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EXTERNAL ENVIRONMENTAL RADIATION MEASUREMENTS IN THE UNITED STATES

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tions of Burch and Libby.

States to establish the approximate range of population exposures to cosmic and terrestrial gamma radiation. An effort was made to obtain results which would be representative of the unperturbed natural background, affected as little as possible by the occasional substantial variations in the observed natural radiation levels produced by localized sources (e.g., proximity of granite buildings, brick paving, fallout, etc.).

Measurements were made with a 20-liter, air-filled, polyethylene-walled ionization chamber at atmospheric pressure. The chamber was kept inside an automobile under essentially identical field conditions of loading and ionization chamber orientation. It had been established previously that the attenuation by the vehicle did not affect the measured values in an important way (about five percent). The ionization current was measured

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* United States Atomic Energy Commission, Health and Safety Laboratory, New York.

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[redacted] classified according to the barometric pressure at the time of measurement in intervals of one inch of mercury. The average values and standard

[redacted]

Millikan, and Neher[9] and by Compton.[10] The most important difference between these two sets of cosmic-ray data is the amount of filtration of the ion chambers used, the first being thin-walled measurements (0.5 mm of steel), while Compton's measurements were made with the argon gas cavity shielded with 5 cm of lead and 2.5 cm of bronze in addition to the steel wall of the chamber.

It should be pointed out that even at sea level the numerical value of the total cosmic-ray intensity is not something on which there is universal agreement. Burch, in his critical review,[11] concludes that the best value for the ionization intensity at sea level may be deduced from the experimental work of Clay. This value is 1.77 ion pairs/cm^3-sec (3.1 microroentgens/hour) compared to Neher's value[12] of 2.74 ion pairs/cm^3-sec (4.8 microroentgens/hour). Hess' value[7] of 1.96 ion pairs/cm^3-sec (3.4 microroentgens/hour) falls between these two. It would appear that the discrepancies are too large to depend merely on differences in ionization chamber wall thickness or calibration technique.

Comparing the results of our measurements with the cosmic-ray data of Bowen, Millikan, and Neher, it is clear that a substantial part of the variability in mean outdoor radiation intensities over extensive areas in the United States is attributable to the variation in the cosmic radiation intensity with altitude. Most of the measurements made at higher altitudes were obtained in Colorado, and the shift of the total radiation curve in Fig. 1 away from the cosmic-ray curve at higher altitudes may be due to a higher terrestrial radiation component in the mountainous areas of Colorado.

Expressed on an annual basis, our measurements indicate a range of approximately 70 to 175 millirads/year for external environmental radiation dose rates in populated areas in the United States, with the lower dose rates prevailing in the more populated eastern and midwestern states. This compares with estimates made in the recent report of the National Academy of Sciences on the biological effects of atomic radiation,[13] which gives an average annual background dose of about 135 millirads and a maximum dose of about 170 millirads in populated areas.

Location	Range of Radiation Levels (microroentgens/hr)	Mean Annual Dose (millirads)*	Average Pressure (inches Hg)	Atypical Radiation Levels (microroentgens/hr)
Harrisburg, Pa.	9.6 - 11.9 (2)	88	29.8	-
Pittsburgh, Pa.	9.8 - 13.9 (3)	96	29.2	-
Cleveland, Ohio	10.5 - 11.8 (2)	91	29.4	
Toledo, Ohio	8.7 - 10.0 (2)	76	29.5	14.9 (over granite paving stone)
Chicago, Ill.	10.3 - 11.6 (4)	88	29.4	17.0 (adjacent to U.S. Post Office Bldg. of granite construction)
Madison, Wisc.	10.1 - 10.4 (3)	84	29.1	-
Minneapolis-St. Paul, Minn.	9.1 - 12.5 (4)	92	29.3	-
Sioux Falls, S. Dakota	11.5 - 11.8 (2)	95	28.8	-
Cheyenne, Wyo.	17.2 - 17.6 (2)	142	24.4	-
Denver, Colo.	16.6 - 19.4 (10)	147	25.0	22.4 (between U.S. Mint and City and County Bldgs.)
Colorado Springs, Colo.	19.3 - 22.3 (4)	168	24.2	-
Grand Junction, Colo.	15.7 - 18.4 (3)	138	25.5	-
Albuquerque, N. Mexico	13.8 - 14.5 (4)	116	25.2	-
Amarillo, Texas	12.9 - 13.6 (4)	108	26.4	-
Oklahoma City, Okla.	9.9 - 10.5 (4)	84	28.7	-
Tulsa, Okla.	10.8 - 11.6 (4)	92	29.3	-
Little Rock, Ark.	12.8 - 13.3 (2)	106	29.7	-
Memphis, Tenn.	9.4 - 11.0 (2)	83	29.8	13.3 (near brick apartment house)
Chattanooga, Tenn.	11.1 - 12.3 (2)	95	29.6	14.8 (near brick-faced motel units)
				16.1 (on narrow business street; 8th between Broad and Market)

* Dose in soft tissue, assuming constant dose rate.
1 rad = 100 ergs/gm, 1 microroentgen/hr = 8.152 mrad/yr.

Table I. Environmental radiation levels measured in principal United States cities during August, 1957. The number of observations for each range are shown in parentheses. Elevated radiation levels produced by localized sources are shown in the last column.

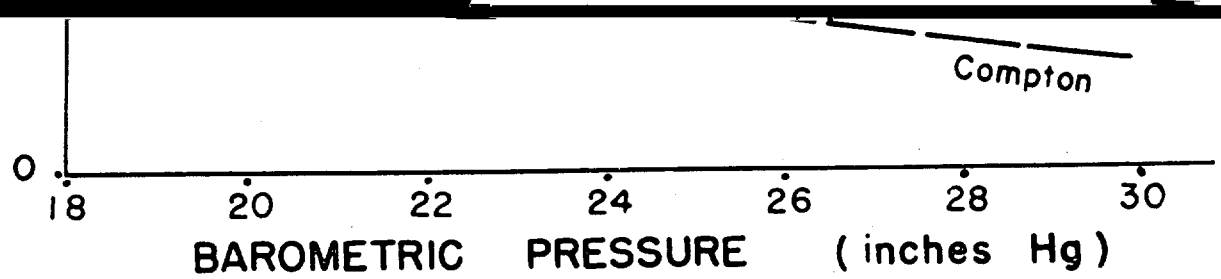

Figure 1. Variation of environmental radiation dose rates with barometric pressure. The lower curves are for cosmic radiation intensities alone. The number of observations incorporated in each point are shown in parentheses. Points marked "P" are observations on Pikes Peak.

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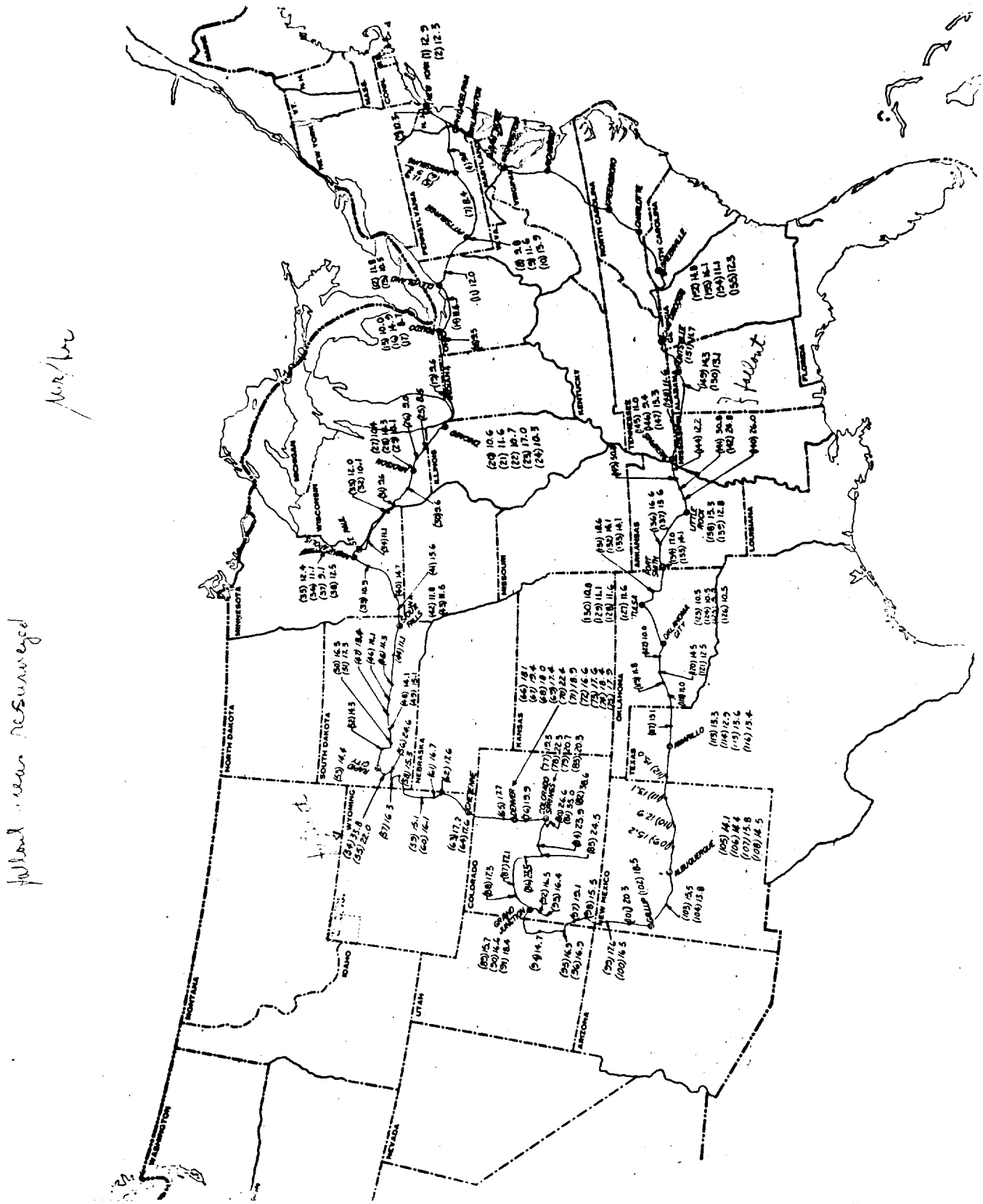
APPENDIX I



