RECEIVED BY TIC MAR 30 1973

1714

MONTE CARLO CALCULATIONS AND SENSITIVITY STUDIES OF THE TIME-DEPENDENT NEUTRON SPECTRA MEASURED IN THE LLL PULSED SPHERE PROGRAM

S. N. Cramer

R. W. Roussin

E. M. Oblow

MASTER

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ORNL-TM-4072

Contract No. W-7405-eng-26

Mathematics Division

MONTE CARLO CALCULATIONS AND SENSITIVITY STUDIES
OF THE TIME-DEPENDENT NEUTRON SPECTRA MEASURED
IN THE LLL PULSED SPHERE PROGRAM

S. N. Cramer, R. W. Roussin,* and E. M. Oblov*

NOTE:

This Work Funded by
DEFENSE NUCLEAR AGENCY PROGRAM
in the
NEUTRON PHYSICS DIVISION
Under Subtask PC104

MARCH 1973

*Neutron Physics Division

NOTICE This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
leg

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ACKNOWLEDGMENTS

The authors wish to acknowledge E. A. Straker, formerly of the Neutron Physics Division, for initiating and maintaining an interest in this work. Appreciation is also extended to M. B. Emmett, C. L. Thompson, and G. W. Morrison of the Mathematics Division for their help in adapting the O6R code to perform these calculations. Discussions with F. G. Perey of the Neutron Physics Division and S. K. Penny of the Mathematics Division were helpful in dealing with cross section data and interpretation of calculated results.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	Page
I. Introduction	1
II. Specifications of the Calculation	4
1. Geometry	4
2. Materials	5
3. Source	5
4. Detector	8
5. Monte Carlo Calculations	10
III. Results of the Calculations of the Pulse Sphere Experiments	18
1. Graphical Compendium	18
2. Discussion	18
IV. Miscellaneous Supporting Calculations	22
1. MORSE Calculations	22
2. Iron Sphere Flux Spectra	23
3. Detector Position for the Nitrogen Sphere	23
4. Calculation Excluding Center Void	24
5. Isotropic Source	24
6. Isotropic Inelastic Scattering From Discrete Levels	24
7. Evaporation Model	25
8. Count Rate Integrals	25
V. Sensitivity Calculations	26
1. Iron Sphere Collision Sensitivity	26

	Page
2. General Discussion of All Calculations	27
a. Collision Sequence	27
b. Interaction Energy	28
c. Reaction Type	30
d. Angular Scattering	32
VI. Summary and Conclusions	34
References	37
VII. Compendium	40

LIST OF TABLES

Table	Page
1. Geometry and Material Specifications of Each Calculated Experiment	6
2. Cumulative Angular Distribution of the Source	7
3. Detector Efficiency	9
4. Supergroup Energy Boundaries Used in the O6R Calculations . .	11
5. Time Interval Boundaries Used for Grouping Results of the O6R Calculations	14
6. Energy Interval Boundaries Used for Grouping Energy Dependent Results in the O6R Calculations	15
7. Inelastic Level Cross Sections	31

LIST OF FIGURES

Figure		Page
1.	Schematic of the Experimental Set-Up (not to scale)	40
2.	Geometry for the Calculations	41
3.	Detector Time Resolution	42
4.	Detector Energy Resolution	43
5.	Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	44
6.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	45
7.	Neutron Count Rate at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	46
8.	Neutron Energy Spectrum at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	47
9.	Neutron Count Rate at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	48
10.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	49
11.	Neutron Count Rate at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	50
12.	Neutron Energy Spectrum at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	51
13.	Neutron Count Rate at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	52
14.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	53
15.	Neutron Count Rate at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	54
16.	Neutron Energy Spectrum at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	55
17.	Neutron Count Rate at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	56

Figure		Page
18.	Neutron Energy Spectrum at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	57
19.	Neutron Count Rate at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	58
20.	Neutron Energy Spectrum at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	59
21.	Neutron Count Rate at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	60
22.	Neutron Energy Spectrum at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	61
23.	Neutron Count Rate at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	62
24.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	63
25.	Neutron Count Rate at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	64
26.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	65
27.	Neutron Count Rate at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	66
28.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	67
29.	Neutron Count Rate at the 30 Degree Detector Angle for the 51.04 cm Diameter Lithium-6 Sphere	68
30.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 51.04 cm Diameter Lithium-6 Sphere	69
31.	Neutron Count Rate at the 30 Degree Detector Angle for the 51.04 cm Diameter Lithium-7 Sphere	70
32.	Neutron Energy Spectrum at the 30 Degree Detector Angle for the 51.04 cm Diameter Lithium-7 Sphere	71
33.	MORSE and O6R Comparison of the Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere . .	72
34.	MORSE and O6R Comparison of the Neutron Count Rate at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	73

Figure		Page
35.	Neutron Energy Spectrum at the 30 Degree Detector Angle of the 8.92 cm Diameter Iron Sphere with no Tail in the Energy Resolution of the Detector	74
36.	Comparison of the Neutron Count Rate at the 27 and 30 Degree Detector Angles for the 39.10 cm Diameter Nitrogen Sphere . .	75
37.	Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter With and Without the Center Void	76
38.	Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter With and Without the Isotropic Source	77
39.	Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter With and Without Isotropic Inelastic Level Scattering	78
40.	Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter With and Without the Appropriate Evaporation Model	79
41.	Integral Neutron Counts at the 30 Degree Detector for the 8.92 cm Diameter Iron Sphere	80
42.	Integral Neutron Count Complement at the 30 Degree Detector for the 8.92 cm Diameter Iron Sphere	81
43.	Elastic and Nonelastic Collision Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	82
44.	Cumulative Elastic and One Nonelastic Collision Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	83
45.	Discrete Elastic and One Nonelastic Collision Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	84
46.	Cumulative Collision Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	85
47.	Discrete Collision Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	86
48.	Cumulative Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere . .	87
49.	Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere . .	88

Figure	Page
50. Cumulative Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere .	89
51. Discrete Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere .	90
52. Cumulative Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere .	91
53. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere .	92
54. Cumulative Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere .	93
55. Discrete Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere .	94
56. Cumulative Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere .	95
57. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere .	96
58. Cumulative Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere .	97
59. Discrete Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere .	98
60. Cumulative Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	99
61. Discrete Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	100
62. Cumulative Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	101
63. Discrete Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	102
64. Cumulative Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	103

Figure	Page
65. Discrete Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	104
66. Cumulative Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.	105
67. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.	106
68. Cumulative Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere .	107
69. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere .	108
70. Cumulative Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere .	109
71. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere .	110
72. Cumulative Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.	111
73. Discrete Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere . .	112
74. Cumulative Interaction Energy Range Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	113
75. Discrete Interaction Energy Range Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	114
76. Cumulative Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	115
77. Discrete Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere .	116
78. Cumulative Interaction Energy Range Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	117
79. Discrete Interaction Energy Range Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere .	118
80. Cumulative Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	119

Figure		Page
81.	Discrete Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	120
82.	Cumulative Interaction Energy Range Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	121
83.	Discrete Interaction Energy Range Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	122
84.	Cumulative Interaction Energy Range Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	123
85.	Discrete Interaction Energy Range Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	124
86.	Cumulative Interaction Energy Range Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	125
87.	Discrete Interaction Energy Range Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	126
88.	Cumulative Interaction Energy Range Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	127
89.	Discrete Interaction Energy Range Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	128
90.	Cumulative Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	129
91.	Discrete Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	130
92.	Cumulative Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	131

Figure		Page
93.	Discrete Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	132
94.	Cumulative Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	133
95.	Discrete Interaction Energy Range Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	134
96.	Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	135
97.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	136
98.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	137
99.	Once Collided Nonelastic Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	138
100.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	139
101.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	140
102.	Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	141
103.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	142
104.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	143
105.	Once Collided Nonelastic Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	144

Figure	Page
106. Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	145
107. Discrete Inelastic Level, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	146
108. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	147
109. Discrete Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	148
110. Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	149
111. Once Collided Nonelastic Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	150
112. Discrete Inelastic Level, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	151
113. Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	152
114. Once Collided Nonelastic Neutron Count Rates at the 27 Degree Detector Angle for the 20.90 cm Diameter Nitrogen Sphere . . .	153
115. Discrete Inelastic Level, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.90 cm Diameter Nitrogen Sphere	154
116. Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.90 cm Diameter Nitrogen Sphere	155
117. Once Collided Nonelastic Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere . . .	156
118. Discrete Inelastic Level, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	157

