g/l concentration. Some of the energies were chosen to prove that, except for a difference in magnitude, the Monte Carlo results follow the shape of the single scattering results as a function of energy quite closely. The remainder of the energies were chosen to give the displacement of the Monte Carlo from the single scattering results. Certain of the energies were rerun with different random numbers to determine the statistical uncertainty of the Monte Carlo results.

The Monte Carlo curve for all initial neutron energies for the 237 g/l concentration could be drawn since the shape of the Monte Carlo curve is known from the single scattering results and the displacement of the Monte Carlo curve from the single scattering curve is known from the individual Monte Carlo runs described in the previous paragraph. The Monte Carlo program was then run for the other bath concentrations at 20 different initial neutron energies to give the displacement of the Monte Carlo curve as a function of manganese sulfate concentration. The Monte Carlo curves for other concentrations may be drawn because their shape is known from the shape of the 237 g/l curve and the displacement from the 237 g/l curve is known from the Monte Carlo runs. The drawn curves were then spot checked with a few more runs of the Monte Carlo program. All points were run for 10000 neutrons. The maximum allowed number of scatterings was 20 but this number of scatterings was never attained before the neutron track was stopped because the neutron had been lost to an (n,p) of (n,α) reaction or because the energy of the neutron had fallen below one MeV. The relation between percentage by weight of $MnSO_4$ and concentration in gram per liter (which was used) is given in table 3. The correction factors for various spectra as a function of $MnSO_4$ concentration are given in table 4.

TABLE 3

Assumed bath concentrations

Gram of $MnSO_4$ per liter of solution	0	237	338	520
Density (20°C)	1.000	1.219	1.300	1.465*
Gram/liter				
Mn	0.0	96.6	123.1	189.0
O	888.9	956.9	998.4	1060.0
H	111.1	109.1	106.9	105.0
S	0.0	56.2	71.6	111.0

* Saturated bath concentration used by McTaggert (1961) (ref. 7).

4. Interpolation of results for other bath concentrations

The correction factor for a particular assumed source spectrum for bath concentrations other than those provided may be determined from the table of values provided by linear interpolation in the relative population of oxygen atoms. If the correction factor for a particular source is denoted by x and the relative population of oxygen atoms by r and if the correction factor is known for concentrations 1 and 2 and if the correction factor is desired for concentration 3 then

$$x_3 = x_1 + (x_2 - x_1)\{(r_3 - r_1)/(r_2 - r_1)\}.$$

The maximum error introduced by this procedure is estimated to be 0.0005.

5. Errors

The error due to statistical fluctuations in the Monte Carlo part of the program was evaluated by making several runs which were identical except for the initial random numbers. It was estimated that the corresponding standard error was about 0.002 in the correction curve and 0.0005 in the integrated correction factors. It is estimated that the errors in graphing the correction curves for various bath concentrations (sec. 3) were random about the true curve and that for a given initial neutron energy the standard error would be about 0.002. Due to the random nature of the graphing error it is estimated that the standard error in an integrated correction factor would be 0.0005.

The uncertainties of errors in the cross sections are not given in collections of cross sections such as BNL 325[14]) or Joanou and Fenech[13]). It is noted that the only cross section which will introduce an appreciable error in the correction curves is the $^{16}O(n,\alpha)$ cross section. The errors in all the other cross sections will

TABLE 4
Correction factors for various spectra as a function of $MnSO_4$ concentration