Itinerary of Survey - August, 1957

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (Inches)	TEMPI (
1. Pelham, N. Y.	12.9	Aug. 11, 1:15 P.M. (EDT)	29.93	3
2. New York City, N.Y.	12.3	Aug. 12, 8:30 A.M.	29.89	2
3. Newark, New Jersey	10.3	Aug. 12, 9:30 A.M.	30.04	2
4. Denver, Pennsylvania	9.0	Aug. 12, 12:30 P.M.	29.57	3
5. Harrisburg, Pennsylvania	11.9	Aug. 12, 2:10 P.M.	29.71	3
6. Harrisburg, Pennsylvania	9.6	Aug. 12, 2:45 P.M.	29.71	3
7. Pennsylvania Turnpike	8.4	Aug. 12, 5:10 P.M.	29.91	3
8. Pittsburgh, Pa.	9.8	Aug. 13, 9:10 A.M.	29.44	2
9. Pittsburgh, Pa.	11.6	Aug. 13, 11:00 A.M.	29.16	2
10. Pittsburgh, Pa.	13.9	Aug. 13, 11:15 A.M.	29.05	2
11. Ohio Turnpike	12.0	Aug. 13, 1:00 P.M.	28.99	2

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (Inches)	TEMPE (
12. Cleveland, Ohio	11.8	Aug. 13, 2:30 P. M.	29.30	29
13. Cleveland, Ohio	10.5	Aug. 13, 3:00 P.M.	29.52	32
14. Ohio Turnpike	11.6	Aug. 13, 4:25 P.M.	29.39	31
15. Toledo, Ohio	10.0	Aug. 13, 6:55 P.M. (EDT) 5:55 P.M. (EST)	29.47	34
16. Toledo, Ohio	14.9	Aug. 13, 6:10 P.M.	29.49	31
17. Toledo, Ohio	8.7	Aug. 13, 6:50 P.M.	29.44	29
18. Ohio Turnpike	9.5	Aug. 14, 7:45 A.M.	29.33	26
19. Indiana Turnpike	9.6	Aug. 14, 10:45 A.M.	29.18	27
20. Chicago, Illinois	10.6	Aug. 14, 12:35 P.M.	29.46	28
21. Chicago, Illinois	11.6	Aug. 14, 12:55 P.M.	29.45	30
22. Chicago, Illinois	10.7	Aug. 14, 1:10 P.M.	29.45	30

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
23. Chicago, Illinois	17.0	Aug. 14, 1:45 P. M.	29.43	31.5	65 West Adams; adjacent to U.S. Post Office of Granite Construction; near intersection with Clark
24 Chicago, Illinois	10 3	Aug. 14, 3:15 P.M.	29.38	35.1	Midway Airport; Parking Lot 5036 W. 63 Street
25. Lake Geneva, Wisconsin	8.5	Aug. 14, 6:40 P.M.	29.11	29.6	Center of Town; outside First National Bank
26. Whitewater, Wisconsin	9.0	Aug. 14, 7:30 P. M.	29.17	27.0	Residential Street
27 Madison, Wisconsin	10.4	Aug. 14, 11:00 P.M	29.08	26.3	Pinckney and Washington; opposite State Capitol
28 Madison, Wisconsin	10.3	Aug. 14, 11:30 P.M.	29.15	24.0	Motel Madison; Junction Route 51 and Route 12; approx. 8 miles east of Madison
29. Madison, Wisconsin	10.1	Aug. 15, 8:15 A.M.	29.08	25.0	Approx. 5 miles east of Madison on Route 12
30. Richland Center, Wis.	9.6	Aug. 15, 9:30 A.M.	29.24	23.5	Corner of East Haseltine and Church Street
31. La Crosse, Wisconsin	9.6	Aug. 15, 11:05 A.M.	29.36	29.0	Cass and 3rd Street near bridge over Mississippi River
32. Winona, Minnesota	10.1	Aug. 15, 12 Noon	29.40	30.1	Parking Lot of Hot Fish Shop Restaurant

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
33. Winona, Minnesota	12.0	Aug. 15, 12:55 P. M.	29.40	35.0	Intersection of Belleview and Carimona; Residential
34. Red Wing, Minnesota	11.1	Aug. 15, 2:45 P. M.	29.39	32.7	Intersection of 3rd St. and Plum; downtown
35. St. Paul, Minnesota	12.4	Aug. 15, 4:00 P. M.	29.29	28.5	On Hastings; near intersection of Maria and Wilson
36. St. Paul, Minnesota	11.1	Aug. 15, 4:25 P.M.	29.35	31.0	Robert St., near 9th St. downtown
37. Minneapolis, Minnesota	9.1	Aug. 15, 5:15 P.M.	29.30	30.2	Intersection 2 St. and Third Avenue, downtown; adjacent to Federal Office Building
38. Minneapolis, Minnesota	12.5	Aug. 15, 6:15 P. M.	29.24	30.4	Intersection, West 41st St. and Vernon; Residential
39. Le Sueur, Minnesota	10.9	Aug. 15, 7:30 P.M.	29.37	27.5	Near Downtown; Intersection of N. Main and Swan; latter a Residential Street
40. Worthington, Minnesota	14.7	Aug. 16, 9:30 A.M.	28.67	23.8	Intersection Grand and Dover, Residential
41. Luverne, Minnesota	13.6	Aug. 16, 10:45 A.M.	28.79	25.3	Freeman Street near Cedar St.
42. Sioux Falls, South Dakota	11.8	Aug. 16, 11:35 A.M.	28.83	31.0	Intersection 10th St. and Phillips Ave., Downtown
43. Sioux Falls, South Dakota	11.5	Aug. 16, 11:50 A.M.	28.75	29.7	Intersection West 10th St. and S. Euclid Ave., Resid.

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	
44. Mitchell, South Dakota	11.1	Aug. 16, 1:20 P.M. (CDT) 12:20 P.M. (CST)	28.92	34.7	Intersec and Firs
45. Chamberlain, South Dakota	11.3	Aug. 16, 2:55 P.M.	28.76	32.5	Junction
46. Presho, South Dakota	11.1	Aug. 16, 4:05 P.M.	28.35	31.9	On U.S. Station
47. Murdo, South Dakota	13.4	Aug. 16, 4:55 P.M.	27.78	30.1	Unmarked street, U. S. 16
48. Kadoka, South Dakota	14.1	Aug. 16, 6:05 P.M. (CST) 7:05 P.M. (CDT) 5:05 P.M. (MST)	27.62	31.0	Silver C south of
49. Kadoka, South Dakota	15.1	Aug. 17, 6:15 A.M.	27.67	21.3	Same as ence pos car load
50. Badlands, South Dakota	16.5	Aug. 17, 7:00 A. M.	27.61	25.0	Entrance
51. Badlands, South Dakota	17.3	Aug. 17, 8:30 A.M.	27.67	29.5	Heart of
52. Wall, South Dakota	14.3	Aug. 17, 10:15 A.M.	27.33	26.4	Center o
53. Rapid City, South Dakota	14.4	Aug. 17, 11:45 A.M.	26.97	23.6	On 6th S St. Jose
54. Keystone, South Dakota	33.8	Aug. 17, 1:00 P. M.	27.85	24.4	In Black Resurvey elevated attribut

RELATIVE ACTIVITY OF BUILDING BR

COUNTS/SECOND whole b

LOCAT	TYPE	HIGH ABSORPTION		MEDIUM ABSORPTION		LOW ABSORPTI	
Salisbury,	--	62	65	68	68	72	7
Atlanta, Ge	Surface Clay	82	83	98	104	94	8
Canton, Oh	Fire Clay						
"	Shale						
Columbus, C	--						
Streator, I	Shale	76	78	77	76	80	7
Chicago, Il	--						
Danville, I	Fire Clay	91	97	103	100	119	1
Fairbury, N	Fire Clay	69	68	67	67	68	6
Denver, Col	Shale and Surface Clay	86	60			76	9
"	Surface Clay			96	96		
"	Surface Clay	111	111	111	134	96	9
"	Fire Clay	135*	144*	165	165	388*	3
"	Fire Clay	236	236	214	214	191	1
Wichita, Ka	Surface Clay						
Austin, Tex	--						
San Francis	--						
New York, N	--						

BACKGROUND: APPROXIMATELY 12 C/SEC.

ese bricks are 1 to 3 pounds heavier than the average bri

ese bricks averaged about 6 pounds in weight.