Figure		Page
119.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	158
120.	Once Collided Nonelastic Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere . .	159
121.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	160
122.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	161
123.	Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Water Sphere	162
124.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Water Sphere	163
125.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Water Sphere	164
126.	Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	165
127.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	166
128.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	167
129.	Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	168
130.	Discrete Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	169
131.	Cumulative Inelastic Level, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	170

Figure		Page
132.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	171
133.	Discrete CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	172
134.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	173
135.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	174
136.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	175
137.	Discrete CM Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	176
138.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	177
139.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere	178
140.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	179
141.	Discrete CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	180
142.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	181
143.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	182

Figure		Page
144.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	183
145.	Discrete CM Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	184
146.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	185
147.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere	186
148.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	187
149.	Discrete CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	188
150.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	189
151.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	190
152.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	191
153.	Discrete CM Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	192
154.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	193
155.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere	194

Figure		Page
156.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	195
157.	Discrete CM Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	196
158.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	197
159.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere	198
160.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	199
161.	Discrete CM Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	200
162.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	201
163.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere	202
164.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	203
165.	Discrete CM Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	204
166.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	205
167.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere	206

Figure		Page
168.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	207
169.	Discrete CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	208
170.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	209
171.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere	210
172.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	211
173.	Discrete CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	212
174.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	213
175.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere	214
176.	Cumulative CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	215
177.	Discrete CM Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	216
178.	Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	217
179.	Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere	218

I. INTRODUCTION

The pulsed sphere experiments¹⁻⁴ performed at Lawrence-Livermore Laboratory fall into a relatively new category of integral measurements which are useful in testing both differential neutron cross section data and techniques for solving the transport equation. Being neither direct differential cross section measurements nor integral experiments designed to mockup a real shielding problem, these experiments cover a middle ground which has some distinct merits of its own for data and methods testing. Basically, such measurements tend to maximize the sensitivity of the calculated results to microscopic cross section data while still retaining sufficient complexity to test out computational schemes. For this reason they are quite useful in uncovering cross section deficiencies in data which has been processed for use in a transport calculation. In the instance of the LLL experiments, the emphasis is on testing partial and differential cross sections for 14 MeV neutron reactions.

While data testing is the primary goal of analyzing such a series of experiments, a secondary purpose is also served in demonstrating the usefulness of sensitivity analysis in trying to pinpoint cross section inadequacies. The experimental results in this case are quite sensitive to the cross sections of a variety of fast neutron reaction processes and, with the complexity of the transport calculations needed to analyze the experimental results, it is no simple matter to

determine what features of the data are responsible for the disagreements which arise. Such experiments, therefore, require careful evaluation in which sensitivity analysis techniques are used to correlate disagreements with the appropriate cross sections.

The basic experimental configuration, shown schematically in Fig. 1, consists of a pulsed deuteron beam striking a tritium-loaded titanium target located at the center of a spherical medium of the material of interest. A nearly isotropic pulsed source of 14 MeV neutrons emerges from the $T(d,n)\alpha$ reaction and enters the spherical sample. Neutrons escaping the sphere at its outer surface are detected by liquid scintillators located at various distances from the spheres and at various angles with respect to the incident deuteron beam. Time-of-flight techniques are used to record the time of arrival of the neutrons at the detector. The final experimental results are obtained by normalizing the measured count rate to the number of neutrons detected with no sphere present.

As part of the overall LLL pulsed sphere program, Hansen et al.^{1,2} and Steltz et al.³ have compared C, O, N, and H_2O experimental data with SORS⁵ Monte Carlo calculations. These results were utilized to point out deficiencies in the cross-section sets in use at Lawrence-Livermore Laboratory and to initiate reevaluations of their files.

In line with the continuing program of cross-section testing and evaluation in the Neutron Physics Division of Oak Ridge National Laboratory, calculations of the pulsed sphere experiments have also

been undertaken. The Monte Carlo transport code O6R⁶ is being used in this effort together with cross section data from the ENDF/B⁷ and the Defense Nuclear Agency (DNA)⁸ libraries. The data from both sources are in the ENDF/B Version III format. Investigations for Fe, N, O, H₂O, and Li have been completed to date and are reported in this document. In addition to comparisons of calculated and experimental results, sensitivity studies have been performed on the Fe, N, O, and H₂O experiments to determine the number, sequence, and type of collision, as well as the reaction energy, and angle of scattering of all neutrons contributing to the detector response. Inelastic scattering events have been separated according to the excitation of specific discrete levels and the model used in describing the continuum, where applicable.

Since such a comprehensive sensitivity study was contemplated, a pseudo-point energy Monte Carlo code was used instead of a more efficient multigroup Monte Carlo code. The usual multigroup cross-section treatment approach lumps all reaction processes into well defined energy groups and a single collision transfer matrix representing the average behavior of all neutrons after a collision. This precludes any investigation of the effects of particular collision processes. However, a few experiments were calculated completely using the MORSE⁹ multigroup Monte Carlo code in order to provide an independent check of the O6R results.

In this general approach to the experiment, calculations were made of time-dependent detector count rates and energy spectra with the O6R code. Since the experimental results are reported in the time mode, this data was converted via the relativistic time-energy relationship to energy spectra for comparison with the calculated spectrum. As is discussed in more detail in Section III, a comparison of the calculated and experimental results indicates that a time-independent analysis of the experiments is also a possible approach to these calculations. For the benefit of those who might choose this alternative calculational model, energy dependent leakage spectra for each sphere calculated have been included as part of the results.

Results of the sensitivity study are presented only in the form of count rates. Since the largest differences between experiment and calculation are for the iron spheres, detailed sensitivity analysis is presented in Section V directed toward a resolution of the disagreements for this nuclide. In this case, as well as the others, an effort has been made to determine the cross section data to which the calculated results are sensitive in the areas of disagreement, and thus give the data evaluator some insight into what improvements might be made to the existing data sets. A discussion of these results for all the materials other than iron also appears in Section V.

II. SPECIFICATIONS OF THE CALCULATION

1. Geometry

The geometry of the calculation is shown in Fig. 2. Any effects of other materials present in the source assembly, detector, or collimator

are included in the detector response as a time dependent background count rate (derived from an experimental measurement). All necessary dimensions are given in Table 1, with other relevant data describing each of the experiments that were calculated.

2. Materials

Table 1 gives the materials, their DNA or ENDF/B-III cross section evaluation numbers and atomic densities, and the dimensions of the spheres for those experiments which have been calculated. The radial dimension is given in terms of the mean free path of 15-MeV neutrons; FWHM is the full width half maximum of the detector time resolution function given with each set of experimental data.

3. Source

a) Spatial dependence - point source at the center of the sphere.

b) Energy dependence - $E = 14.145 + 1.045 \mu + 0.048 \mu^2 + 0.033 \mu^3$ (1)
where E is in MeV and $\mu = \cos\theta$.¹ This spectrum has slightly higher energies at small angles and slightly lower ones at large angles than that given in ref. 4.

c) Angular dependence - μ is selected from the cumulative distribution in Table 2 using linear interpolation.¹ The source is assumed to be azimuthally symmetric. Unlike that given in ref. 4, this distribution includes a slight dip at 90°. The slight differences in source energy and angular dependence reported in ref. 1 and ref. 4 have a negligible effect on the results.⁴

Table 1. Geometry and Material Specifications of Each Calculated Experiment

Material	DNA Material Identification	Density (at/barn-cm)	θ (degrees)	OD (cm)	ID (cm)	λ (15 MeV mfp)	R (cm)	FWHM (nsec)
Fe	4124, MOD 1	0.08285	30	8.92	0.95	0.82	766	3
			120	8.92	0.95	0.82	975.2	3
			30	25.87	0.95	2.56	766	3
			120	25.87	0.95	2.56	975.2	3
			30	44.60	0.95	4.48	766	3
			120	44.60	0.95	4.48	975.2	3
N	4133, MOD 2	0.03475	27	20.95	1.09	0.55	754	7
			27	39.10	1.093	1.05	763.3	5
			27	111.76	2.4	3.01	765.2	2.5
O	4134, MOD 0	0.04293	30	20.96	1.098	0.75	754	5
H ₂ O	O 4134, MOD 0	0.03347	30	20.96	1.098	1.02	754.2	5
	H 4148, MOD 0	0.06694	30	38.10	1.098	1.90	754.2	5
⁶ Li	1115*	0.05345	30	51.04	0.95	1.82	765.2	4
⁷ Li	1116*	0.04584	30	51.04	0.95	1.62	765.2	4

*ENDF/B material numbers.

