MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES
3 4456 0364436 8

ORNL-3180
UC-34 – Physics
TID-4500 (16th ed.)

CERENKOV RADIATION INTENSITY CALCULATIONS FOR Sr^{90} AND Co^{60} IN WATER

R. G. Wymer
R. E. Biggers

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.

Printed in USA. Price $0.50. Available from the

Office of Technical Services
Department of Commerce
Washington 25, D.C.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL-3180

Contract No. W-7405-eng-26

Chemical Technology Division

Analytical Chemistry Division

CERENKOV RADIATION INTENSITY CALCULATIONS FOR Sr^{90} AND Co^{60} IN WATER

R. G. Wymer

R. E. Biggers

DATE ISSUED

SEP 1961

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

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0364436 8

ABSTRACT

A method for calculating Cerenkov radiation intensity from an initial electron energy distribution is presented. The Cerenkov radiation intensity from 1 curie of Sr^{90} in secular equilibrium with Y^{90} in water is calculated from the beta-particle energy spectrum to illustrate the use of the method for a pure beta-particle emitter. The Cerenkov radiation intensity from 1 curie of Co^{60} in water is calculated from the Compton electron energy spectrum to illustrate the use of the method for a gamma-ray emitter. The steps necessary to obtain the Compton electron energy spectrum from a gamma-ray emitter are indicated.

CONTENTS

		Page
1.0	Introduction	4
2.0	Basic Phenomenon	4
3.0	Theoretical Considerations	5
4.0	Calculation of Specific Cases	8
	Sr^{90}	8
	Co^{60}	9
5.0	Discussion	15
6.0	References	16
7.0	Appendix	16

1.0 INTRODUCTION

A method for quantitatively calculating the Cerenkov radiation intensity from specified beta-particle- or gamma-ray- (or both) emitting sources is presented in this report. Such a method is needed because extraneous light from Cerenkov radiation is a potential source of interference in spectrophotometic and other light-dependent measurements made on radioactive solutions. The extent of the interference may be evaluated by quantitatively calculating the Cerenkov radiation intensity. The work was done in connection with the high-temperature aqueous-systems spectrophotometer program being carried out as a cooperative effort between the Chemical Technology and Analytical Chemistry Divisions of Oak Ridge National Laboratory.

Acknowledgment. The authors wish to acknowledge the contribution of J. Steinfeld in independently checking and verifying the calculations in this report.

2.0 BASIC PHENOMENON

When a charged particle passes through a refracting medium with a velocity greater than the local phase velocity of light in that medium, electromagnetic radiation may be emitted. This radiation is called "Cerenkov radiation." It arises from interaction of the charged particle with the interatomic fields rather than with the atoms themselves. The requirement that the charged particle have a velocity greater than that of light in the medium follows from the fact that, unless the charged particle can move faster than the light it creates, there is no chance for light created subsequently by the particle to be in phase with the light first created. Unless this coherence is achieved there is no emitted light. Since the refractive index of a medium is the ratio of velocity of light in a vacuum to that in the medium, it is reasonable to expect that the refractive index will be related to the minimum particle velocity necessary to produce Cerenkov radiation. In fact, the governing relation for a single charged particle is

$$\cos \Theta = 1/\beta n \qquad (1)$$

where Θ is the angle the emitted light makes with the direction of the charged particle

β is the ratio of charged particle velocity, v, to the velocity of light in vacuo, c ($\beta = v/c$)

n is the refractive index of the medium

Additional requirements to achieve coherence are that the path length of the charged particle in the medium be large compared with the wavelength of the emitted light (to prevent diffraction) and that the time for the particle to travel a distance equal to the wavelength, λ, of the emitted light be small compared with the period (λ/c) of the emitted light. It should be noted that Cerenkov radiation is different from Bremsstrahlung, which results from the acceleration of a relatively slowly moving charged particle in the electrostatic field of an atom.

3.0 THEORETICAL CONSIDERATIONS

The theory of Cerenkov radiation has been covered in a book by Jelley,[1] and several pertinent articles[2,3] provide experimental verification of the theory. Of special interest is an article by Belcher,[4] whose approach was modified and extended for the purpose of this report.

The object of this section is to present the relations necessary to calculate for any known initial electron energy distribution the Cerenkov radiation spectrum from any medium of known refractive index and to indicate how they are used. In the case of gamma rays penetrating a refracting substance, it is necessary first to determine the initial electron energy distribution (the electrons will usually be Compton electrons, or, in the case of gamma rays with energies greater than 1 Mev, positrons from pair production). These distributions have been tabulated[5,6] for a wide range of photon energies.

The electrons may be related[4] to a number of light quanta by

$$N_{pj} = \frac{2N_j\pi}{137} \left(\frac{\Delta\lambda}{\lambda^2_{avg}}\right) \int_{\beta_{max}}^{1/n} \left(1 - \frac{1}{\beta^2 n^2}\right) dx \qquad (2)$$

where N_{pj} is the number of light quanta in the wavelength interval $\Delta\lambda$ about wavelength λ_{avg} generated in unit time by N_j electrons of specified initial energy coming to rest in the medium

x is the track length in the medium

β_{max} is the initial relative velocity of the electrons

$1/n$ is the limiting relative velocity for the Cerenkov effect

The integral in eq 2 may be evaluated graphically from a plot of $1 - (1/\beta^2 n^2)$ vs x. Figure 1 is such a plot made for water ($n = 1.333$). Although n is a function of λ, for most substances the assumption of constant n results in only a few percent error. Figure 2 is a plot of electron range as a function of energy for electrons in water for establishing values of x corresponding to specified initial electron energies. Integration up to each range corresponding to abscissa midpoint values of selected initial electron energy groups may be carried out and the values of the integral so obtained used in eq 2, as indicated. Each N_j may be substituted into eq 2 and N_{pj} evaluated for each initial electron energy group over the wavelength range of interest. From this, N_{pt}, the total number of light quanta generated in unit time at a wavelength λ_{avg}, may be obtained by summation according to

$$N_{pt} = \sum_j N_{pj} \tag{3}$$

where the sum is taken over all the j initial electron energy groups. The number of light quanta at each wavelength may then be plotted vs wavelength λ_{avg} to obtain the spectral distribution.