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	
55. Black Hills, South Dakota	22.0	Aug. 17, 1:30 P. M.	25.1	24.0	Mo Po
56. Black Hills, South Dakota	24.6	Aug. 17, 2:45 P. M.	26.0	28.0	Sta Pos
57. Custer, South Dakota	16.3	Aug. 17, 4:30 P.M.	25.0	26.5	Adj
58. Hot Springs, South Dakota	15.3	Aug. 17, 5:45 P.M.	26.67	25.7	Adj
59. Lusk, Wyoming	15.1	Aug. 17, 8:30 P.M.	25.28	24.0	Cor Bar to
60. Lusk, Wyoming	16.1	Aug. 18, 7:00 A. M.	25.25	13.7	Sam com
61. Lingle, Wyoming	16.7	Aug. 18, 9:20 A.M.	26.06	23.3	1 b on
62. Torrington, Wyoming	17.6	Aug. 18, 9:45 A.M.	26.11	23.7	Cen Tra Nat
63. Cheyenne, Wyoming	17.2	Aug. 18, 11:45 A.M.	24.30	27.4	On Ave
64. Cheyenne, Wyoming	17.6	Aug. 18, 12:20 P.M.	24.51	30.5	Adj Cap nea
65. Denver, Colorado	17.7	Aug. 18, 2:55 P.M.	25.02	33.6	App Den feet with

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
66. Denver, Colorado	18.1	Aug. 18, 4:05 P. M.	24.85	32.5	On Evans near Fillmore
67. Denver, Colorado	19.4	Aug. 18, 5:05 P. M.	24.95	32.9	Carport of Royal Motel, intersection of South Broadway and Iowa Avenue
68. Denver, Colorado	18.0	Aug. 18, 5:30 P.M.	24.98	32.6	Intersection of Raritan and Nevada; residential
69. Denver, Colorado	17.4	Aug. 18, 5:45 P.M.	24.97	32.4	Intersection of Santa Fe Drive, West eighth Avenue; Shopping area
70. Denver, Colorado	22.4	Aug. 18, 6:00 P. M.	24.97	32.5	On Cherokee St. between 14 St. and Colfax between U.S Mint and City & County Building.
71. Denver, Colorado	18.9	Aug. 18, 6:30 P.M.	24.99	30.8	East corner of Wilton and 23rd St., near downtown
72. Denver, Colorado	16.6	Aug. 18, 6:45 P.M.	25.03	31.3	Near 18th St. & Wyncoop in Union Station Parking Lot
73. Denver, Colorado	17.6	Aug. 18, 7:10 P.M.	24.94	30.5	Intersection of 38th Ave. and Tejon
74. Denver, Colorado	18.4	Aug. 18, 7:45 P.M.	24.93	27.2	Adjacent to Denver Museum of Natural History
75. Denver, Colorado	17.9	Aug. 18, 8:00 P.M.	24.85	28.6	Intersection of 7th Ave. and Monroe, residential

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
76. Denver, Colorado	19.9	Aug. 19, 9:20 A.M.	24.31	32.3	On U.S. 85, approximately 44 miles north of Colorado Springs, Colorado
77. Colorado Springs, Colorado	19.3	Aug. 19, 10:45 A.M.	24.22	33.0	Intersection of East Madison and North Nevada; residential
78. Colorado Springs, Colorado	22.3	Aug. 19, 11:25 A.M.	24.30	32.8	Kiowa Ave. between Cascade and Tejon; downtown
79. Colorado Springs, Colorado	20.7	Aug. 19, 12:30 P.M.	24.25	33.4	Vermijo at 23rd Street; unpaved residential street
80. Pikes Peak Highway, Col.	26.6	Aug. 19, 1:00 P.M.	22.97	33.5	One mile beyond Cascade, Colorado
81. Pikes Peak Highway, Col.	35.0	Aug. 19, 1:40 P.M.	21.28	30.5	Halfway Water Station, actual altitude, 9,950 feet
82. Pikes Peak Summit, Col.	38.6	Aug. 19, 3:00 P.M.	18.46	34.0	Actual altitude 14,110 feet
83. Colorado Springs, Col.	20.3	Aug. 20, 6:05 A.M.	24.12	16.0	Town House Motel Parking Lot
84. Hartsel, Colorado	23.9	Aug. 20, 9:10 A. M.	22.03	24.0	Sand & Gravel Parking lot of Holiday Inn Hotel
85. Buena Vista, Colorado	24.5	Aug. 20, 10:10 A.M.	22.50	25.0	Near intersection, US 24 and Colorado 306
86. Leadville, Colorado	23.5	Aug. 20, 11:10 A.M.	21.10	25.4	Center of Town, East 6th St. near Harrison; unpaved
87. Glenwood Springs, Col.	17.1	Aug. 20, 3:10 P.M.	24.52	23.0	Intersection of Grand Avenue and Eighth Street; downtown

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
88. Rifle, Colorado	17.3	Aug. 20, 5:10 P. M.	24.87	25.0	On East 3rd Street just west of White River Avenue; residential, one block from business district
89. Grand Junction, Col.	15.7	Aug. 20, 7:15 P. M.	25.47	27.2	Intersection Cannell and Glenwood, residential, outside Calvary Bible Church
90. Grand Junction, Col.	16.6	Aug. 21, 7:10 A. M.	25.54	20.0	Lazy Bar X Motel driveway
91. Grand Junction, Col.	18.4	Aug. 21, 9:30 A.M.	25.60	24.7	Outside AEC Operations Office
92. Colorado Plateau, Col.	16.5	Aug. 21, 12:00 Noon	23.54	29.0	Between towns of Whitewater and Gateway Unaweep Canyon, approximately 25 miles south of Whitewater
93. Colorado Plateau, Col.	16.4	Aug. 21, 1:05 P. M.	25.30	24.8	Approx. two miles north of Gateway
94. Moab, Utah	14.7	Aug. 21, 6:20 P. M.	25.96	31.8	Outside, 160 Main Street, downtown
95. Monticello, Utah	16.9	Aug. 21, 8:30 P. M.	23.50	23.8	Adjacent to Hills Triangle Motel
96. Monticello, Utah	16.9	Aug. 22, 7:40 A. M.	23.54	18.0	Same as Position 95
97. Dove Creek, Colorado	19.1	Aug. 22, 8:35 A.M.	23.72	24.2	On unpaved portion on US 160 in construction area
98. Cortez, Colorado	15.5	Aug. 22, 9:35 A. M.	24.29	27.0	Center of town; off pavement

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
99. Navajo Indian Reservation, New Mexico	17.6	Aug. 22, 11:30 A. M.	25.12	32.4	—
100. Shiprock, New Mexico	16.5	Aug. 22, 12:00 Noon	24.97	34.8	—
101. Buffalo Springs Trading Post, New Mexico	20.3	Aug. 22, 1:30 P. M.	24.33	33.2	On US 666 between towns Gallup and Naschitti
102. Gallup, New Mexico	18.5	Aug. 22, 2:40 P. M.	23.95	33.2	On East 66th St. near F Avenue, downtown
103. Grants, New Mexico	15.5	Aug. 22, 5:15 P. M.	23.94	29.0	Outskirts over unpaved ground adjacent to trai camp
104. Grants, Nex Mexico	13.8	Aug. 22, 5:35 P. M.	23.98	29.5	"Downtown", on paved US
105. Albuquerque, New Mexico	14.1	Aug. 23, 6:45 A.M.	25.30	22.4	Monterey Court Parking west side of City, off US 66
106. Albuquerque, New Mexico	14.4	Aug. 23, 7:20 A. M.	25.30	23.6	"Old City", adjacent t Church of San Felipe d
107. Albuquerque, New Mexico	13.8	Aug. 23, 7:45 A. M.	25.29	25.0	Intersection of Centra and Fourth Street; dow
108. Albuquerque, New Mexico	14 5	Aug. 23, 8:30 A. M.	25.13	30.6	West side near Trinity dist Church off U. S.
109. Albuquerque, New Mexico	15.2	Aug. 23, 10:00 A. M.	24.14	26.1	"Open Country" between Albuquerque and Santa approximately 43 miles of Santa Rosa, across Standard Asphalt Plan

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
110. Santa Rosa, New Mexico	12.9	Aug. 23, 11:15 A. M.	25.60	30.0	Adjacent to Santa Rosa Town Hall on U. S. 66
111. Tucumcari, New Mexico	13.1	Aug. 23, 12:40 P.M. (MST) 1:40 P.M. (CST)	26.06	31.5	Intersection; E. Hines Ave. and S. First Ave., residential street one block from U. S. 66
112. Amarillo, Texas	15.0	Aug. 23, 3:20 P. M.	26.22	33.5	Between Tucumcari, New Mexico and Amarillo, Texas, approximately 65 miles west of Amarillo over red soil on plains
113. Amarillo, Texas	13.3	Aug. 23, 4:45 P. M.	26.39	34.2	W. edge of town, Ranch 66 Motel
114. Amarillo, Texas	12.9	Aug. 24, 8:15 A.M.	26.36	23.9	Same as Position 113
115. Amarillo, Texas	13.6	Aug. 24, 10:00 A.M.	26.40	26.0	Intersection, south Filmore Street and East 6th Avenue; downtown
116. Amarillo, Texas	13.4	Aug. 24, 10:15 A.M.	26.39	27.6	Intersection NE 7th Avenue and North Pierce, Residential
117. McLean, Texas	13.1	Aug. 24, 11:50 A.M.	27.12	29.2	One block North of U.S. 66 and one block West of Main Street; residential
118. Sayre, Oklahoma	11.0	Aug. 24, 1:15 P.M.	28.11	32.0	Downtown, outside City National Bank

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRES (inc
119. Elk City, Oklahoma	11.8	Aug. 24, 2:25 P.M.	27.
120. Clinton, Oklahoma	14.5	Aug. 24, 3:05 P.M.	28.
121. Clinton, Oklahoma	12.5	Aug. 24, 3:25 P.M.	28.
122. El Reno, Oklahoma	10.0	Aug. 24, 4:55 P.M.	28.
123. Oklahoma City, Oklahoma	10.5	Aug. 24, 5:45 P.M.	28.
124. Oklahoma City, Oklahoma	10.5	Aug. 24, 6:10 P.M.	28.
125. Oklahoma City, Oklahoma	9.9	Aug. 24, 6:40 P.M.	28.
126. Oklahoma City, Oklahoma	10.5	Aug. 24, 6:50 P.M.	28.
127. Tulsa, Oklahoma	11.6	Aug. 25, 7:35 A.M.	29.
128. Tulsa, Oklahoma	11.6	Aug. 25, 9:30 A.M.	29.