Table 2. Cumulative Angular Distribution of the Source

μ	$P(\mu)$	μ	$P(\mu)$
1.0	1.0	-0.1	0.427
0.9	0.9447	-0.2	0.377
0.8	0.8901	-0.3	0.327
0.7	0.835	-0.4	0.277
0.6	0.782	-0.5	0.229
0.5	0.729	-0.6	0.182
0.4	0.676	-0.7	0.135
0.3	0.625	-0.8	0.089
0.2	0.575	-0.9	0.044
0.1	0.526	-1.0	0.0
0.0	0.477		

d) Time dependence - the time dependence of the source is included in the detector response as a resolution effect.

4. Detector

a) Spatial position - point detector at distance R from center of sphere.

b) Angular position - detector positioned at an angle θ with respect to the direction of the incident deuteron beam.

c) Energy response - the detector efficiency was that for an NE 213 liquid scintillator and is given as a function of energy in Table 3.¹ Linear interpolation is assumed. In both the experiment and calculation efficiency ratios were used and only the shape of the efficiency curve is important.

d) Time response - each experiment was calculated with one or both of two detector time resolution functions. One was a triangular distribution peaked at a nominal time of arrival with the specified FWHM for each experiment. The nominal time is the relativistic time for neutrons to reach the detector from their last collision in the sphere or from the source. The other detector time resolution was taken from experimental and calculational results which account for the effects of the source assembly, air scattering, detector, and detector collimator⁴ on the measurements. The result is a time resolution function with not only a sharp peak at the time of arrival of unscattered source neutrons but also a long tail to account for background scattering effects. In these calculations, for $\theta = 30^\circ$

Table 3. Detector Efficiency

<u>Energy (MeV)</u>	<u>Efficiency (cm²)*</u>
16	3.110
15	3.061
14	3.004
13	2.984
12	3.062
11	3.217
10	3.410
9	3.618
8	3.787
7	4.069
6	4.250
5	4.386
4.5	4.375
4	4.325
3	3.876
2.5	3.255
2.25	2.721
2	1.974
1.8	1.139
1.6	0.003

*Efficiency = $A\epsilon$, where A is the detector area.

and $R = 766$ cm, this detector time resolution has been approximated as follows:

$$G(t) = 0.2 - 0.04|144.2 - t| \text{ counts/nsec} \quad (2)$$

$$139.2 \text{ nsec} \leq t \leq 149.2 \text{ nsec}$$

$$G(t) = 13.554 e^{-0.06275t} \text{ counts/nsec} \quad (3)$$

$$149.2 \text{ nsec} \leq t \leq 184 \text{ nsec}$$

$$G(t) = 2.226 \times 10^{-4} e^{-2.783 \times 10^{-3}t} \text{ counts/nsec} \quad (4)$$

$$184 \text{ nsec} \leq t \leq 420 \text{ nsec}$$

Note that $G(t)$ in the first time range corresponds to a $\text{FWHM} = 5$ nsec for the peak.

Figure 3 shows the detector count rate with no material present which results from selecting from this detector time resolution function. For other values of θ and R the same basic shape is used, but with an appropriate adjustment of the location of the peak in Eq. 2 to coincide with the time of arrival of uncollided source neutrons for the particular experiment being calculated.

5. Monte Carlo Calculations

The calculations in this study were performed using a modified version of the O6R⁶ code with a spherical geometry package. The pseudo-point cross section treatment utilized the supergroup energy structure given in Table 4. All cross-section quantities were processed onto a grid that had 512 equally spaced fine energy groups per broad energy supergroup except

Table 4. Supergroup Energy Boundaries Used in the O6R Calculations

<u>Energy (MeV)</u>
19.2800
9.6420
4.8210
2.4100
1.2050
0.6025

the anisotropic angular scattering probabilities which were put on a 128 fine group grid. A $1/E$ weighting spectrum was used to generate all the fine group averaged cross sections. The center-of-mass Legendre series expansion used for anisotropic elastic and inelastic discrete level scattering angular distributions was taken out to order 16. Continuum inelastic and $(n,2n)$ scattering was treated as being isotropic in the center-of-mass (in the lithium sphere calculations all nonelastic collisions were treated in this manner). All $(n,2n)$ and inelastic scattering secondary neutron energy distributions were treated as specified by the particular ENDF/B or DNA evaluation for the material in question (i.e. both evaporation model and tabulated distributions were handled properly).

An estimate of the contribution to the neutron flux at the detector, C , was made for each source neutron and each neutron coming out of a collision in the sphere using the next flight flux estimator:

$$C = WT \times P(\Omega) \times \frac{e^{-\eta}}{r^2} \quad (5)$$

where

WT = statistical weight before event,

$P(\Omega)$ = probability per steradian of emerging from the event in the direction of the detector,

η = number of mean free paths of material at the energy of the emerging neutron between the site of the event and the detector,

r = distance between event site and detector.

Both the time and energy dependent flux was estimated by calculating relativistic flight times and scoring each contribution in an appropriate time-energy bin. The time and energy intervals listed in Tables 5 and 6, respectively, were used for this purpose. The energy dependent flux was determined at the end of the run by summing the time and energy dependent scored events over all time in each energy bin of interest.

The detector count rate was obtained using the same estimator as given in Eq. 5 with the added step of multiplying the flux estimates by $R(E)$, the detector efficiency given in Table 3. The time dependent count rate was determined by placing the estimate in the appropriate time bin using the time intervals from Table 5. The count rate was normalized at the end of the run by dividing by the count rate resulting from source neutrons in the case of no sphere in the experimental set-up.

The number of scattering interactions in the sphere during the tracking phase of the Monte Carlo calculation was increased by using non-escape path length selection between collision sites and by using non-absorption weighting at each collision site. Classical collision mechanics were used in the random walk through the sphere, but for making last flight estimates as indicated by Eq. 5 the flight time to the detector was based on the relativistic velocity. For 14 MeV neutrons traveling 760 cm, this increases the flight time by about 2 nsec. The detection times were then spread according to the detector

Table 5. Time Interval Boundaries Used for Grouping Results
of the O6R Calculations

27° and 30° Detector Angle		120° Detector Angle	
	Midpoint Energy (MeV), R = 766 cm		Midpoint Energy (MeV), R = 975.2 cm
Time (nsec)		Time (nsec)	
130	18.11	180	15.37
134	17.03	184	14.70
138	16.29	188	14.23
140	15.81	190	13.93
142	15.37	192	13.63
144	14.93	194	13.35
146	14.52	196	13.07
148	14.13	198	12.81
150	13.75	200	12.55
152	13.38	202	12.30
154	13.03	204	12.05
156	12.69	206	11.82
158	12.37	208	11.59
160	11.98	210	11.31
163	11.54	213	10.99
166	11.12	216	10.69
169	10.73	219	10.39
172	10.36	222	10.11
175	9.887	225	9.753
180	9.090	230	9.131
190	8.170	240	8.391
200	7.383	250	7.738
210	6.705	260	7.158
220	5.851	270	6.404
240	5.150	290	5.764
250	4.751	300	5.388
260	4.397	310	5.049
270	4.081	320	4.741
280	3.798	330	4.460
290	3.544	340	4.204
300	3.207	350	3.858
320	2.829	370	3.460
340	2.587	390	3.201
350	2.442	400	3.045
360	2.310	410	2.898
370	2.188	420	2.763
380	2.022	430	2.578
400	1.829	450	2.357
420	1.391	470	1.843
450		570	

Table 6. Energy Interval Boundaries Used for Grouping
Energy Dependent Results in the O6R Calculations

<u>Energy (MeV)</u>
20.0
16.6
16.2
15.8
15.4
15.0
14.6
14.2
13.8
13.5
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.6

time resolution used. There are two sets of time bins that are given in Table 5, one set for detectors at 27° and 30° at a source to detector distance of about 760 cm, and one set for detectors at 120° and a distance of 975 cm.

In addition to the calculations of neutron count rate for each material, time and energy dependent neutron flux distributions were also computed. These were obtained using the same type of flux estimator except that no detector efficiency was needed since fluxes, not counts, were being scored. The energy bins used for these calculations are given in Table 6, the time bins being the same as those used to estimate the count rates.