Gram of $MnSO_4$ per liter of solution		Ref.	0	237	338	520
Am-Be(α,n)	Geiger (1964)	18	1.0333	1.0388	1.0419	1.0466
Ra-Be(α,n)	22 percent in low group, Geiger (1964)	10	1.0243	1.0286	1.0313	1.0346
Ra-Be(α,n)	37 percent in low group, Geiger (1964)	10	1.0193	1.0228	1.0249	1.0276
Ra-Be(α,n)	52 percent in low group, Geiger (1964)	10	1.0147	1.0173	1.0190	1.0210
Ra-Be(α,n)	Medvecsky (1961)	2	1.0253	1.0301	1.0329	1.0366
Ra-Be(α,n)	calculated, Hess (1957)	8	1.0244	1.0285	1.0307	1.0342
Ra-Be(α,n)	experimental, Hill (1947) (Hess low group)	9	1.0193	1.0228	1.0250	1.0275
Po-Be(α,n)	experimental, Notarrigo et al. (1962)	30	1.0287	1.0340	1.0373	1.0412
Po-Be(α,n)	calculated, Notarrigo et al. (1962)	30	1.0274	1.0326	1.0360	1.0394
Po-Be(α,n)	with carrier, Medvecsky (1961)	2	1.0305	1.0363	1.0401	1.0440
Po-Be(α,n)	carrier free, Medvecsky (1961)	2	1.0438	1.0510	1.0556	1.0611
Po-Be(α,n)	Murray (1958)	3	1.0319	1.0374	1.0407	1.0452
Pu-Be(α,n)	experimental, Anderson (1963)	19	1.0273	1.0320	1.0348	1.0385
Pu-Be(α,n)	calculated, Anderson (1963)	19	1.0318	1.0372	1.0405	1.0446
Pu-Be(α,n)	St. Romain and Stewart (1962)	20,21	1.0299	1.0349	1.0379	1.0420
Pu-Be(α,n)	Broek (1960)	22	1.0341	1.0397	1.0430	1.0478
Pu-Be(α,n)	Stewart (1955)	21	1.0328	1.0385	1.0420	1.0464
Po-B(10)	Geiger (1962)	23	1.0032	1.0045	1.0053	1.0061
Po-B(11)	Geiger (1962)	23	1.0028	1.0047	1.0057	1.0067
Po-B	Cochran (1955)	24	1.0037	1.0056	1.0068	1.0078
Po-B	Perlman (1946)	25	1.0024	1.0038	1.0046	1.0053
Po-O(18)	Khabakhpashev (1960)	26	1.0004	1.0012	1.0016	1.0020
Po-F(19)	Szilvasi (1960)	27	1.0000	1.0001	1.0001	1.0001
Ac-Be(α,n)	Dixon (1957)	28	1.0365	1.0425	1.0456	1.0511
Fission	Watt (1951)	11	1.0040	1.0051	1.0058	1.0066
Cf(252) spont. fission	Smith (1957)	29	1.0061	1.0076	1.0086	1.0096

tend to cancel. The uncertainty in the $^{16}O(n,\alpha)$ cross section is assumed to be such that the fluctuations in the graphs and tables are justified either experimentally or theoretically. An estimate of the difference between the true value for the $^{16}O(n,\alpha)$ cross section and the values of Joanou is given by the difference between the Joanau values and the BNL 325 values. It is estimated that the systematic error in the correction curves is not greater than ±0.002 and that the corresponding error in the integrated correction factor for a given spectrum is not greater than ±0.0005. This assumes that the principal errors in the cross section are random.

The uncertainty in the various neutron spectra is by far the largest contribution to the uncertainty in the integrated correction factor for a given spectrum. It is estimated that this uncertainty is about 0.005 for the newer spectra and is larger for the older spectra.

Other errors which were estimated to be less than 0.0005 for the correction curves and less than 0.0001 for the integrated corrections are due to: energy bin size, angle bin size, angular distribution uncertainties, bath composition, density of input data points and integration procedure.

In summary:

Error	Correction Curves	Integrated Corrections
Monte Carlo sampling	0.002	0.0005
Gaphing	0.002	0.0005
Cross sections	0.002	±0.0005 (systematic)
Spectra	—	±0.005 (systemati
Totals		
Random	0.003	0.0007
Systematic	±0.002	±(0.0005 plus 0.00 spectrum error)
Total sum	±0.005	0.0012 plus 0.00 spectrum error

6. Conclusions and comments

It is concluded from the comparison of the corre tion factors for the various published spectra that th largest uncertainty in the correction factor for a give source is the knowledge of the source spectra. There i therefore, a need for more accurate measurements neutron source spectra, particularly at low energi The correction factor for any new spectrum measur ment may be easily computed with the existing pr ram. It is also concluded that the variation of the orrection factor as a function of practical concenrations of $MnSO_4$ is not large.

It is noted, as should be expected, that the principal ontribution to the correction is $^{16}O(n,\alpha)$ and the ariation with $MnSO_4$ concentration is due almost ntirely to the change in the oxygen concentration. The nly noticeable sulfur effects were observed in the nergy range of 2 to 3.8 MeV where there is no $^{16}O(n,\alpha)$ competition. As is to be expected in this nergy region, the correction factor tends to one as the $MnSO_4$ concentration is reduced to zero.

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