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
129. Tulsa, Oklahoma	11.1	Aug. 25, 9:55 A. M.	29.28	32.3	Fourth St. and South Main, one block from City Hall, downtown
130. Tulsa, Oklahoma	10.8	Aug. 25, 10:20 A. M.	29.28	32.8	On East 14th St. between Rockford and St. Louis Avenues; residential
131. Muskogee, Oklahoma	18.6	Aug. 25, 11:45 A. M.	29.39	34.7	Okmulgee Street near S. 26 Street; residential
132. Muskogee, Oklahoma	14.1	Aug. 25, 12:05 P. M.	29.39	35.5	Intersection of West Okmulgee St. and N. 4th St. downtown
133. Muskogee, Oklahoma	14.1	Aug. 25, 12:20 P. M.	29.41	36.2	South B and Kalamazoo over dirt road
134. Fort Smith, Arkansas	17.0	Aug. 25, 2:20 P. M.	29.55	38.3	On North 6th Street between Rogers and Parker, between U. S. Post Office and County Building, downtown
135. Fort Smith, Arkansas	14.1	Aug. 25, 2:35 P. M.	29.55	37.2	Intersection of North 13 St. and N. A St., across from First Christ Church, edge of downtown section
136. Russellville, Arkansas	16.6	Aug. 25, 5:25 P. M.	29.65	33.6	Intersection of Main and Commerce on Main, center of town
137. Russellville, Arkansas	13.6	Aug. 25, 5:45 P. M.	29.65	34.3	East 5th St. & S. Cleveland; residential

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERAT (°C)
138. Little Rock, Arkansas	13.3	Aug. 25, 8:00 P. M.	29.72	29.7
139. Little Rock, Arkansas	12.8	Aug. 25, 8:20 P. M.	29.72	31.2
140. Hazen, Arkansas	26.0	Aug. 25, 9:55 P. M.	29.85	26.3
141. Brinkley, Arkansas	30.8	Aug. 26, 8:05 A. M.	30.04	29.2
142. Brinkley, Arkansas	24.8	Aug. 26, 9:35 A.M.	30.04	30.5
143. Wheatley, Arkansas	50.2	Aug. 26, 10:00 A. M.	30.03	33.5
144. Forrest City, Arkansas	12.2	Aug. 26, 11:00 A. M.	29.96	32.6
145. Memphis, Tennessee	11.0	Aug. 26, 12:15 P. M.	29.95	34.9

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	
146. Memphis, Tennessee	9.4	Aug. 26, 12:45 P. M.	29.59	35.8	Inters Third
147. Memphis, Tennessee	13.3	Aug. 26, 1:15 P. M.	29.91	36.6	Inters Aubern apartm
148. Corinth, Mississippi	11.6	Aug. 26, 3:30 P. M.	29.71	33.0	Southe unpave Kathy'
149. Decatur, Alabama	14.3	Aug. 26, 6:25 P. M.	29.55	30.2	Inters Church Strip edge o tremel tribut vated
150. Decatur, Alabama	13.1	Aug. 26, 6:40 P. M.	29,59	31.2	Inters Church
151. Huntsville, Alabama	11.7	Aug. 26, 7:35 P.M. (CST) 6:35 P.M. (EST)	29.55	29.2	On Hol west o bus st Nazare
152. Chattanooga, Tennessee	14.8	Aug. 27, 7:00 A. M.	29.50	18.0	Wester sand a of Tur U. S. motel what e

LOCATION	RADIATION LEVEL (μr/hr)	DATE AND TIME (1957)	PRESSURE (inches)	TEMPERATURE (°C)	COMMENTS
153. Chattanooga, Tennessee	16.1	Aug. 27, 9:20 A. M.	29.59	28.2	On 8th St. between Broad and Market, narrow street with stores and offices; downtown
154. Chattanooga, Tennessee	11.1	Aug. 27, 9:45 A. M.	29.59	30.0	Outside 921 Market near 10th Street, wide business thoroughfare, downtown
155. Chattanooga, Tennessee	12.3	Aug. 27, 10:00 A. M.	29.57	30.9	Intersection of West Duncan and South Kelly; residential

APPENDIX II

Instrumentation

In this appendix are described the instrument and the technique of measurement. As mentioned in the main portion of this paper, measurements were made with a 20-liter ionization chamber filled with air at atmospheric pressure. The instrument was operated inside an automobile under essentially identical conditions of vehicle loading and orientation. The ionization current was measured with a vibrating reed electrometer connected as a continuously reading voltmeter driving a pen recorder. Power for the electrometer and recorder was obtained from an alternating current inverter operated from the 12-volt automobile storage battery. The entire assembly was secured to a wooden carrying board as shown in the photograph (Fig. II-1).

The chamber was improvised from a 20-liter polyethylene carboy having a 3/32-inch wall. To suppress completely the beta response, the chamber was positioned in a solid 1/8-inch aluminum shield. Including the polyethylene wall, the gas volume was enclosed by 1.08 g/cm^2 of material, corresponding to the Feather range of a 2.26 Mev beta particle.

A schematic diagram of the ionization chamber showing the details of the center electrode assembly is shown in Figure II-2.

The chamber has two guard rings with the top of the center electrode secured by the guard ring assembly to the carboy. The top and bottom guard rings are connected together by an insulated wire strung through the stainless steel electrode. For laboratory use one could dispense with the top assembly but for field use the additional mechanical rigidity is advantageous. There is sufficient air leakage in the chamber so that the chamber maintains atmospheric pressure. This was verified in the field by checking the response of the chamber to a weak source against the known barometric pressure.

As is well known, minute alpha contamination of an ionization chamber at atmospheric pressure can produce a current which may be of the same order as the current being measured. For this reason it is essential that the effect of contamination be measured or that the current produced by alpha particles be suppressed. A method of evaluating the alpha current is furnished by Hess and Vancour.[a] Essentially, the method depends on the limited range of alpha particles resulting in the alpha-produced ionization being independent of the pressure, whereas the ionization produced by gamma radiation (or charged relativistic particles in the cosmic radiation) is almost exactly proportional to the pressure.

A frequently used procedure is to pressurize the chamber filling (usually purified argon) so that the alpha contribution is negligible compared to the ionization produced by an external radiation field.

[redacted] to effect total collection of ion pairs produced by particles of low and high specific ionization; i.e., electrons from gamma-ray and alpha-particle interactions respectively.

Figure II-3 shows an ion collection characteristic for two different radiation fields measured with our apparatus. The upper curve is for an external field of 215 microroentgens/hour from a radium source at a distance of several meters from the chamber. The lower curve is for the radiation background for the same position in the Health and Safety Laboratory. During this measurement the background was about eight microroentgens/hour. It can be seen that for the elevated radiation field the saturation potential is reached with a collecting potential of 20 volts across the chamber. On the other hand, for the background curve, where the saturation collecting potential must be less than that required for the higher radiation field, the characteristic shows a pronounced rise from 50 to 300 volts. This rise follows a plateau between 10 and 50 volts. At 300 volts the measured ionization current is more than fifty percent greater than the ionization current in the 10- to 50-volt interval. Figure II-4, which plots the fraction of the ion current at 300 volts against the collecting potential, shows this effect more graphically.

The explanation for this is simple. While saturation for the ionization produced by gamma rays is quickly achieved, collection for the alpha ionization is relatively inefficient and in fact saturation is not reached up to the maximum collecting potential used. The important feature of the curves shown in Fig. II-3 and Fig. II-4 is that for a considerable range in collecting potential, up to about fifty volts, the alpha contribution is suppressed to the point where it makes a negligible contribution to the total ion current. This situation prevails provided one reads the minimum envelope of the output trace.