Neutron energy spectra were not measured in the experiment; however, in order to test the feasibility of analyzing the pulsed spheres with a time-independent calculational model, spectra data were artificially created from the given time dependent data. This was done by simply converting the measured count rate into an energy dependent count spectrum assuming a time-of-flight to energy conversion factor. Results were then compared with the calculated energy distribution, appropriately converted to an equivalent form. This comparison is expected to be valid only if the flight time for a neutron within the sphere is small compared to the flight time from sphere to detector. The conversion has the form:

$$CE(E) = CR(t) \left| \frac{dt}{dE} \right| \quad (\text{counts/MeV}) / (\text{source count}) \quad (6)$$

where

$$E = 939.5 \left[\frac{1}{\sqrt{1 - (R/tc)^2}} - 1 \right] \text{ MeV} \quad (7)$$

and

$$\frac{dt}{dE} = \frac{t}{939.5} \left(\frac{tc}{R} \right)^2 \left[1 - \left(\frac{R}{tc} \right)^2 \right]^{3/2} \quad (8)$$

Here c is the speed of light and R is the distance from the center of the sphere to the detector.

The conversion from calculated neutron spectrum to count spectrum was done by adding two components together. First the calculated spectrum of collided neutrons was multiplied by the detector efficiency and then normalized by dividing by the detector reading with no material present. Since the collided spectrum was determined in histogram form, the value used for detector efficiency corresponded to that for the average energy in each interval. This "collided" count spectrum was then added to what corresponds to a histogram representation of the detector energy resolution function shown in Fig. 4. The function in Fig. 4 was obtained from Fig. 3 using Eq. 6. Hence, there are three energy dependent quantities which were compared. One is the count spectrum obtained by time of flight conversion of the experimental count rate, which will be called the "experimental count spectrum." The second is the count spectrum obtained from a time of flight conversion of the calculated count rate, which will be called the "calculated count spectrum." The third is the count spectrum obtained from the calculated neutron spectrum, which will be called the "count spectrum."

III. RESULTS OF THE CALCULATIONS OF THE PULSED SPHERE EXPERIMENTS

1. Graphical Compendium

The calculational results of the experiments listed in Table 1 are shown in Figs. 5 through 32. Both time dependent and energy dependent quantities are shown for each sphere. The count rates are given for both detector resolution functions (triangular alone and triangular with a time dependent tail, Fig. 3). These results are correlated in each case (i.e. the same histories were used in the random walk). The count spectra are given only for the resolution function shown in Fig. 4. The plotted points represent the mid-point histogram value for the intervals given in Tables 5 and 6. The error bars indicate one standard deviation of the mean.

2. Discussion

What is clear from the compendium of graphical results is that, except for the case of water, there is significant disagreement ($>20\%$) between the calculations and the experimental results over a range of sphere sizes for the different nuclides. In all cases agreement is best in the count rate peak corresponding to the arrival of uncollided and first elastically scattered neutrons. The water results are the exception with generally good agreement ($< 5\%$) with the experimental data over the whole 2 - 15 MeV range. With the nitrogen, oxygen, and Li^6 and Li^7 spheres disagreement ranges up to 40% in some places, while in the case of iron the agreement is poorest with discrepancies as large as factors of two to four present near 8 MeV. A discussion of possible deficiencies in the basic cross section data which can be deciphered from these comparisons is reserved for the section on

sensitivity analysis. Here, it will only be possible to briefly point out some of the limitations of both the experimental and calculated results which might reflect on these comparisons. Basically, these limitations revolve around time dependent background and detector resolution effects (both of which are handled by an empirical detector response function) and geometric and material considerations.

In the case of the iron spheres where the discrepancies were the largest, proper treatment of the time dependent background effect is an important part of the calculations. Typically, this background is almost 20% of the detected counts outside the 14 MeV peak for the small spheres. This effect increases the statistical uncertainty of the scattered flux results. Unfortunately this background effect has only been determined by the Livermore group at the 30° detector angle position for the collimator used with the intermediate sized spheres. The reported resolution function which accounts for this effect (as given in Fig. 3) is based on calculations from ref. 4 and verified in an experiment at the 30° position. It is certainly possible that the smallest (8.92 cm O.D. iron sphere) and largest (111.76 cm O.D. nitrogen sphere) samples and also all spheres with a 120° detector orientation could be better calculated with more appropriate detector time resolution functions. Only the small spheres, however, should show any large effect due to the proper treatment of this background count spectrum.

Since the larger iron spheres are affected far less by the background treatment and because they show the same large discrepancies disclosed in the small sphere comparisons, it is safe to surmise here

that the basic cross section data is at fault. It is unfortunate from a sensitivity point of view, however, that the experimental arrangement most sensitive to first collided neutrons (i.e. the small spheres) are most affected by the uncertainty in the background spectrum. Cross section uncertainties could have most easily been identified from a first scattered count rate calculation on the small samples.

In the large nitrogen sphere, the detector time resolution has no effect on the tail of the calculation, but in this instance neither the reported FWHM nor that from Fig. 3 adequately describes the peak count rate. The FWHM of 5 nsec indicated in Eq. (2) describes the peak of each calculation at least as well as, and in most cases better than, the FWHM reported for each experiment in Table 1. The experimental results in Fig. 5 (small iron sphere at 30°) are shifted 2 nanoseconds toward shorter times compared with the data reported in ref. 4. The experimental results used for this plot were available on cards¹⁰ prior to publication of the tabulated results in ref. 4 and the convenience of this form dictated their continued use. The exclusion of this shift would improve agreement between calculation and experiment in the peak, especially in the 150-160 nanosecond range. The count rate in this time range and corresponding times in the other spheres is also influenced by any uncertainties in the detector time resolution approximation derived from Fig. 3. Preliminary calculations with this detector time resolution indicate that the time range where the peak and tail merge is the only area where the count rate increased due to the inclusion of the resolution for both collided and uncollided neutrons (as compared with using the resolution function

in Fig. 3 for the uncollided and the reported FWHM in Table 1 for the collided neutrons). Unless otherwise stated, all results shown in this report use the resolution in Fig. 3 for both collided and uncollided count rate.

Another factor which might cause the calculations to be high on the longer time side of the uncollided peak is the exclusion of the source assembly void at $\theta = 180^\circ$ (see Figs. 1 and 2). In this experiment, neutrons emitted in this direction escape the sphere with no collisions, but in the calculation this area of the sphere does contribute to the count rate. In the small iron sphere the portion of the total sphere occupied by the source assembly is approximately 5%.

Finally, it should be mentioned that the iron spheres were calculated with 100% natural iron at a density of 7.68 g/cm^3 . In ref. 4 the iron sphere compositions are given as Fe > 97%, C < 1.2%, Mn < 1%, P < 0.7%, and S < 0.1% with a density of 7.85 g/cm^3 . Also, there is no allowance in the calculations for the various stainless steel liners and containers used in the experiments.

In comparing the "experimental" and "calculated" count spectra, the same degree of agreement or disagreement is exhibited as was found in the corresponding count rates. In addition to these disagreements, however, the count spectra are low on the low-energy side of the peak because the collided spectra have no detector resolution spread as do the converted calculated count rates, as explained in the previous section. The count spectra agree best with the converted count rates for the smaller spheres, especially in the peaks. The agreement lessens as the sphere size increases. This is a result of the smaller

spheres having a majority of the peak count contribution from uncollided source neutrons for which the conversion from time to energy in Eq. (6) is exact (i.e. there is no time lag of neutrons colliding in the spheres). As the sphere size increases, the source becomes more attenuated and neutrons having multiple elastic events contribute more significantly to the peak count rate. The finite size of the sphere and the finite time between collisions cause Eq. (7) to become only an approximation. It can also be seen from the iron spheres that agreement between count spectra and converted count rates is better for the 120° oriented detectors. Both the lower source energy, see Eq. (1), and the longer source-detector distance cause the flight times to the detector to be longer in this case than those in the 30° oriented detector, and thus the flight times within the sphere become less significant. It is evident from these results, however, that even in the worst case a time-independent analysis of these time-dependent experiments can be made without serious error due to the conversion from time to energy dependence.

IV. MISCELLANEOUS SUPPORTING CALCULATIONS

Several additional sets of calculations have been made of selected experiments in order to investigate calculational techniques and possible sources of error in the iron calculations.