When gamma rays are the incident radiation, the initial electron energy distribution may be obtained from tabulated values.[5,6] The tabulations are given in terms of the cross section, σ, for Compton electron production per electron of material per photon per square centimeter. Therefore, for 1 cc of water at room temperature the number of electrons in each initial electron energy group, N_j, is

$$N_j = 3.34 \times 10^{23} \sum_i \phi_i \, \sigma_{ij} \tag{4}$$

where ϕ_i is the gamma ray flux

σ_{ij} is the cross section for Compton electron production in the jth electron energy group from a gamma ray in the ith gamma-ray energy group

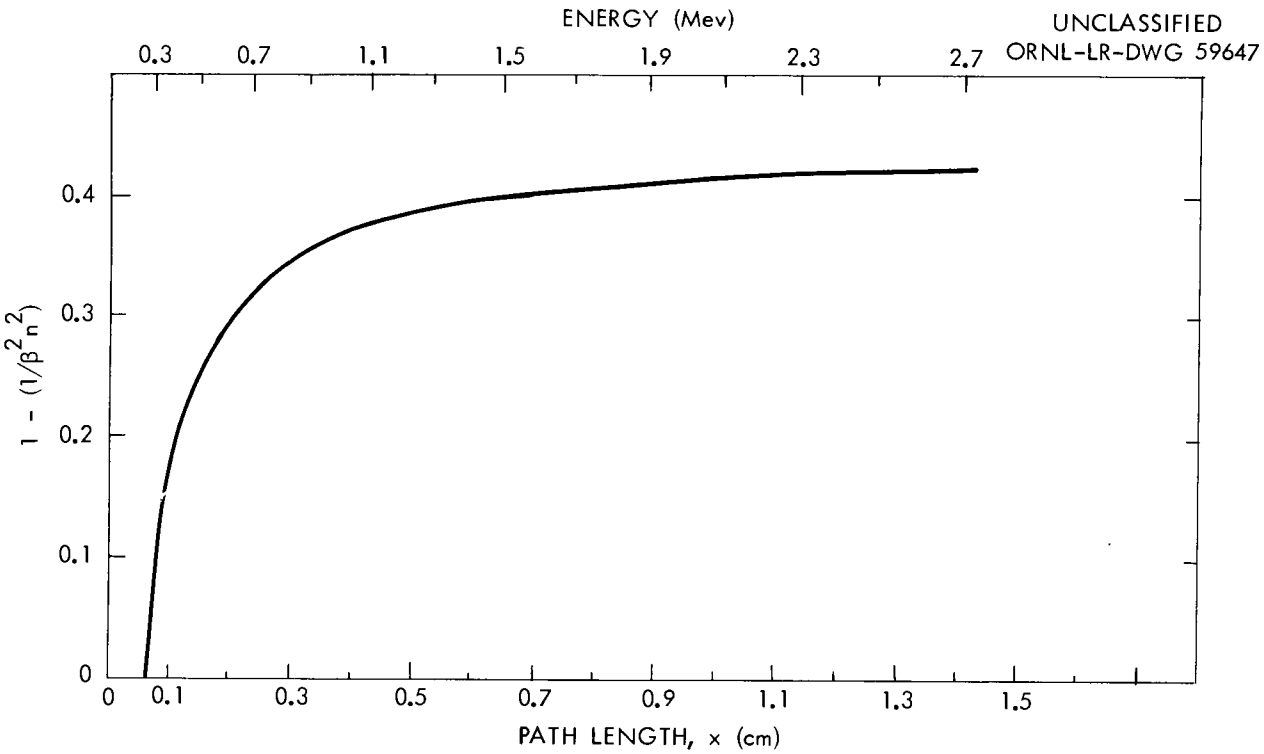

Fig. 1. Path length of a beta particle in water (n = 1.333) as a function of $1 - (1/\beta^2 n^2)$.