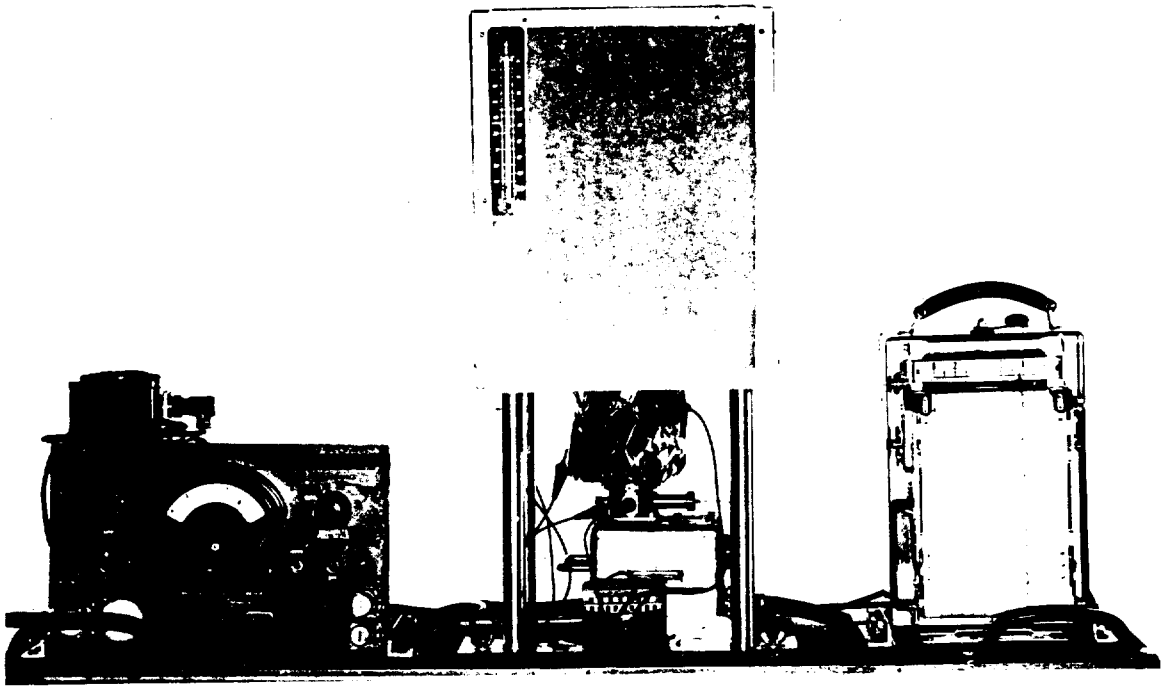
The character of the trace obtained with different collecting potentials is shown in Fig. II-5. The figure shows the trace of the electrometer zero (A), the trace with no collecting potential applied to the chamber (B), and the background trace with the different collecting potentials up to 300 volts (C). One may observe the alpha pulses becoming more prominent as the collecting potential is increased. The saturation curves previously described were taken at the lower envelope or minima of these traces. When runs are made over an extended period (of the order of ten or more minutes) minima occur with the same amplitude. One infers that these minima are associated with the absence of ionization caused by alpha particles.

The general behavior of the phenomena described can be interpreted in terms of the Jaffé-Zanstra theory of columnar recombination.[b] However, the theory is not sufficiently precise to furnish much more than a qualitative description of the difference in saturation characteristics for radiations of different specific ionizations in air-filled chambers.

alternative and possibly superior method of calibration is to position the source in a number of points around the chamber and average the calibration factors so obtained. This method of calibration would correct in some measure for the shielding of terrestrial radiation furnished by the components surrounding the ion chamber, but also would result in an overestimation of the

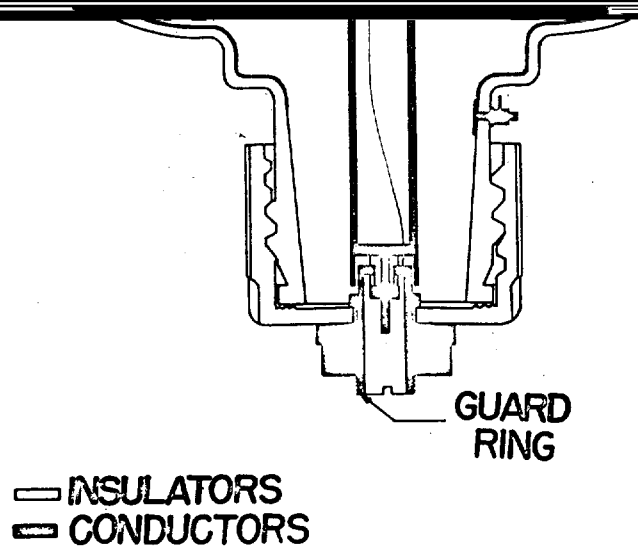
[redacted]

refinement in the calibration constant is indicated considering the grosser errors inherent in field measurements of this type.