1. MORSE Calculations

Although the multigroup MORSE Monte Carlo code⁹ is not applicable for the type of sensitivity study to be presented in the next section, it was useful for checking the O6R calculations. Figures 33 and 34 show comparisons of preliminary calculations using the two codes. All details of the calculations were made as similar as possible. The

MORSE code used the same basic data as O6R, this data being processed into a 70 energy group structure in the 2 - 16 MeV range. The agreement between the two calculations, especially in the case of the iron sphere, indicates that both codes are handling the cross-section data properly since the processing in the two codes is completely different (i.e. group vs point data handling). The only significant difference in this comparison is that the peak of the nitrogen curve is calculated somewhat better by MORSE than O6R. The differences are small in all cases.

2. Iron Sphere Flux Spectra

Figure 35 shows an energy dependent comparison for the small iron sphere for which the time and energy resolution of the detector included only a sharp peak, in contrast to Fig. 6 where a tail was included in the detector resolution. Count rate comparisons with the two detector resolutions is shown in Fig. 5. Although the discrepancy between calculation and experiment in Fig. 35 is lessened somewhat on the low-energy side of the peak as compared with Fig. 6, it is apparent that this difference is not due to the detector resolution. In Fig. 35 both collided and uncollided neutrons have the same detector resolution applied for both spectra and converted count rate. The disagreement in the peak values between calculation and experiment in Fig. 35 is due to the FWHM used (see Table 1 and Eq. (2)); its effect is also evident in Fig. 5.

3. Detector Position for the Nitrogen Sphere

Nitrogen sphere experiments have been reported^{3,4} for detector orientation at both 27° and 30°. Figure 36 shows the mid-size nitrogen

sphere calculation for the two detector angles compared with the experimental results at 27° . The calculated results are correlated and show essentially no disagreement. The 30° results are those shown in Fig. 19 for the detector resolution which includes peak and tail.

4. Calculation Excluding Center Void

Figure 37 shows an uncorrelated comparison between the calculation with the center void (Fig. 5) and a calculation without it. The difference in the peak is due to the approximately 10% difference in material attenuation. Otherwise, there is no difference. This type of calculation indicates that the exclusions of the void due to the source assembly and the containers for the fluids is probably inconsequential.

5. Isotropic Source

Figure 38 shows a comparison of an isotropic source calculation and one that used the source distribution in Table 2. Although these calculations are uncorrelated, there is a real 20% difference in the peak values due to the slightly forward anisotropic source. The source energy is related to the angle of emission by Eq. (1) and the isotropic approximation has a non-negligible effect on both the energy and angle of the emitted source neutrons.

6. Isotropic Inelastic Scattering from Discrete Levels

A calculation for which the scattering from inelastic levels was assumed to be isotropic in the CM system is compared in Fig. 39

with that from Fig. 5 in which the distributions specified by the evaluator were used. These uncorrelated results show essentially no disagreement, indicating that isotropic inelastic scattering is adequate.

7. Evaporation Model

The 06R code selects the outgoing neutron energy in a continuum inelastic scattering event from a distribution normalized to the maximum possible outgoing energy ($\mu = 1$ for isotropic CM emission). However, the iron data used in the calculation was evaluated using a normalization based on the average outgoing energy ($\mu = 0$).¹¹ A calculation using the average energy normalization was made and compared with that given in Fig. 5. These uncorrelated results seen in Fig. 40 indicate that the difference in evaporation models have little effect on the difference between calculation and experiment.

8. Count Rate Integrals

Although the discrepancy between experiment and calculation in the iron spheres appears quite large at certain times after and certain energies below the uncollided peak, these values are two to three orders of magnitude below the peak values, which compare favorably. The integral of the count rates from Fig. 5, using the calculation with the tail in the detector resolution, indicates that the disagreement creates almost no difference in the total number of counts detected. Figure 41 also verifies that the normalization between experiment and calculation is correct. To complement the integral results of Fig. 41, Fig. 42 shows the discrepancy in the total counts for all times after any particular time.

V. SENSITIVITY CALCULATIONS

1. Iron Sphere Collision Sensitivity

In addition to the general sensitivity study described below, several specific calculations were made on iron spheres in an effort to determine how the sequence of collisions affect the energy region in which the disagreement with the experiments occurs. Figure 43 shows two correlated collision sequence calculations compared with the Fig. 5 results. The bottom curve shows the contribution to the calculation of any sequence of elastic and first level (0.846 MeV) inelastic events. No other events are counted, and the history is terminated if one of these other events occurs. This curve does not include the uncollided contribution. The tail is a result of applying the detector time resolution to the collided neutrons and there is no actual contribution in the area of the discrepancy. The next lowest curve, in addition to the results of the bottom curve, includes the contribution of any nonelastic first event and also the uncollided count rate. This curve has the same shape as the complete calculation, indicating that the disagreement is caused by the events included, which are singly scattered followed by any sequence of an elastic or first level inelastic scattering event.

Figures 44 through 47 show the contribution to the complete calculation for sequences of elastic collisions followed by one nonelastic event for the small and intermediate iron spheres. The large error bars seen in Figs. 45 and 47 are a result of the difference between

successive curves in Figs. 44 and 46 being small compared to the standard deviations. These collision sequences curves also have the same shape as the full calculation (within the limits of the poor statistics for third and fourth collisions), again indicating that the disagreement is in the curves shown and not in the uncollided or higher order collision count rates.

From Figs. 44 through 47 it can be inferred that the discrepancies in the iron sphere calculations are due to nonelastic scattering since the disagreement occurs at times corresponding to energies much lower than the energy of first and second elastic collisions, which create the results shown. With these curves and those to follow in the next section, it is possible to further isolate the cause of the disagreement.

2. General Discussion of All Calculations

a. Collision Sequence

Figures 48 through 71 show the contributions to the total count rate of first, second, third, and fourth collided neutrons. Only the complete calculation includes the uncollided count rate. All the results presented in each figure are the result of correlated calculations. These curves show the increasing significance of the higher order collisions as the sphere size increases and also as the mass number of the material increases for spheres of comparable optical thicknesses. All curves with reasonably good statistics have the same shape as the complete calculation, indicating that the results are very sensitive to the first few collisions.

By comparing the time scale of these collision sequence curves with the energies corresponding to arrival from the sphere center (Table 5), it can be seen that first collisions contribute to the entire energy range: small energy losses coming from small angle elastic scattering, moderate losses from discrete level inelastic scattering, and large energy losses from continuum inelastic scattering events. The spectrum softens with increasing numbers of collisions, however, and there is sufficient multiple elastic scattering in the larger spheres so that third and fourth collision contributions to the count rate at all times is significant.

b. Interaction Energy

Figures 72 through 95 show the contribution to the complete calculation of neutron interactions in specific energy ranges. The uncollided count rate has been excluded in all cases, and each set of results is fully correlated. These curves reflect the energy-angle source dependence where, for instance, from Eq. (1) it is seen that the peak energy at 30° is 15.11 MeV while at 120° it is 13.63 MeV. In the area of the disagreement in the iron spheres the discrete energy interval count rates have the same general shape as the complete calculation. However, there is no significant contribution to the tail of any iron sphere calculations from reactions in the 10 to 12 MeV energy interval, even though this interval occupies different positions relative to the uncollided source energy for the 30° and 120° detectors. Collisions in this energy range are also insignificant

in the low mass sphere calculations. The amount of energy loss in the collisions making up each curve can be estimated by noting the times and energies from Table 5 at which each reaction energy interval contributes to the count rate. That is, in the 30° oriented detector calculations, the $E > 15$ MeV peak indicates that not only did the collisions take place in the 15 MeV energy range, but that the exit energies were also in this range being the result of small angle elastic scattering events. In these same curves the $E > 15$ MeV contribution in the 150-160 nanosecond range is from discrete level inelastic scattering, and contributions at longer times are the result of continuum inelastic scatterings. The peak contribution resulting from collisions in each reaction energy interval appears at times corresponding to arrival time for that interval, indicating that the peaks are due to elastic scattering. In the small mass number spheres this peaking is broader and less well defined due to the larger energy loss in an elastic event. The contribution at long times from the high energy intervals is due to continuum scattering, except for the detector resolution effects. The contribution for collisions with initial energies < 10 MeV is spread out over the entire lower energy range and is a result of elastic events with small energy losses. That is, if the reaction energy interval investigation were extended down through the lower energies, each curve would show a peak at times corresponding to arrival times for that interval.