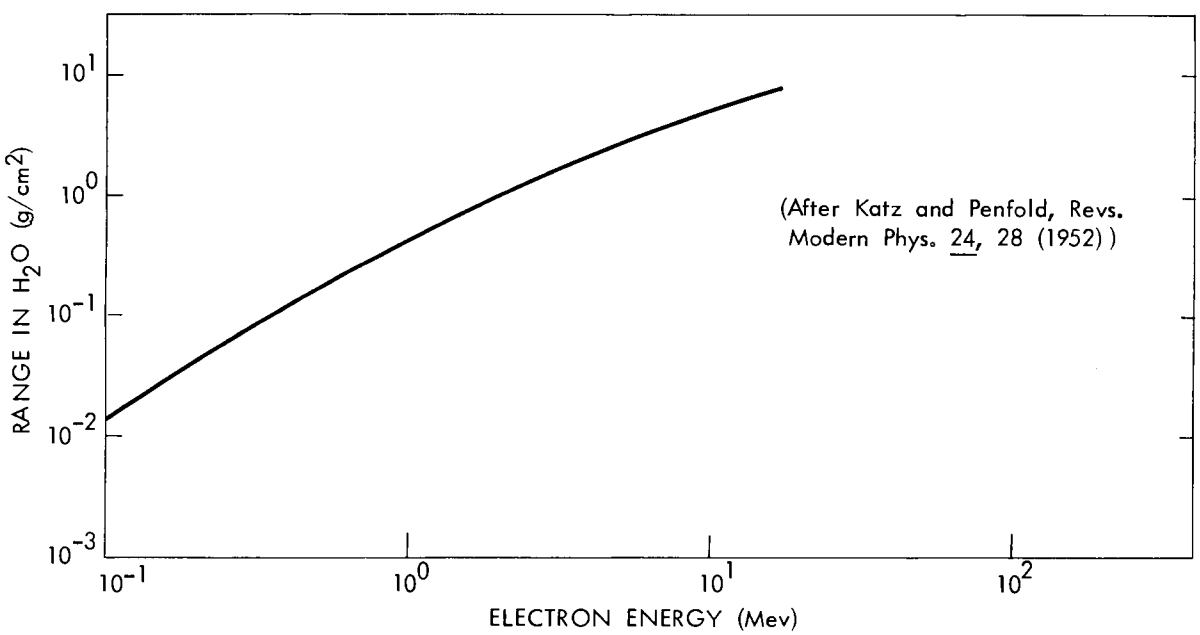

Fig. 2. Range-energy relation for monoenergetic electrons.

The sum is taken over the i gamma-ray energy groups at constant electron energy group for all the electron groups desired. Each N_j is substituted into eq 2, and the values of N_{pt} is obtained from eq 3, as before. From this the spectral distribution follows, as is described above.

To obtain the radiant energy emitted per unit time in the wavelength interval $\Delta\lambda$ about λ_{avg}, use is made of the relation

$$E_k = N_{pt} \frac{hc}{\lambda_{avg}} \tag{5}$$

where E_k is the energy in ergs radiated in unit time at the kth wavelength in interval $\Delta\lambda$

h is Planck's constant

A plot of E_k vs λ_{avg} between wavelengths of interest produces a curve which bounds an area proportional to the total Cerenkov radiation energy between those wavelengths. Thus, the total Cerenkov radiation energy, E_t, is given by

$$E_t = \int_{\lambda_{avg}(1)}^{\lambda_{avg}(2)} E' \, d\lambda \tag{6}$$

where E_t has the dimensions of ergs/sec when λ's are expressed in centimeters, and

$$E' = E_k/\Delta\lambda \tag{7}$$

4.0 CALCULATION OF SPECIFIC CASES

Sr^{90}. Sr^{90} may be used as an example in the calculations which must be performed to obtain the Cerenkov radiation from a beta-particle-emitting radioisotope in water. From eq 1 the lower limiting value of β that can make Cerenkov radiation coherent in a medium of refractive index 1.333 is 1/1.333, or 0.750. The relation between particle energy, E, and β is

$$E = m_o c^2 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1 \right) \tag{8}$$

where m_o is the rest mass of the particle. Equation 8 may be rearranged to give

$$\beta = \sqrt{1 - \left(\frac{0.511}{E + 0.511} \right)^2} \tag{9}$$

where the value 0.511 is the energy equivalent (in Mev) of m_0c^2 for an electron. From eq 8 the limiting value of E for production of Cerenkov radiation by electrons is

$$E = 0.511\left(\frac{1}{\sqrt{1 - (0.75)^2}} - 1\right) = 0.253 \text{ Mev}$$

Figure 3 is a plot of the beta-particle energy spectrum from Sr^{90} in secular equilibrium with its daughter Y^{90}. The bounded area above 0.253 Mev is the area of importance in the Cerenkov radiation calculations. This area has been subdivided into 10 subareas for the purpose of calculating N_j's for insertion into eq 2. The value of electron energy at the abscissa midpoint of each subarea is used to determine β from eq 9, which is then used with Figs. 1 and 2 to evaluate the integral in eq 2 for each of the ten initial electron energy intervals. The values obtained by carrying out the steps indicated in Sect. 3.0 are tabulated in the Appendix. A Sr^{90} source strength of 1 curie was assumed as a basis of calculation. It was assumed to be in a volume of sufficient size to attenuate all but a negligible fraction of the emitted beta particles. The Cerenkov radiation emitted was assumed to be unattenuated, and the calculations are for total light emitted between 2000 and 8000 A. Because of the cutoff at 0.253 Mev there is no significant contribution from secondary or cascade electrons to the Cerenkov radiation.[7]

Figure 4 is a plot of E_k vs λ_{avg}. Integration under the curve between any two wavelengths gives the total radiant energy in ergs per second due to Cerenkov radiation in that interval from 1 curie of Sr^{90} in equilibrium with its daughter Y^{90}. As an illustration, the total rate of Cerenkov energy production in the interval from 3100 to 6600 A is 12.4 ergs/sec. The rate of total decay energy release from such a source is 6.62×10^4 ergs/sec.

<u>Co^{60}</u>. Co^{60} may be used as an example in the calculations to obtain the Cerenkov radiation from a gamma-ray emitting radioisotope in water. Although Co^{60} is also a beta-particle emitter, the maximum beta-particle energy is 0.314 Mev, and only a negligible fraction of the beta particles have energies in excess of 0.253 Mev. Therefore only the Compton electrons