TWENTY LITER IONIZATION CHAMBER
AND ASSOCIATED APPARATUS

FIGURE II-1



Twenty Liter Ionization Chamber

Figure II-2

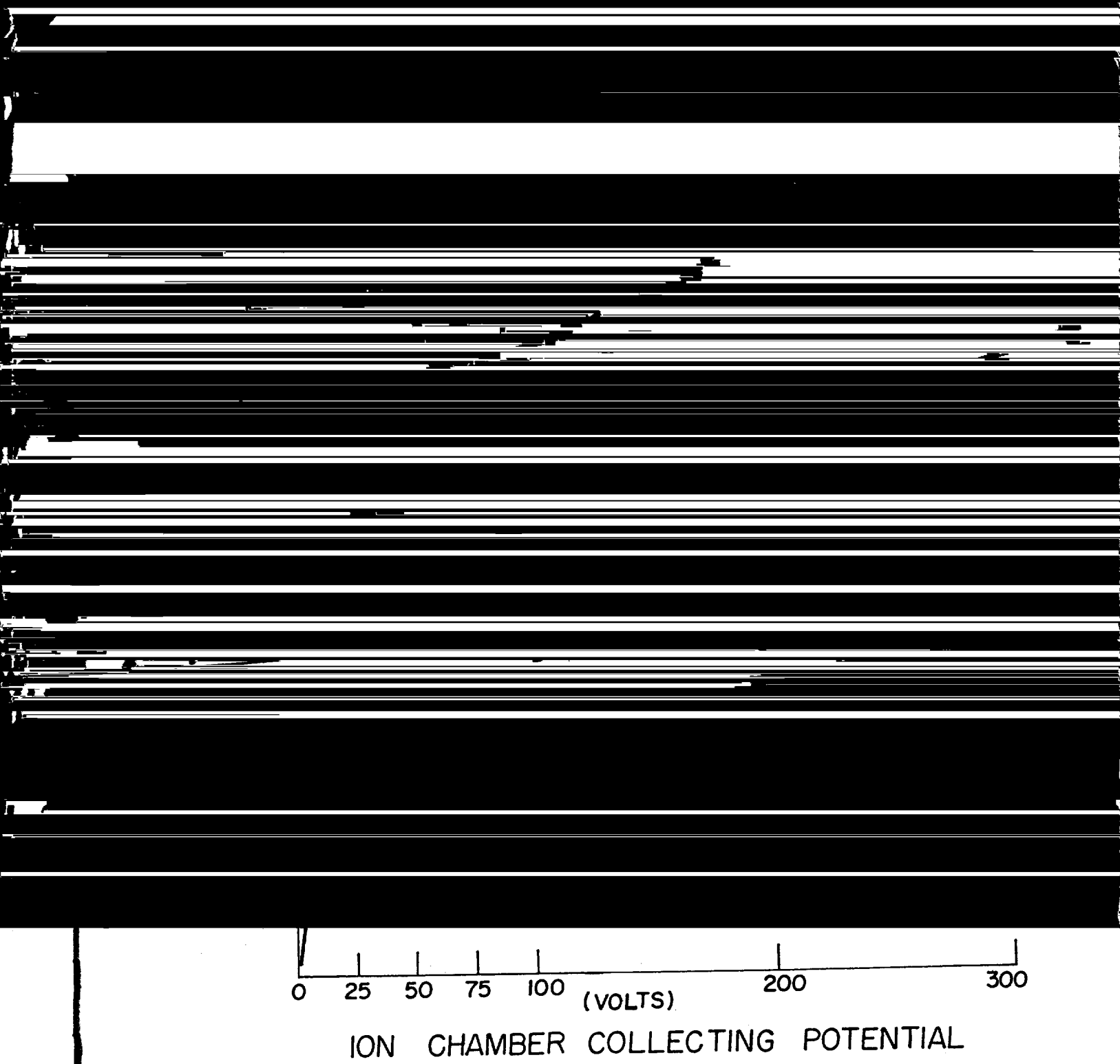

0
25
50
75
100
(VOLTS)
200
300
ION CHAMBER COLLECTING POTENTIAL

Figure II-3

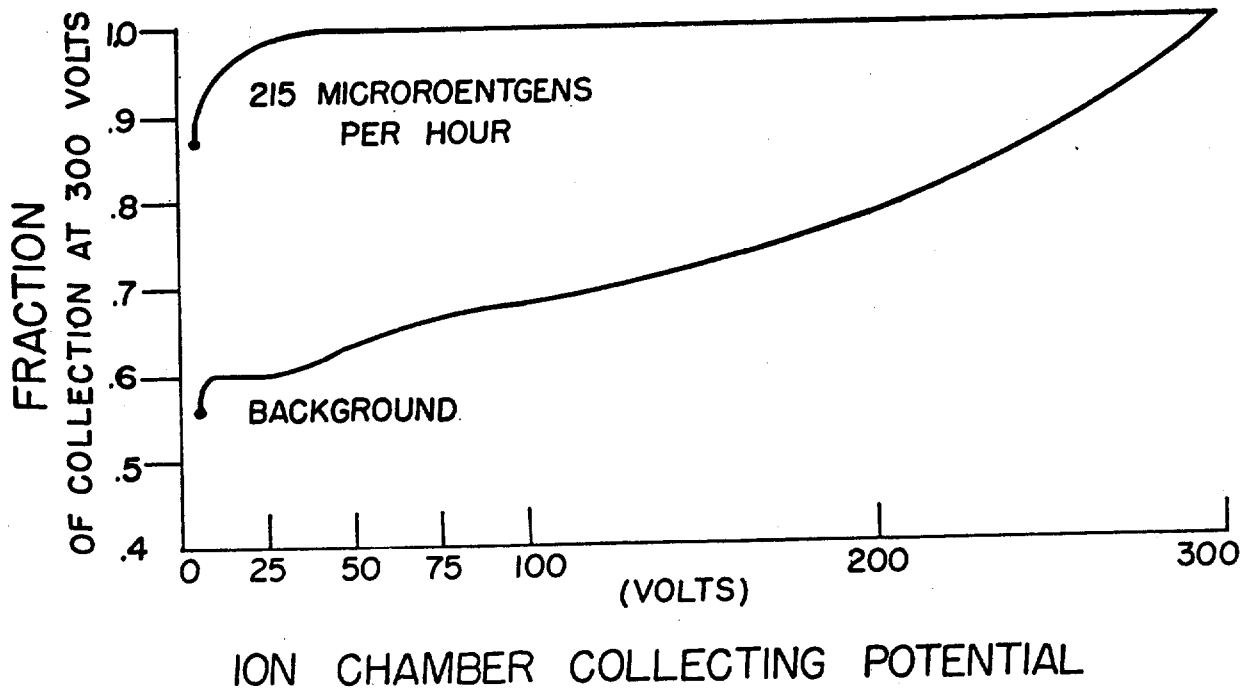
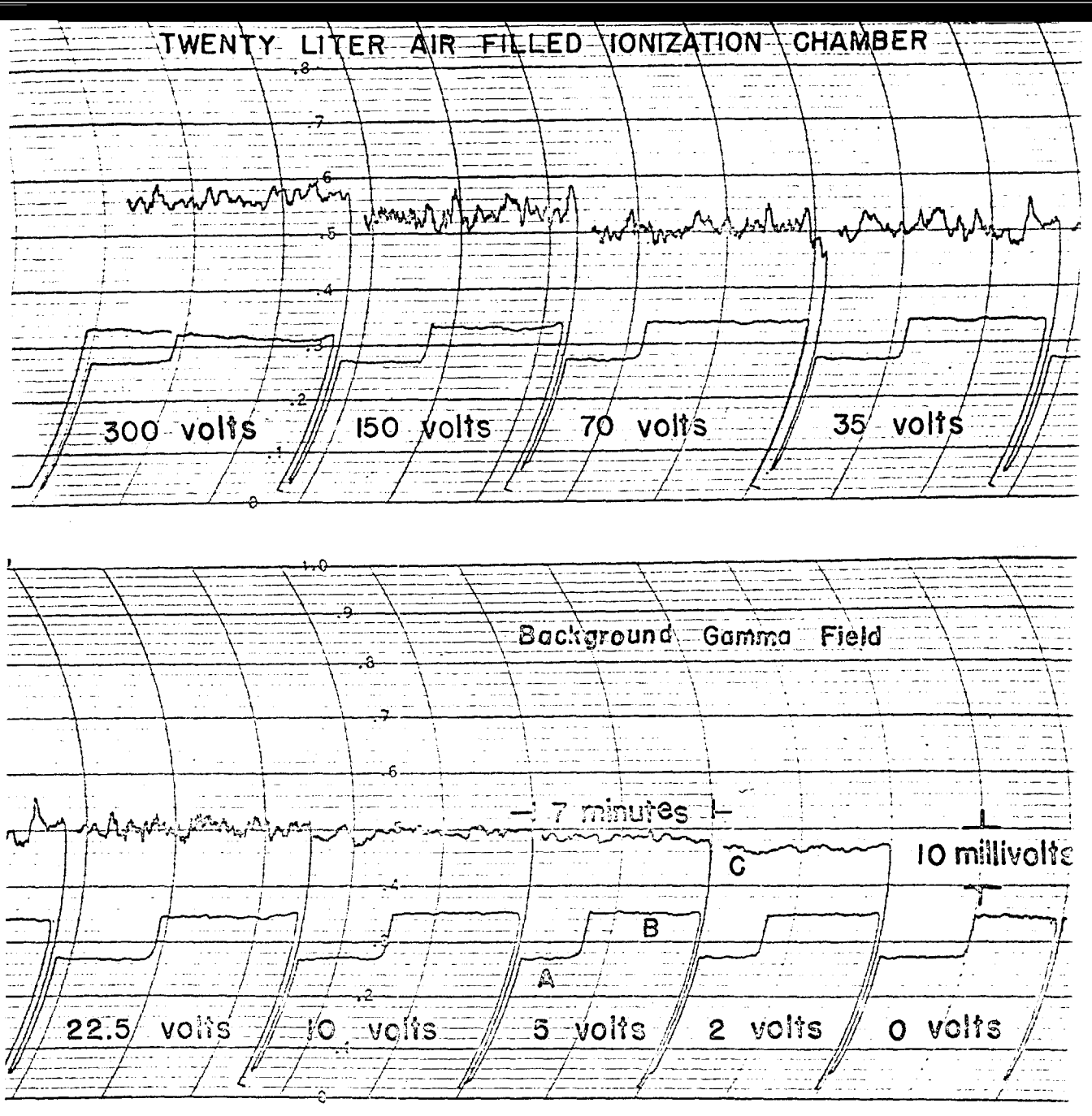

FRACTION
OF COLLECTION AT 300 VOLTS
1.0
.9
.8
.7
.6
.5
.4
215 MICROROENTGENS
PER HOUR
BACKGROUND
0
25
50
75
100
200
300
(VOLTS)
ION CHAMBER COLLECTING POTENTIAL

Figure II-4



Radiation Background Traces for
Different Collecting Potentials

Figure II-5

the aluminum holder (1.82 mm) combined is closely equivalent to a filtration of 0.43 mm platinum. In this connection, it is noted that the dose output of radium in equilibrium with its daughter products has recently been revised to 0.825 rhm/1 mg Ra with 0.5 mm platinum filtration (cf. National Bureau of Standards Technical News Bulletin, 41, 12, P. 198, Dec. 1957). Using this new figure and taking into account the slightly smaller filtration of our source, our recalculated estimate for the dose rate output would be 0.83 rhm/1 mg Ra.

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ACKNOWLEDGMENTS

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A Semiempirical Method of Calculating the Energy Absorption Buildup Factor with an Application to a Uniformly Contaminated Space Having Spherical Boundaries

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Received April 15, 1957

A form for the point-source gamma-ray energy absorption buildup function valid for a material in the energy range where it is essentially a Compton scatterer is suggested as a modification of the asymptotic forms derived by U. Fano. Its parameters are evaluated by means of an energy equilibrium condition and a fit to experimental data. The results are compared with those obtained by other methods, and an application to the problem of uniformly and continuously distributed point sources is discussed.

The point-source energy absorption buildup factor, as conventionally defined, is the ratio of the energy absorption rate from the total-radiation flux to that from the primary flux at some point in the material surrounding the point source. This material is assumed to be uniform and infinite in extent. The buildup function for a given source energy describes the variation of the buildup factor as a function of mean free path and will be designated by $b(t)$.

If we assume a form of the buildup function consistent with the considerations of Fano (*1*), it is possible to compute buildup factors for Compton scatterers by using an energy-equilibrium condition (*2–6*) in combination with a fit to experimental data (*7–9*).

The dose rate in a uniformly contaminated medium of infinite extent, when the contaminant is a monochromatic gamma emitter, is given by

$$I = \frac{E\mu_e}{\rho\mu_t} \int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta \int_0^{\infty} \frac{dt\, b(t)e^{-t}}{4\pi} \tag{1}$$

where I is the dose rate in Mev/sec-gram, E the energy emitted by the contaminant in Mev/sec-cm^3, μ_e the energy absorption coefficient for the medium corresponding to the source energy in cm^{-1}, μ_t is the total attenuation coefficient for