c. Reaction Type

Figures 96 through 131 show the cumulative and discrete contributions to the once collided count rate resulting from the inelastic levels, the continuum, and (n,2n) reactions. The iron data evaluation presents the continuum in two forms: an evaporation model and an arbitrary tabulated function.¹⁰ The nitrogen¹² and oxygen¹³ evaluations represent inelastic scattering in the continuum region by means of discrete levels in order to preserve the energy-angle correlation of the scattering process. This was done by allowing a single excitation energy to represent a group of discrete levels in the continuum region. This model starts at energies of 8.489 and 12.967 MeV for nitrogen and oxygen, respectively. The calculations involving oxygen and nitrogen were split up into two ranges corresponding to excitation energies above and below the continuum energy range which was fitted with a discrete level model. In the calculations showing the contribution of individual levels, those with the largest 15-MeV cross sections were chosen for investigation (see Table 7). The tails in these curves are due to the detector time resolution for each level. Except for the complete calculation, all results in each figure are fully correlated and do not include the uncollided count rate. The complete calculations shown in these figures were taken from results discussed in Section III. Only a first collision count rate has been calculated in order to investigate the effects of nonelastic reactions since elastic scattering effects would appear in multiple collision calculations. The first collision

Table 7. Inelastic Level Cross Sections

	Level Energy (MeV)	15 MeV Cross Section (barns)
Fe	0.856	0.0640
	1.408	0.0081
	2.654	0.01
	3.122	0.0061
O	6.131	0.0730
	8.872	0.0427
	11.08	0.0391
	11.44	0.0440
N	5.834	0.0262
	7.028	0.0432
	11.75	0.0253
	13.25	0.0340

contributions are seen to decrease with increasing sphere size. The significance of elastic scattering can also be inferred from these curves. Only in the water spheres is there any elastic scattering contribution to the first collision count rate at long times. This is due to the possibility of large energy losses in elastic scattering events with hydrogen.

The disagreement between experiment and calculation in the iron spheres appears in this first collision nonelastic count rate in a time range where only continuum inelastic scattering appears to contribute. The point of greatest discrepancy is in a range covered equally by the evaporation model data and that described by an arbitrary tabulated function. The overlap of these two continuum models is due to the detector resolution used and also to the time binning process, because the two models for treating secondary energy distributions do not allow for such an overlap. It is apparent that the dip in the iron sphere calculations is created by first scattering interactions which excite the inelastic continuum, and not as a result of secondary multiple scattering effects originating from high energy elastic and discrete level inelastic scattering events.

d. Angular Scattering

Figures 132 through 179 show the first collision sensitivity to the angle of scatter, both in the laboratory (COSLB) and center-of-mass (COSCM) systems. The angles corresponding to the cosine intervals are given below.

<u>Cosine</u>	<u>Angle (degrees)</u>
1.00000	0
0.97815	12
0.80902	36
0.30903	72
-0.50000	120
-1.00000	180

These results are correlated in all cases and do not include the uncollided count rate. In order to investigate specific angle intervals, only first collisions were chosen in order to eliminate multiple scattering effects. Differences in correlating the laboratory and center-of-mass scattering angles in the iron spheres is due to the inelastic scattering. The smallest angle interval contributes only in the peak, indicating this scattering is purely elastic. The long, low tail is due to the detector resolution used. From Fig. 2 and Eq. (1) it is possible to determine at what angle and energy the neutrons were emitted in order for their first scatter to be in the intervals indicated and at the same time be directed toward the detector. The discrete curves indicate a peak in the count rate due to initial scatterings in each angular interval. For the 30° detector experiments these maxima shift to longer times for increasing angle of scatter, but for the 120° detector calculations these maxima all appear at about the same time at the peak of the complete calculation. This could be explained from the fact that for the 30° cases the contributions from first large angle scattering come from neutrons emitted in backward, and low energy directions, and have longer flight times

to the detector. For the 120° cases first large angle collisions come from forward emitted neutrons with energies higher than those emitted toward the detector, resulting in comparable arrival times from all first collisions. In the area of disagreement between calculation and experiment in the iron sphere, it can be seen that the first collision contribution is made up primarily from collisions in the 12° to 120° range, indicating a wide range of laboratory energy loss in inelastic scattering events exciting the continuum. As the sphere size increases, this range shifts toward the 12° to 36° interval.

VI. SUMMARY AND CONCLUSIONS

This report has presented an extensive calculational study of the LLL pulsed sphere experiments on Fe, N, O, H_2O , Li^6 , and Li^7 . In all the cases which were calculated, except for the water spheres, significant disagreements ($>20\%$) between the calculations and the experiments were uncovered in some energy range. For the iron spheres the disagreement was most severe with the calculations being low by a factor of two to four around 8 MeV. These results indicate that the DNA and ENDF/B-III data files used in the calculations are deficient in some aspects for investigating the transport of 14 MeV neutrons. Since in the regions of disagreement the experiments are very sensitive to partial cross sections at around 14 MeV, it can be generally concluded that the deficiencies in the data are in the magnitude of certain

partial cross sections at 14 MeV and the shape of their secondary energy distributions.

In the course of analyzing the calculational results two completely independent Monte Carlo techniques were used, one a pseudo-point and the other a group averaged data processing approach. Both methods were in good agreement for the sphere calculations they were tested against, thus lending confidence to the calculational models and data handling techniques used in this study. Also included in this test phase was a time independent analysis of these time-dependent pulsed experiments. The energy spectra results here indicate that with proper care in handling the detector response function uncertainties, a time-independent calculational model for these experiments yields satisfactory results. That is, the time taken up by neutrons colliding in the spheres is small compared with their flight time to the detector.

A series of sensitivity calculations were performed to investigate the mechanics of transport and collision processes in the sphere. This study required the use of the pseudo-point energy Monte Carlo transport code O6R in order to record any desired feature of a particular reaction process. Consideration was given to the type of reaction process, initial and final energies of neutrons involved in a reaction, final neutron angles and treatment of the basic nuclear data in different calculational models. Particular emphasis was placed on uncovering the possible cross section deficiencies which would account for the large disagreement between the experimental and calculated results.

Scrutiny of the iron sphere sensitivity calculations revealed that contributions to the detector response in the area of disagreement with experiment came from: (1) neutrons which have had few collisions in the sphere before leaking out with a sizable contribution from those having had only a single collision, (2) collisions involving neutrons with initial energies near or at the source energy, (3) inelastic scattering events which excite the continuum, formulated as a combination of an evaporation model and an arbitrary tabulated function, and (4) a wide range of scattering angles including both the forward and backward directions. The first collision effect seems to preclude the possibility that the trouble results from a sequence of nonelastic events with large energy losses per collision. The special iron sensitivity calculations show that when the elastic and first level inelastic collisions are preceded by other nonelastic collisions, the disagreement appears in the count rate. Since the cross sections of higher excited discrete levels at the source energy are insignificant compared with that of the first level, it appears the added contribution is due to continuum scattering. As mentioned above, MORSE calculations of an iron sphere experiment reveals the same disagreement as seen in O6R comparisons indicating that all data, including the continuum data, is being handled properly and the basic nuclear data is at fault. Specifically, the continuum data has been singled out as the cause of the disagreements in the iron calculations, because the sensitivity results show this data provides the only contribution to the count rate in the time range of concern. However, it is always possible that the error could be caused from the total absence of some other reaction process.

REFERENCES

1. L. F. Hansen, et al., "Time Spectra from Spheres Pulsed with 14-MeV Neutrons," Nucl. Sci. Eng. 35, 227-239 (1969).
2. L. F. Hansen, et al., "Predictions for Neutron Transport in Air, Based on Integral Measurements in Nitrogen and Oxygen at 14 MeV," Nucl. Sci. Eng. 40, 262-282 (1970).
3. M. L. Stelts, et al., "Spectra of Fast Neutrons from Water Pulsed with 14-MeV Neutrons," Nucl. Sci. Eng. 46, 53-60 (1971).
4. C. Wong, et al., "Livermore Pulsed Sphere Program: Program Summary Through July 1971," Lawrence Livermore Laboratory, UCRL-51144 Rev. I (February 1972).
5. J. Kimlinger and E. F. Plechaty, "SORS Monte Carlo Neutron Transport Code for CDC 6600," UCRL-50532 (1968).
6. C. L. Thompson and E. A. Straker, "O6R - ACTIFK, Monte Carlo Neutron Transport Code," ORNL-CF-69-8-36 (1969).
7. M. K. Drake, Editor, "Data Formats and Procedures for the ENDF Neutron Cross Section Library," BNL50274 (ENDF 102 Vol. I) (October 1970).
8. R. W. Roussin, "The Defense Nuclear Agency Working Cross Section Library: Description and Contents," ORNL-RSIC-34 (August 1972).
9. E. A. Straker, P. N. Stevens, D. C. Irving, and V. R. Cain, "The MORSE Code - A Multigroup Neutron and Gamma-Ray Monte Carlo Transport Code," ORNL-4585 (September 1970).