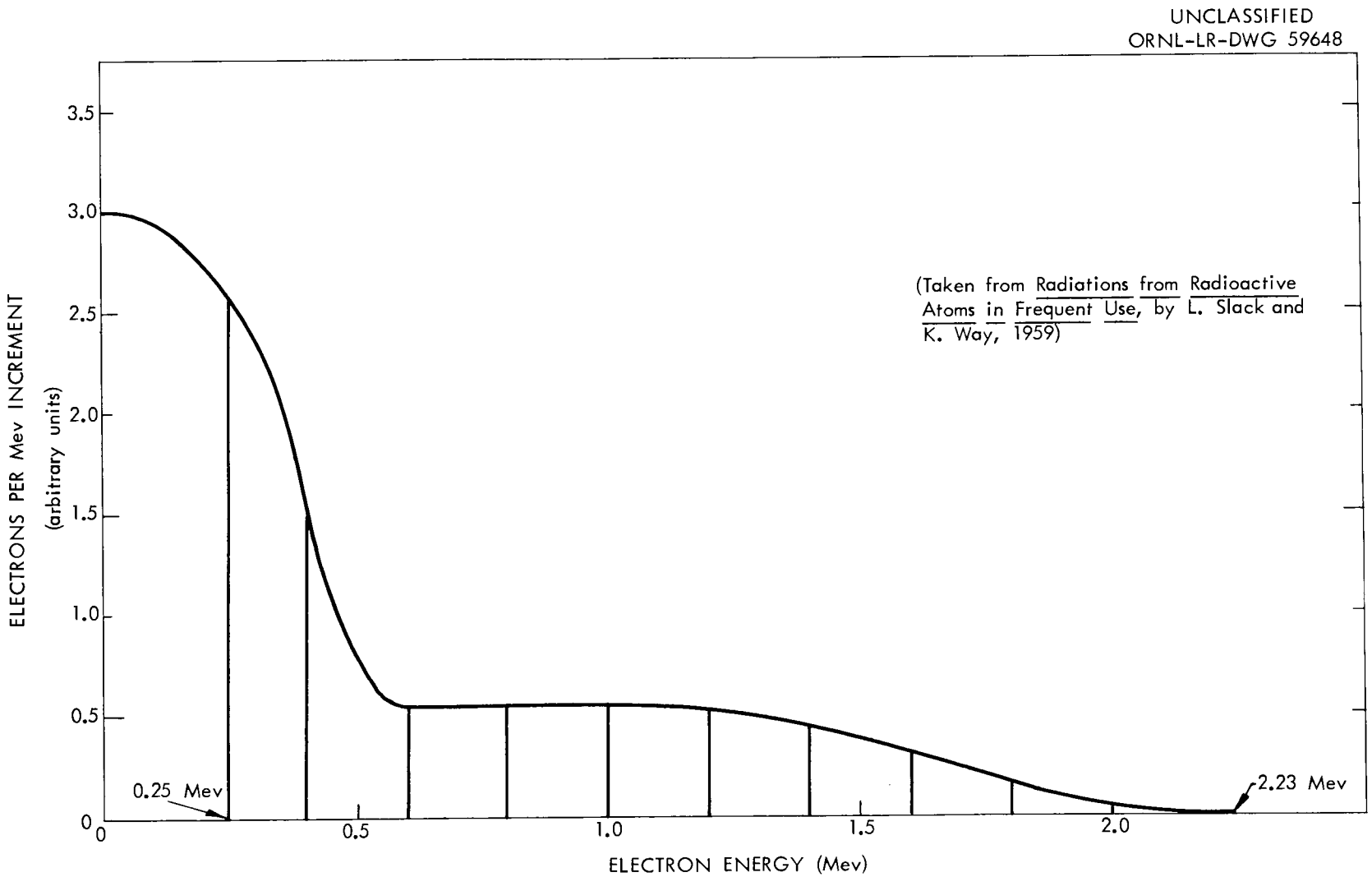

Fig. 3. Sr^{90}-Y^{90} beta particle energy spectrum.