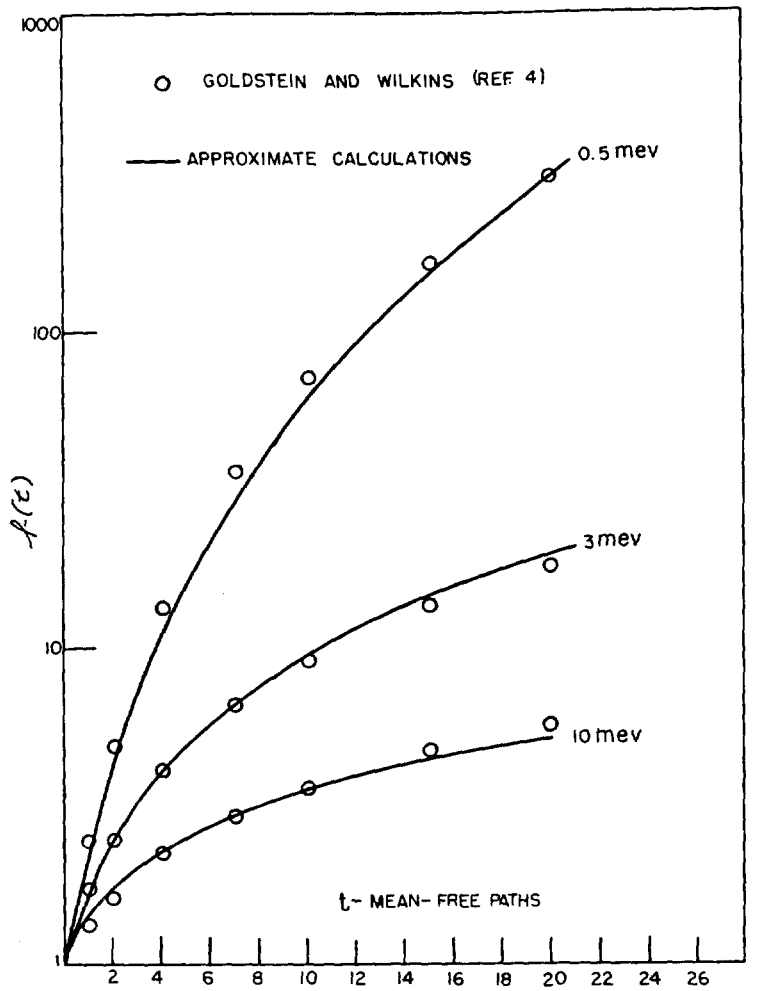


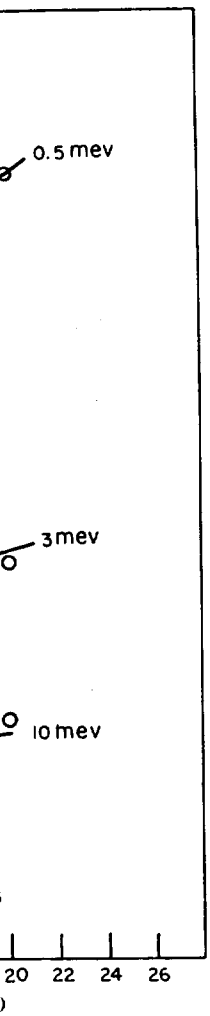
FIG. 1. Buildup factors for H_2O

the medium corresponding to the source energy in cm^{-1}, ρ is the density of the medium in g/cm^3, t the distance to a differential emitter dV in units of mean free path ($= \mu_t x$, where x is this distance in cm). The system is in spherical coordinates, and ϕ and θ are the azimuthal and altitudinal angles respectively.

According to Fano (*1*) the asymptotic form of the buildup function value of the attenuation coefficient is given by x^k. We propose to modify this and write

$$b(t) = (1 + \alpha t)^{\beta}. \tag{2}$$

If the use of a single form for the buildup function is to be justified it must be



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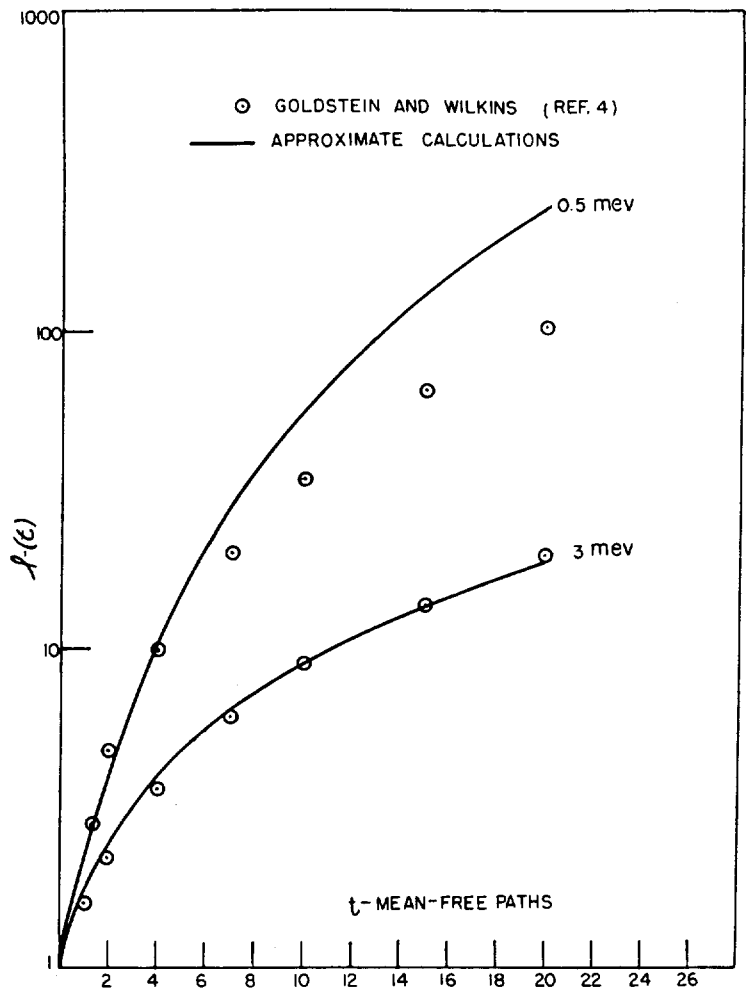


FIG. 2. Buildup factors for Fe.

confined to a region where $d\mu_t/dE_0$ (E_0 being the source energy) has a regular behavior. For this reason and because this is the region for which our experimental data are applicable, we restrict Eq. (2) to the energy region where the material is a Compton scatterer.

Substituting Eq. (2) in Eq. (1) we get an answer in terms of the incomplete gamma function:

$$I = \frac{E\mu_e}{\rho\mu_t}\int_0^\infty e^{-t}(1+\alpha t)^\beta\, dt = \frac{E\mu_e}{\rho\mu_t}\,\alpha^\beta e^{1/\alpha}\Gamma(\beta+1, 1/\alpha). \tag{3}$$

Because the rate of energy absorption per gram equals the rate of energy production (the equilibrium condition), $I = E/\rho$ and therefore

$$\int_0^\infty e^{-t}(1 + \alpha t)^\beta \, dt = \alpha^\beta e^{1/\alpha}\Gamma(\beta + 1, 1/\alpha) = y \tag{4}$$

where $y = \mu_t/\mu_e$.

Because of the way that α and β appear in Eq. (4) it is difficult to perform numerical operations using it, and for convenience we have made use of two approximations. For $y < 2.8$ we use

$$\beta = \frac{\ln [y(y - 1) + 1]}{\ln (1 + \alpha y)} \tag{5}$$

and for $y > 2.8$

$$\beta = \frac{y - 1}{\ln (1 + \alpha y)}. \tag{6}$$

These approximations are discussed in the appendix.

The buildup function now has the form

$$b(t) = \begin{cases} \exp\left\{\dfrac{\ln [y(y - 1) + 1]}{\ln(1 + \alpha y)} \ln (1 + \alpha t)\right\} & y < 2.8 \\ \exp\left\{\dfrac{y - 1}{\ln (1 + \alpha y)} \ln (1 + \alpha t)\right\} & y > 2.8 \end{cases} \tag{7}$$

Fitting Eq. (4) to the experimental data (*7–9*) we find that $\alpha \simeq 1/y$.[1] Substituting this in Eq. (7) we have for the buildup function

$$b(t) = \begin{cases} \exp\left\{\dfrac{\ln [y(y - 1) + 1]}{\ln 2} \ln \left(1 + \dfrac{t}{y}\right)\right\} & y < 2.8 \\ \exp\left\{\dfrac{y - 1}{\ln 2} \ln \left(1 + \dfrac{t}{y}\right)\right\} & y > 2.8 \end{cases} \tag{8}$$

Figures 1, 2, and 3 show comparison of Eq. (8) with the calculations of Goldstein and Wilkins (*4*). The calculations for lead and for low-energy photons on iron represent cases where departures from our assumptions become important. 500-kev photons on iron have energies close to the photoelectric region, and lead is hardly a Compton scatterer even at 1 and 2 Mev. Equation (8) agrees very poorly with the calculations of Goldstein and Wilkins for 0.255 Mev and

[1] The work of M. A. Van Dilla and G. J. Hine [*Nucleonics* **10**, No. 7, 54 (1952)] furnishes different results. For a discussion of this experiment see Ref. (*4*)