10. John Kammerdiener, Lawrence Livermore Laboratory, private communication.
11. S. K. Penny and W. E. Kinney, "A Re-Evaluation of Natural Iron Neutron and Gamma-Ray Production Cross Sections - ENDF/B Material 1124," ORNL-4617 (April 1971).
12. P. G. Young and D. G. Foster, Jr., "A Preliminary Evaluation of the Neutron and Photon-Production Cross Sections of Nitrogen," LA-4725 (September 1972).
13. D. G. Foster, Jr. and P. G. Young, "A Preliminary Evaluation of the Neutron and Photon-Production Cross Sections of Oxygen," LA-4780 (ENDF-174), (August 1972).

VII. COMPENDIUM

ORNL-DWG 72-2972

Fig. 1. Schematic of the Experimental Set-Up (not to scale).

Fig. 2. Geometry for the Calculations.

Fig. 3. Detector Time Resolution.

Fig. 4. Detector Energy Resolution.

Fig. 5. Neutron Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 6. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 8.92 cm Diameter Iron Sphere.

Fig. 7. Neutron Count Rate at the 120 Degree Detector Angle
for the 8.92 cm Diameter Iron Sphere.

Fig. 8. Neutron Energy Spectrum at the 120 Degree Detector Angle
for the 8.92 cm Diameter Iron Sphere.

Fig. 9. Neutron Count Rate at the 30 Degree Detector Angle
for the 25.87 cm Diameter Iron Sphere.

Fig. 10. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 25.87 cm Diameter Iron Sphere.

Fig. 11. Neutron Count Rate at the 120 Degree Detector Angle
for the 25.87 cm Diameter Iron Sphere.

Fig. 12. Neutron Energy Spectrum at the 120 Degree Detector Angle
for the 25.87 cm Diameter Iron Sphere.

Fig. 13. Neutron Count Rate at the 30 Degree Detector Angle
for the 44.60 cm Diameter Iron Sphere.

Fig. 14. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 44.60 cm Diameter Iron Sphere.

Fig. 15. Neutron Count Rate at the 120 Degree Detector Angle
for the 44.60 cm Diameter Iron Sphere.

Fig. 16. Neutron Energy Spectrum at the 120 Degree Detector Angle
for the 44.60 cm Diameter Iron Sphere.

Fig. 17. Neutron Count Rate at the 27 Degree Detector Angle
for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 18. Neutron Energy Spectrum at the 27 Degree Detector Angle
for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 19. Neutron Count Rate at the 27 Degree Detector Angle
for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 20. Neutron Energy Spectrum at the 27 Degree Detector Angle
for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 21. Neutron Count Rate at the 27 Degree Detector Angle
for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 22. Neutron Energy Spectrum at the 27 Degree Detector Angle
for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 23. Neutron Count Rate at the 30 Degree Detector Angle
for the 20.76 cm Diameter Oxygen Sphere.

Fig. 24. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 20.76 cm Diameter Oxygen Sphere.

Fig. 25. Neutron Count Rate at the 30 Degree Detector Angle
for the 20.96 cm Diameter Water Sphere.

Fig. 26. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 20.96 cm Diameter Water Sphere.

Fig. 27. Neutron Count Rate at the 30 Degree Detector Angle
for the 38.10 cm Diameter Water Sphere.

Fig. 28. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 38.10 cm Diameter Water Sphere.

Fig. 29. Neutron Count Rate at the 30 Degree Detector Angle
for the 51.04 cm Diameter Lithium-6 Sphere.

Fig. 30. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 51.04 cm Diameter Lithium-6 Sphere.

Fig. 31. Neutron Count Rate at the 30 Degree Detector Angle
for the 51.04 cm Diameter Lithium-7 Sphere.

Fig. 32. Neutron Energy Spectrum at the 30 Degree Detector Angle
for the 51.04 cm Diameter Lithium-7 Sphere.

Fig. 33. MORSE and O6R Comparison of the Neutron Count Rate
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 34. MORSE and O6R Comparison of the Neutron Count Rate
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 35. Neutron Energy Spectrum at the 30 Degree Detector Angle of the 8.92 cm Diameter Iron Sphere with no Tail in the Energy Resolution of the Detector.

Fig. 36. Comparison of the Neutron Count Rate at the 27 and 30 Degree Detector Angles for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 37. Neutron Count Rate at the 30 Degree Detector Angle
for the 8.92 cm Diameter With and Without the Center Void.

Fig. 38. Neutron Count Rate at the 30 Degree Detector Angle
for the 8.92 cm Diameter With and Without the Isotropic Source.

Fig. 39. Neutron Count Rate at the 30 Degree Detector Angle
for the 8.92 cm Diameter With and Without Isotropic Inelastic Level
Scattering.

Fig. 40. Neutron Count Rate at the 30 Degree Detector Angle
for the 8.92 cm Diameter With and Without the Appropriate Evaporation
Model.

Fig. 41. Integral Neutron Counts at the 30 Degree Detector
for the 8.92 cm Diameter Iron Sphere.

Fig. 42. Integral Neutron Count Complement at the 30 Degree
Detector for the 8.92 cm Diameter Iron Sphere.

Fig. 43. Elastic and Nonelastic Collision Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 44. Cumulative Elastic and One Nonelastic Collision Neutron
Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter
Iron Sphere.

Fig. 45. Discrete Elastic and One Nonelastic Collision Neutron
Count Rate at the 30 Degree Detector Angle for the 8.92 cm Diameter
Iron Sphere.

Fig. 46. Cumulative Collision Neutron Count Rates at the 30 Degree
Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 47. Discrete Collision Neutron Count Rates at the 30 Degree
Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 48. Cumulative Collision Sequence Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 49. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 50. Cumulative Collision Sequence Neutron Count Rates
at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 51. Discrete Collision Sequence Neutron Count Rates
at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 52. Cumulative Collision Sequence Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 53. Discrete Collision Sequence Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 54. Cumulative Collision Sequence Neutron Count Rates
at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 55. Discrete Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 56. Cumulative Collision Sequence Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 57. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 58. Cumulative Collision Sequence Neutron Count Rates
at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 59. Discrete Collision Sequence Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 60. Cumulative Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 61. Discrete Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 62. Cumulative Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 63. Discrete Collision Sequence Neutron Count Rates at the
27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 64. Cumulative Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 65. Discrete Collision Sequence Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 66. Cumulative Collision Sequence Neutron Count Rates at the
30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 67. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 68. Cumulative Collision Sequence Neutron Count Rates at the
30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 69. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 70. Cumulative Collision Sequence Neutron Count Rates at the
30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 71. Discrete Collision Sequence Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 72. Cumulative Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 73. Discrete Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 74. Cumulative Interaction Energy Range Neutron Count Rates
at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 75. Discrete Interaction Energy Range Neutron Count Rates
at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 76. Cumulative Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 77. Discrete Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 78. Cumulative Interaction Energy Range Neutron Count Rates
at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 79. Discrete Interaction Energy Range Neutron Count Rates
at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 80. Cumulative Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 81. Discrete Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 82. Cumulative Interaction Energy Range Neutron Count Rates
at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 83. Discrete Interaction Energy Range Neutron Count Rates
at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 84. Cumulative Interaction Energy Range Neutron Count Rates
at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 85. Discrete Interaction Energy Range Neutron Count Rates
at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 86. Cumulative Interaction Energy Range Neutron Count Rates
at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 87. Discrete Interaction Energy Range Neutron Count Rates
at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 88. Cumulative Interaction Energy Range Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 89. Discrete Interaction Energy Range Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 90. Cumulative Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 91. Discrete Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 92. Cumulative Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 93. Discrete Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 94. Cumulative Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 95. Discrete Interaction Energy Range Neutron Count Rates
at the 30 Degree Detector Angle for the 38.1C cm Diameter Water Sphere.