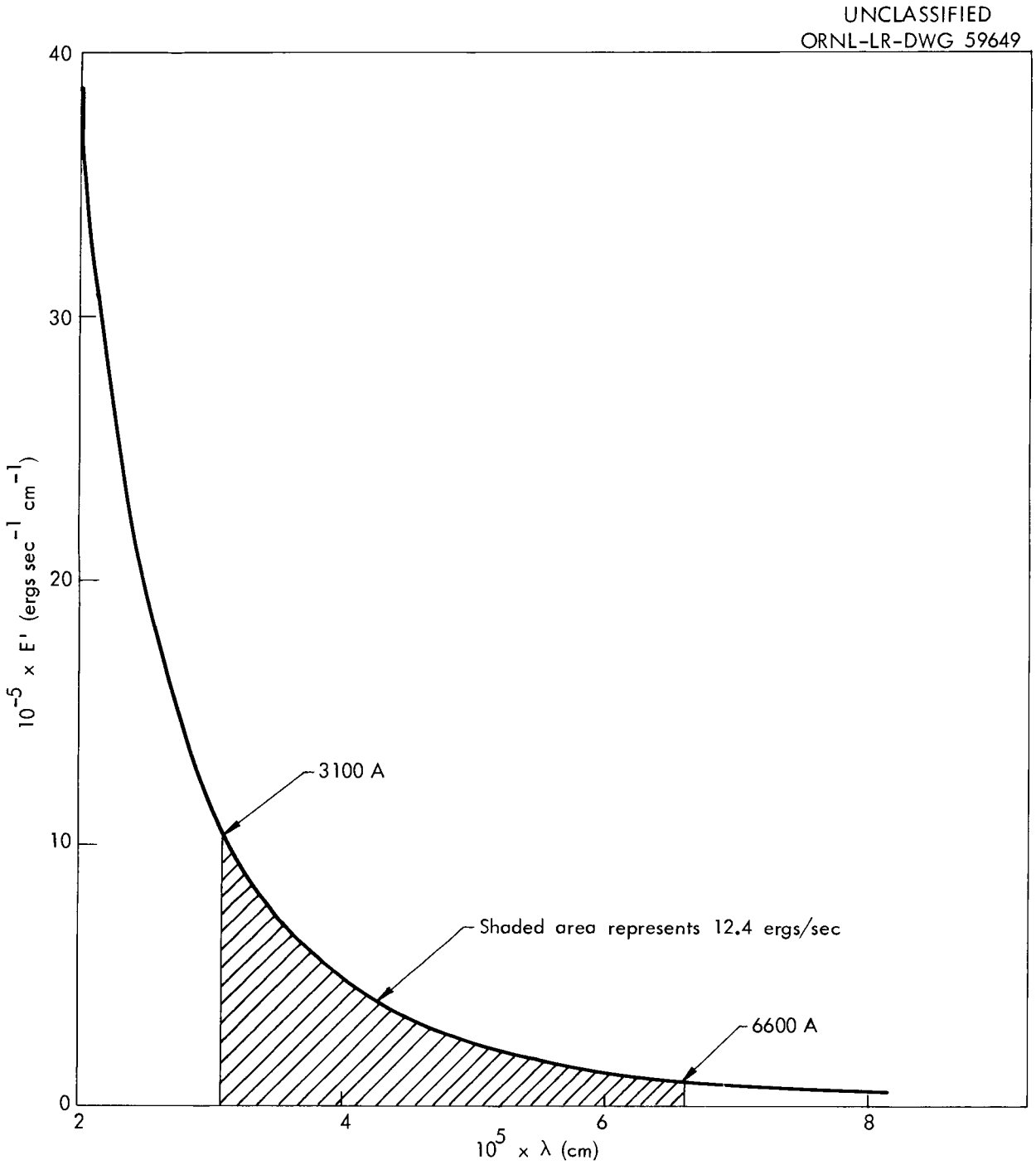

Fig. 4. Calculated Cerenkov spectral distribution from 1 curie of Sr^{90} in H_2O.

are of consequence in the production of Cerenkov radiation (both pair production and photoelectric effect are negligible for the 1.17- and 1.33-Mev Co^{60} gamma rays, which are produced in cascade with each beta particle emission). The Compton electron energy spectrum, calculated from information in reference 6, is plotted in Fig. 5. It was assumed that 1 curie of Co^{60} was homogeneously distributed throughout a volume of water so large that only a negligible fraction of the Co^{60} gamma rays escaped without producing a Compton electron. The ordinate of Fig. 5 is left in terms of cross-section for the Compton process to produce an electron of any specified energy, rather than being expressed in terms of electrons per Mev-interval per second, which is customary. This was done to avoid determining the photon flux for the homogeneously distributed source. The problem is circumvented by graphically integrating under the curve of Fig. 5 and identifying the area with the total number of Compton electrons produced, which must equal the number of gamma rays produced in the same time interval in the steady state since it was specified that the volume is large enough that only a negligible number of gamma rays escape before Compton interaction. The area under the curve in Fig. 5 was divided into 10 subareas, as indicated, and the electrons in each subarea were assigned the abscissa midpoint energy value, as in the previous example. The fraction which each subarea is of the total, multiplied by the total number of Compton electrons, gives N_j, as before. From 1 curie of Co^{60}, 7.4×10^{10} Compton electrons are produced per second. The values obtained by carrying out the steps indicated in Sect. 3 are tabulated in the Appendix. The calculations were made for the Cerenkov radiation emitted between 2000 and 8000 A, as in the example with Sr^{90}.

Figure 6 is a plot of E_k vs λ_{avg} for 1 curie of Co^{60} contained in an effectively infinite volume of water. The rate of Cerenkov radiation energy production in the 3100- to 6600-A interval is 11.3 ergs/sec. The rate of total decay energy release is 1.54×10^5 ergs/sec.