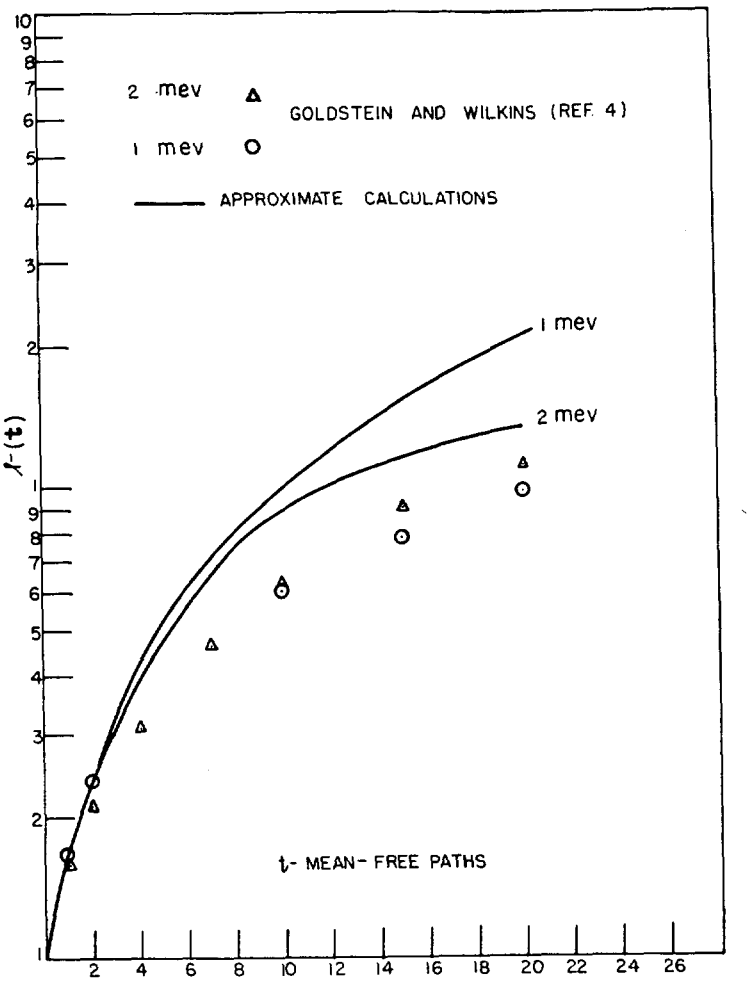


FIG. 3. Buildup factors for Pb.

water. However, experimental values for the buildup function, normalized to four mean free paths, are given for gammas from Hg^{203} (0.28 Mev) (8) and are in reasonable agreement with Eq. (8). These buildup factors are exhibited with those of Goldstein and Wilkins for comparison in Fig. 4.

It is possible to modify Eq. (1) to include the dose rate at a distance from a medium with a spherical boundary.

$$I = \frac{E\mu_e}{\mu_t\rho} \int_0^{\phi_0} d\phi \int_0^{\theta_0} d\theta \sin\theta \int_{f(\phi,\theta,t)}^{g(\phi,\theta,t)} \frac{dt(1 + \alpha t)^{\beta} e^{-t}}{4\pi}. \tag{9}$$

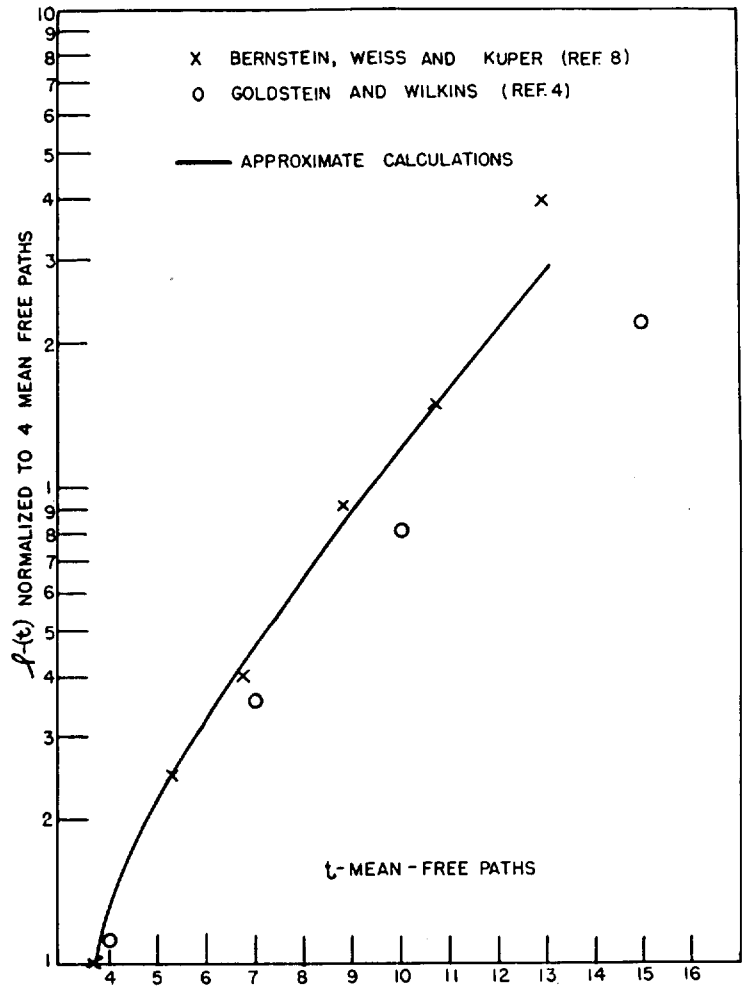
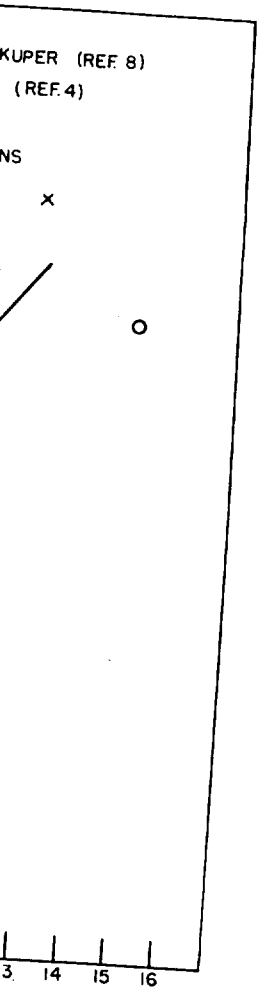


FIG. 4. Comparison of theoretical and experimental buildup factors for 0.28-Mev photons on H_2O

As this equation is rather difficult to solve exactly except for simple boundaries, we introduce another approximation. Let us expand Eq. (2) binomially, terminating it at n terms, where n is the largest integer less than $\beta + 2$. This approximation is, of course, exact when β is integral. A partial solution for Eq. (9) is then

$$I = -\frac{E\mu_c}{\rho\mu_t}\int_0^{\phi_0} d\phi \int_0^{\theta_0} \frac{d\theta \sin\theta e^{-t}}{4\pi} \sum_{\nu=0}^{n} \frac{A_\nu t^\nu}{\nu!}\Bigg|_f^a \tag{10}$$



dup factors for 0.28-Mev

ept for simple boundaries,
(2) binomially, terminat-
$\beta + 2$. This approxima-
lution for Eq. (9) is then

$$\left.\frac{A_\nu t^\nu}{\nu!}\right|_f^\theta$$

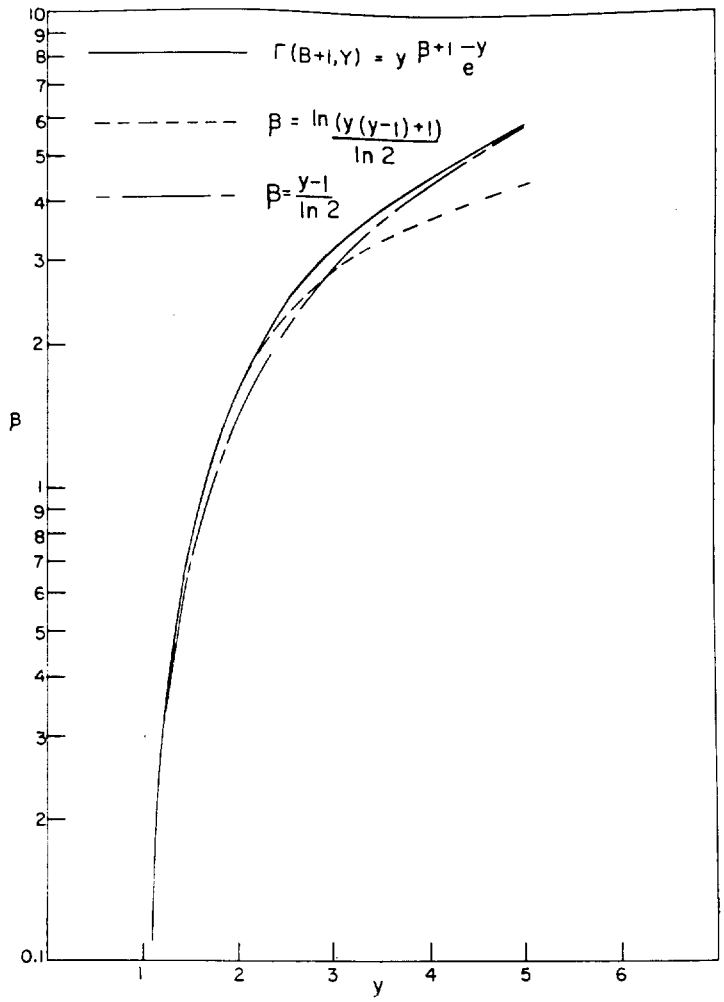


FIG. 5. Comparison of various approximations to the incomplete gamma function.

where

$$A_0 = y$$
$$A_1 = y - 1$$
$$A_2 = y - 1 - \alpha\beta$$
$$A_3 = y - 1 - \alpha\beta - \alpha^2\beta(\beta - 1)$$
$$* \quad * \quad *$$
$$A_{n+1} = 0.$$

[illegible] Eqs. (4) and (6) are very close. All parameters are positive here, of course.

It is possible to better this approximation in the region about $\beta = 1$ by noting from Eq. (4) that $\beta = 1$ implies $\alpha = y - 1$. We substitute $t_0 = y + ky/(y - 1)$ and, only in the last stages letting k go to zero Eq. (5) follows.

A comparison of Eqs. (4), (5), and (6) is shown in Fig. 5 for the particular case of $\alpha = 1/y$.

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