Fig. 96. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 97. Cumulative Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 98. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 99. Once Collided Nonelastic Neutron Count Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 100. Cumulative Inelastic Level, Once Collided Neutron Count
Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 101. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 102. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 103. Cumulative Inelastic Level, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 104. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 105. Once Collided Nonelastic Neutron Count Rates at the
120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 106. Cumulative Inelastic Level, Once Collided Neutron Count
Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 107. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 108. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 109. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 110. Cumulative Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 111. Once Collided Nonelastic Neutron Count Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 112. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 113. Cumulative Inelastic Level, Once Collided Neutron Count

Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 114. Once Collided Nonelastic Neutron Count Rates at the 27 Degree Detector Angle for the 20.90 cm Diameter Nitrogen Sphere.

Fig. 115. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 20.90 cm Diameter Nitrogen Sphere.

Fig. 116. Cumulative Inelastic Level, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 20.90 cm Diameter Nitrogen Sphere.

Fig. 117. Once Collided Nonelastic Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 118. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 119. Cumulative Inelastic Level, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 120. Once Collided Nonelastic Neutron Count Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 121. Discrete Inelastic Level, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 122. Cumulative Inelastic Level, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 123. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Water Sphere.

Fig. 124. Discrete Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Water Sphere.

Fig. 125. Cumulative Inelastic Level, Once Collided Neutron Count
 Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Water Sphere.

Fig. 126. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 127. Discrete Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 128. Cumulative Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 129. Once Collided Nonelastic Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 130. Discrete Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 131. Cumulative Inelastic Level, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 132. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 133. Discrete CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 134. Cumulative Laboratory Angle, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 135. Discrete Laboratory Angle, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 136. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 137. Discrete CM Angle, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 6.92 cm Diameter Iron Sphere.

Fig. 138. Cumulative Laboratory Angle, Once Collided Neutron Count

Rates at the 120 Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 139. Discrete Laboratory Angle, Once Collided Neutron Count

Rates at the 12C Degree Detector Angle for the 8.92 cm Diameter Iron Sphere.

Fig. 140. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 141. Discrete CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 142. Cumulative Laboratory Angle, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 143. Discrete Laboratory Angle, Once Collided Neutron Count

Rates at the 30 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 144. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 145. Discrete CM Angle, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 146. Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 147. Discrete Laboratory Angle, Once Collided Neutron Count
Rates at the 120 Degree Detector Angle for the 25.87 cm Diameter Iron Sphere.

Fig. 148. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 149. Discrete CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 150. Cumulative Laboratory Angle, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 151. Discrete Laboratory Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 152. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 153. Discrete CM Angle, Once Collided Neutron Count Rates
at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 154. Cumulative Laboratory Angle, Once Collided Neutron Count

Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 155. Discrete Laboratory Angle, Once Collided Neutron Count
Rates at the 120 Degree Detector Angle for the 44.60 cm Diameter Iron Sphere.

Fig. 156. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 157. Discrete CM Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 158. Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen Sphere.

Fig. 159. Discrete Laboratory Angle, Once Collided Neutron Count
Rates at the 27 Degree Detector Angle for the 20.96 cm Diameter Nitrogen
Sphere.

Fig. 160. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 161. Discrete CM Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 162. Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 163. Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 27 Degree Detector Angle for the 39.10 cm Diameter Nitrogen Sphere.

Fig. 164. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 165. Discrete CM Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 166. Cumulative Laboratory Angle, Once Collided Neutron Count
Rates at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen
Sphere.

Fig. 167. Discrete Laboratory Angle, Once Collided Neutron Count Rates
at the 27 Degree Detector Angle for the 111.76 cm Diameter Nitrogen Sphere.

Fig. 168. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 169. Discrete CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 170. Cumulative Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 171. Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.76 cm Diameter Oxygen Sphere.

Fig. 172. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 173. Discrete CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 174. Cumulative Laboratory Angle, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 175. Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 20.96 cm Diameter Water Sphere.

Fig. 176. Cumulative CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 177. Discrete CM Angle, Once Collided Neutron Count Rates
at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

Fig. 178. Cumulative Laboratory Angle, Once Collided Neutron Count
Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water
Sphere.

Fig. 179. Discrete Laboratory Angle, Once Collided Neutron Count Rates at the 30 Degree Detector Angle for the 38.10 cm Diameter Water Sphere.

INTERNAL DISTRIBUTION

1-3.	L. S. Abbott	49.	B. J. McGregor
4.	R. G. Alsmiller, Jr.	50.	G. L. Morgan
5.	T. W. Armstrong	51.	G. W. Morrison
6.	D. E. Bartine	52.	F. J. Muckenthaler
7.	H. W. Bertini	53.	F. R. Mynatt
8.	A. A. Brooks	54-58.	E. M. Oblow
9.	A. R. Buhl	59.	J. V. Pace
10.	H. P. Carter	60.	R. W. Peele
11.	K. C. Chandler	61.	S. K. Penny
12.	R. L. Childs	62.	F. G. Perey
13-14.	C. E. Clifford	63.	A. M. Perry
15-24.	S. N. Cramer	64.	L. M. Petrie
25.	N. F. Cross	65.	W. A. Rhoades
26.	J. K. Dickens	66-70.	R. W. Roussin
27.	M. B. Emmett	71.	A. H. Snell
28.	W. W. Engle, Jr.	72.	P. N. Stevens
29.	G. F. Flanagan	73.	J. G. Sullivan
30.	W. E. Ford, III	74.	D. Sundberg
31.	R. M. Freestone, Jr.	75.	D. B. Trauger
32.	T. A. Gabriel	76.	D. K. Trubey
33.	N. M. Greene	77.	J. E. White
34.	M. L. Gritzner	78.	G. E. Whitesides
35.	W. O. Harms	79.	L. R. Williams
36.	O. W. Hermann	80.	H. A. Wright
37.	R. J. Hinton	81.	R. Q. Wright
38.	T. J. Hoffman	82.	H. Feshbach (consultant)
39.	L. B. Holland	83.	P. F. Fox (consultant)
40.	W. H. Jordan	84.	C. R. Mehl (consultant)
41.	W. E. Kinney	85.	H. T. Motz (consultant)
42.	J. R. Knight	86-87.	Central Research Library
43.	J. Lewin		ORNL Y-12 Technical Library
44.	T. A. Love	88.	Document Reference Section
45.	J. L. Lucius	89-93.	Laboratory Records
46.	R. E. Maerker	94.	Laboratory Records ORNL RC
47.	F. C. Maienschein	95-104.	Math. Division Library
48.	P. G. McCarty	105.	ORNL Patent Office

EXTERNAL DISTRIBUTION

- 106. C. E. Burgart, 122 La Veta Dr., N.E., Albuquerque, New Mexico 87108
- 107. W. A. Coleman, Science Applications, Inc., P. O. Box 2351, La Jolla, California 92037
- 108. Dr. H. Goldstein, Room 242, Mudd Bldg., Columbia University, New York 27, New York
- 109. L. F. Hansen, Lawrence Livermore Laboratory, P. O. Box 808, Livermore, California 94550
- 110. W. H. Hannum, Division of Reactor Development and Technology, U. S. Atomic Energy Commission, Washington, D. C. 20545
- 111. P. B. Hemmig, Division of Reactor Development and Technology, U. S. Atomic Energy Commission, Washington, D. C. 20545
- 112. Dr. V. A. Kamath, Scientific Advisor; Attention: P. K. Patwardhan, Bhabha Atomic Research Centre, Trombay, Bombay, India
- 113. K. O. Laughon, AEC Site Representative, ORNL
- 114. P. F. Pasqua, Department of Nuclear Engineering, University of Tennessee, Knoxville, Tennessee
- 115. J. N. Rogers, Division 8321, Sandia Laboratories, P. O. Box 969, Livermore, California 94550
- 116. Dr. Milton E. Rose, Mathematics and Computer Branch, Division of Research, U. S. Atomic Energy Commission, Washington, D. C. 20545
- 117. E. A. Straker, Science Applications, Inc., Clinton Building, Suite 432, 2109 Clinton Ave., Huntsville, Alabama
- 118. C. R. Weisbin, Los Alamos Scientific Laboratory, T2 Division, Los Alamos, New Mexico 87544
- 119-120. Technical Information Center (TIC)
- 121. Research and Technical Support Division, ORO
- 122-256. Given DNA Radiation Transport Distribution (Updated 10-20-72)