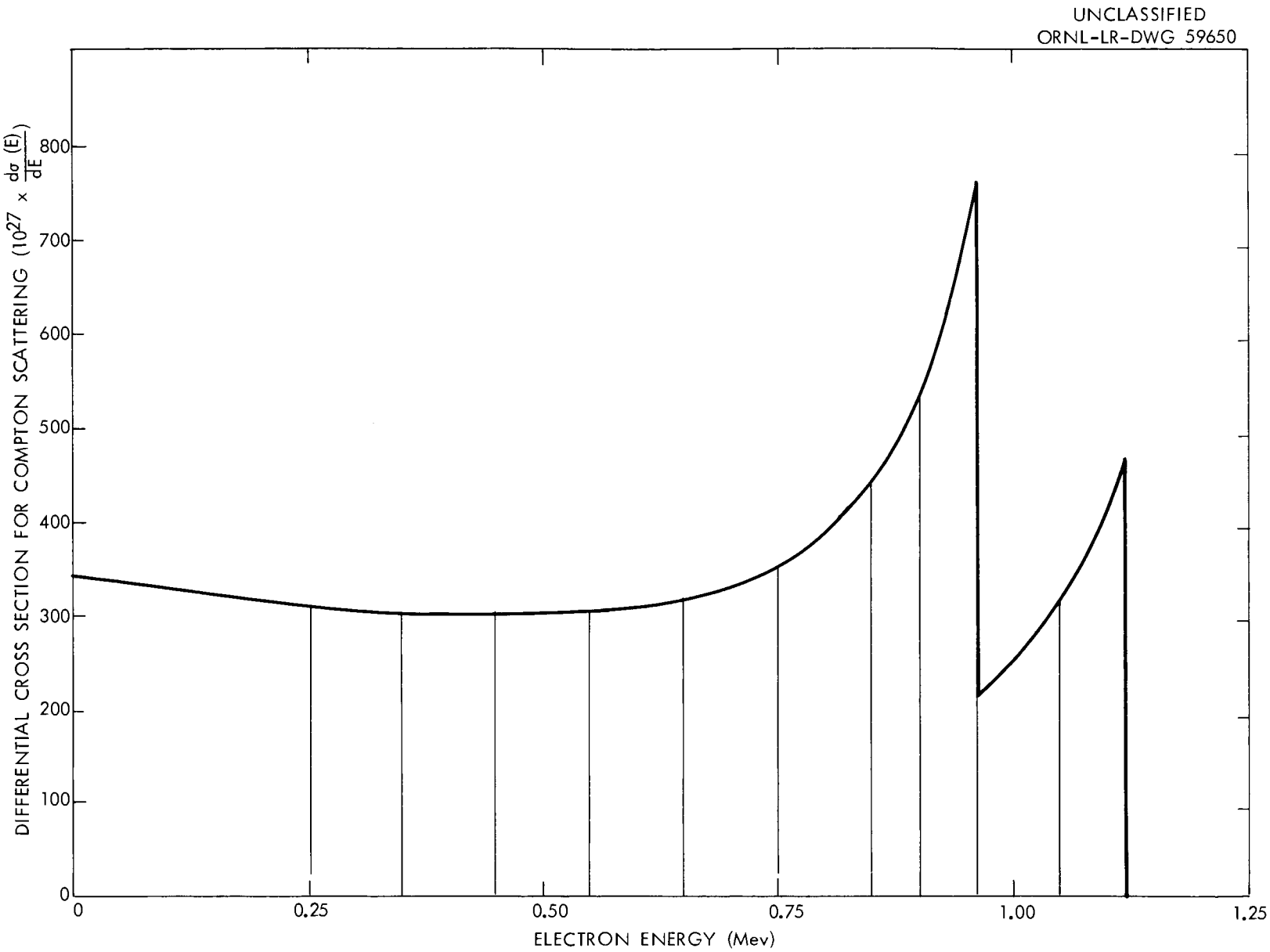

Fig. 5. Compton electron energy distribution for Co^{60} in H_2O.

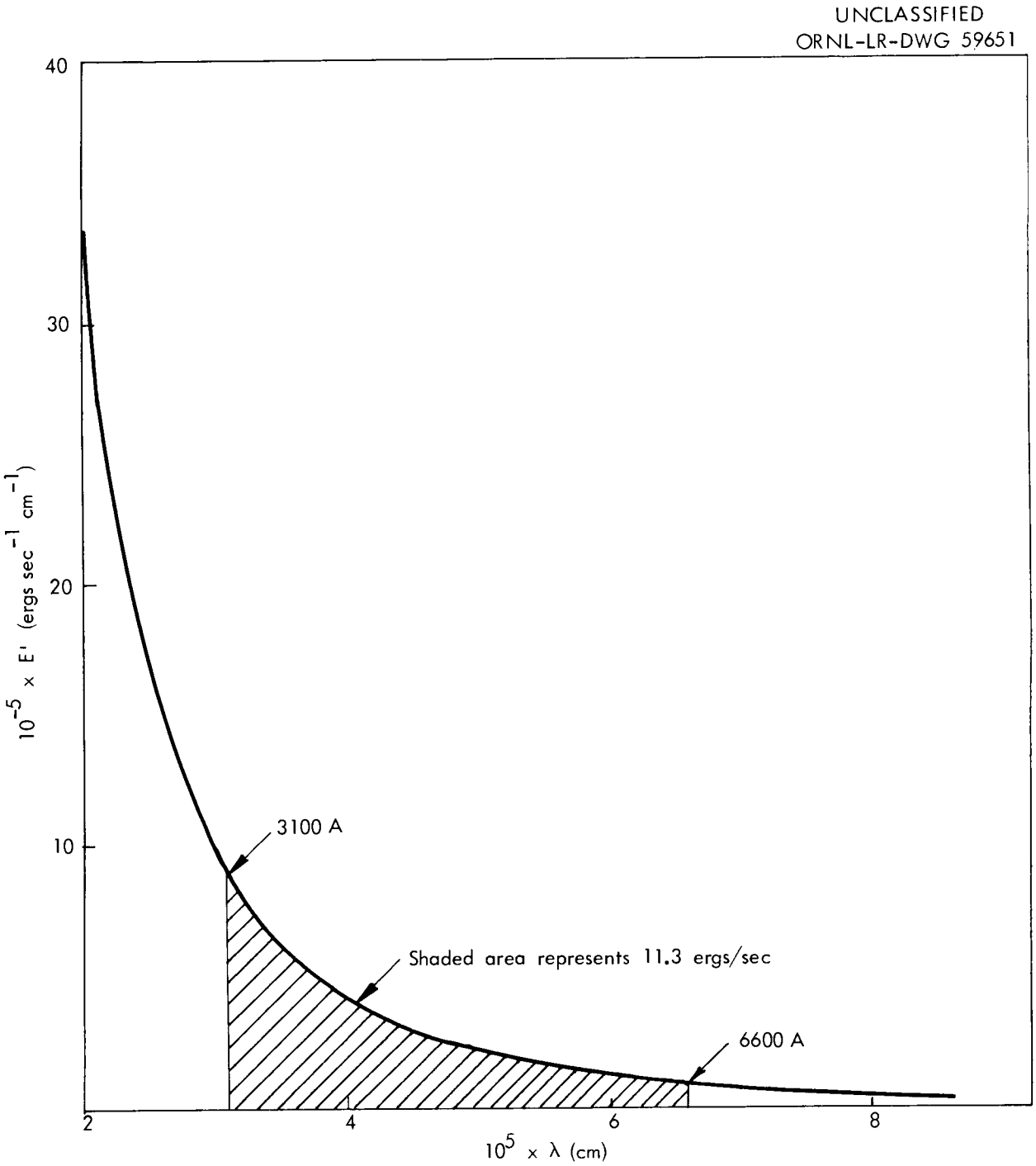

Fig. 6. Calculated Cerenkov spectral distribution from 1 curie of Co^{60} in H_2O.

5.0 DISCUSSION

By the method described above it is possible to calculate the Cerenkov radiation intensity and spectrum from any source of gamma rays (or x rays) and from any source of beta rays (or electrons). It should be possible, therefore, to evaluate the extent of interference from Cerenkov radiation with spectrophotometric and other similar measurements. It should be noted that the limiting energy for observing Cerenkov radiation from alpha-particle emission in water is 465 Mev (eq 8).

In the case of gamma ray emitters it should be mentioned that the method as described in this report may lead to low answers, since no account has been taken of the scattered photons after the first Compton interaction. The fraction of scattered photons possessing energies in excess of 0.407 Mev (the minimum energy which can produce a 0.25-Mev Compton electron) may be significant. For example, experimental measurements[2] made on Co^{60} in water gave the total radiant energy from Cerenkov radiation between 3100 and 6500 A as 22.6 ergs/sec. This is to be compared with the value of 11.3 ergs/sec calculated in this report. The analagous criticism should not be valid for the case of beta-particle emitters, because secondary electron contributions will be negligible in most cases of interest, as has already been mentioned.

The fact that such Cerenkov radiation intensity calculations can be made also suggests the possibility of making a standard source of ultraviolet light with a minimum of calibration and uncertainty as to output. For example, a Sr^{90}-Y^{90} source of well-defined geometry could be fabricated in a material of high refractive index and low absorption coefficient in the ultraviolet and used as a portable, versatile standard. Geometry corrections could be easily calculated, as could interfacial losses and internal absorption in the source from absorption coefficient-wavelength relations. Neglecting such corrections, the radiant energy from 1 curie of Sr^{90}, as calculated in this report, would be 0.019 erg/sec in the 1-angstrom-wavelength interval between 2537 and 2538 A. This rate of energy production is readily measured with a standard multiplier phototube such as the RCA 1P28, which has a signal-to-noise ratio of 1 at 2537 A and an energy input of 8×10^{-9} erg/sec.

It is worth noting that the above method also may prove useful for calculating Cerenkov radiation intensity from a mixture of radioisotopes for the purpose of deciding whether it is possible to monitor a system containing the mixture by collecting and measuring the Cerenkov radiation.[8] A focusing mirror might be used to improve the geometry when intensities are very low. In the case of a mixture of radioisotopes, the simplest approach to the calculations would be to add the appropriately weighted electron energy spectra and treat the sum curve as though it came from a single emitter.

6.0 REFERENCES

1. J. V. Jelley, "Cerenkov Radiation and Its Applications," Pergamon Press, New York, 1958.
2. J. A. Rich and R. E. Slovacek, "Gamma-induced Light Production in Water," AECD-3807 (Sept. 19, 1952).
3. M. A. Greenfield, A. Norman, A. H. Dowdy, and P. M. Kratz, J. Opt. Soc. Am., 43: 42 (1953).
4. E. H. Belcher, Proc. Royal Soc. London, A-216: 90 (1953).
5. H. E. Johns, J. E. Till, and D. V. Cormack, Nucleonics, 12: 40 (1954).
6. H. E. Johns, D. V. Cormack, S. A. Denesuk and G. F. Whitmore, Can. J. Phys., 30: 556 (1952).
7. G. J. Hine and G. L. Brownell, "Radiation Dosimetry," p 36, Academic Press, Inc., New York, 1956.
8. G. W. Hutchinson, "Cherenkov Detectors," pp 197-236 in "Progress in Nuclear Physics," vol 8, ed. by O. R. Frisch, Pergamon Press, New York, 1960.

7.0 APPENDIX

The values obtained by carrying out the steps indicated in Sect. 3 for Sr^{90} and Co^{60} in water are given in the appended table.

Cerenkov Radiation from 1 curie of Sr^{90} in Secular Equilibrium with Y^{90} and from 1 curie of Co^{60} in H_2O

Avg. Electron Energy (Mev)	$N_j \cdot 10^{-9}$ (electrons)	$\int\left(1-\frac{1}{\beta^2 n^2}\right) dx$ (cm)	$2\pi N_j/137 \cdot \int\left(1-\frac{1}{\beta^2 n^2}\right) dx \cdot 10^{-6}$	$N_{pj} \cdot 10^{-7}$ 2000 A	2500 A	3000 A	4000 A	5000 A	6000 A	7000 A	8000 A
				Sr^{90} in Secular Equilibrium with Y^{90}							
0.33	12.54	0.0016	0.92	2.30	1.47	1.02	0.55	0.37	0.26	0.19	0.14
0.50	8.188	0.0148	5.56	13.90	8.90	6.18	3.48	2.22	1.55	1.14	0.87
0.70	4.481	0.0444	9.12	22.81	14.60	10.15	5.70	3.65	2.54	1.86	1.43
0.90	4.625	0.0790	16.75	41.89	26.81	18.61	10.46	6.70	4.65	3.42	2.62
1.10	4.481	0.1186	24.39	60.98	39.02	27.10	15.24	9.76	6.78	4.98	3.81
1.30	4.096	0.1588	29.81	74.56	47.73	33.12	18.65	11.94	8.28	6.08	4.66
1.50	3.171	0.2032	29.60	74.01	47.39	32.90	18.50	11.85	8.22	6.04	4.63
1.70	2.109	0.2484	24.00	60.00	38.41	26.67	15.00	9.60	6.67	4.90	3.75
1.90	0.921	0.2938	12.40	31.00	19.85	13.78	7.75	4.96	3.45	2.53	1.94
2.11	0.205	0.3440	3.23	8.08	5.18	3.59	2.04	1.29	0.90	0.66	0.50
			$10^{-7} \cdot N_{pt}$	389	249	173	97.4	62.3	43.3	31.8	24.3 quanta/sec
			$10^{-5} \cdot E_k$	38.7	19.8	11.5	4.84	2.48	1.43	0.90	0.61 ergs sec^{-1} cm^{-1}
				Co^{60}							
0.126	15.62										
0.301	5.68	0.0005	0.13	0.33	0.21	0.15	0.08	0.05	0.04	0.03	0.02
0.400	5.74	0.0052	1.37	3.42	2.19	1.52	0.86	0.56	0.38	0.28	0.21
0.500	5.76	0.0152	4.02	10.04	6.42	4.46	2.51	1.61	1.11	0.82	0.63
0.600	5.89	0.0281	7.59	18.68	12.14	8.43	4.74	3.04	2.11	1.55	1.19
0.700	6.44	0.0422	12.46	31.16	19.94	13.85	7.79	5.98	3.46	2.54	1.95
0.800	7.38	0.0595	20.14	50.34	32.22	22.38	12.59	8.05	5.59	4.11	3.15
0.876	5.02	0.0731	16.83	42.07	26.93	18.70	10.52	6.73	4.68	3.43	2.63
0.933	6.91	0.0820	25.98	64.96	41.58	28.87	16.24	10.39	7.22	5.30	4.06
1.011	4.43	0.0984	19.99	49.98	31.99	22.21	12.49	8.00	5.55	4.08	3.12
1.084	5.11	0.1131	26.50	66.26	42.41	29.45	16.56	10.60	7.36	5.41	4.14
			$10^{-7} \cdot N_{pt}$	337.24	216.03	150.02	84.38	55.01	37.50	27.55	21.10 quanta/sec
			$10^{-5} \cdot E_k$	33.5	17.2	9.93	4.17	2.18	1.24	0.78	0.52 ergs sec^{-1} cm^{-1}

ORNL-3180
UC-34 — Physics
TID-4500 (16th ed.)

INTERNAL DISTRIBUTION

1. Biology Library
2-3. Central Research Library
4. Reactor Division Library
5. ORNL — Y-12 Technical Library
Document Reference Section
6-60. Laboratory Records Department
61. Laboratory Records, ORNL R.C.
62. E. D. Arnold
63-67. R. E. Biggers
68. R. E. Blanco
69. W. D. Bond
70. C. J. Borkowski
71. C. R. Boston
72. G. E. Boyd
73. J. C. Bresee
74. K. B. Brown
75. F. R. Bruce
76. R. H. Busey
77. W. R. Busing
78. A. E. Cameron
79. C. E. Center
80. A. Chetham-Strode
81. T. E. Cole
82. L. T. Corbin
83. D. A. Costanzo
84. J. H. Crawford, Jr.
85-86. F. L. Culler
87. W. Davis
88. J. S. Drury
89. C. Feldman
90. D. E. Ferguson
91. L. M. Ferris
92. D. J. Fisher
93. J. L. Fowler
94. J. H. Frye, Jr.
95. J. H. Gillette
96. H. E. Goeller
97. A. T. Gresky
98. W. R. Grimes
99. E. Guth
100. C. E. Guthrie
101. C. W. Hancher
102. C. S. Harrill
103. J. C. Hart
104. P. N. Haubenreich
105. C. J. Hochanadel
106. A. Hollaender
107. A. S. Householder
108. G. S. Hurst
109. J. S. Johnson
110. R. G. Jordan (Y-12)
111. W. H. Jordan
112. S. Katz (K-25)
113. M. T. Kelley
114. F. Kertesz
115. N. A. Krohn
116. H. Kubota
117. J. A. Lane
118. G. W. Leddicotte
119. T. A. Lincoln
120. S. C. Lind
121. H. G. MacPherson
122. W. L. Marshall
123. H. F. McDuffie
124. K. Z. Morgan
125. J. P. Murray (K-25)
126. M. L. Nelson
127. J. A. Norris
128. G. W. Parker
129. D. Phillips
130. S. A. Reynolds
131. J. T. Roberts
132. S. M. Rush
133. H. E. Seagren
134. C. H. Secoy
135. M. J. Skinner
136. G. P. Smith
137. J. I. Steinfeld
138. R. W. Stoughton
139. J. A. Swartout
140. E. H. Taylor
141. P. F. Thomason
142. J. W. Ullmann
143. W. E. Unger
144. W. C. Waggener
145. A. M. Weinberg
146. M. E. Whatley
147. J. C. White
148. C. E. Winters
149-153. R. G. Wymer

154. J. P. Young
155. J. W. Youngblood
156. D. L. Katz (consultant)
157. C. E. Larson (consultant)
158. I. Perlman (consultant)
159. J. H. Rushton (consultant)
160. H. Worthington (consultant)
161. T. H. Pigford (consultant)

EXTERNAL DISTRIBUTION

162. W. W. Meinke, University of Michigan
163. J. W. Nehls, AEC, ORO
164. R. E. Wedemeyer, AEC, ORO
165. J. Vanderryn, AEC, ORO
166. R. C. Hawes, Applied Physics Corporation, Monrovia, California
167. R. Eno, Applied Physics Corporation, Monrovia, California
168. W. Houston, Industrial Reactor Laboratory, Plainsboro, New Jersey
169. W. C. Whitley, Georgia Institute of Technology, Atlanta, Georgia
170. R. A. Day, Department of Chemistry, Emory University, Atlanta, Georgia
171. Division of Research and Development, AEC, ORO
172-799. Given distribution as shown in TID-4500 (16th ed.) under Physics category (75 copies – OTS)