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SCATTERED RADIATION (SKYSHINE) CONTRIBUTION
TO AN OPEN BASEMENT LOCATED IN A SIMULATED FALLOUT FIELD

FINAL REPORT

by

Michael J. Schumchyk
Murray A. Schmoke
Walter O. Egerland
Ernest L. Schulman

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OCD Work Order OCD-PS-64-91, Subtask 1111F

DECEMBER 1966

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ABSTRACT

The objective of this work was to determine, experimentally, the shielding afforded by an open, concrete-walled basement located in a simulated fallout field and to compare these experimental results with theoretical results published in National Bureau of Standards (NBS) Monograph 42.

A cobalt-60 point-source circulation system was used to simulate a uniformly-contaminated residual gamma radiation area out to a radius of 600 feet. Experimental exposure-rate measurements were made in the free field and at various locations within the structure as a function of height above the basement floor. Ionization chamber dosimeters were used as radiation detectors. Experimental measurements were extrapolated to infinite-field conditions by use of analytical procedures and compared with other related experimental data and theoretical results.

The following conclusions were established:

(1) Analysis of the position function $f(h,\omega)$ at various detector levels above the basement floor indicates the presence of radiation back-scattering contribution that is dependent on height above the floor and solid-angle fraction and is not adequately estimated by a single correction factor (1.2 suggested in NBS Monograph 42).

(2) Agreement within 21 percent was obtained between experimental reduction factors and theoretical reduction factors calculated by Equation 31.1 of NBS Monograph 42 for detector locations in the center or near the center of the basement (detector locations C and B).

(3) Theoretical reduction factors underestimate experimental reduction factors at the off-center detector locations close to the basement walls (detector locations A, D, and E) by as much as 47 percent. The differences appear to be caused by radiation scattered from the walls and floor of the basement; this scattering is not completely accounted for in the theoretical calculations.

(4) Extrapolation to the ground surface ($\omega = 1$) of the experimentally measured reduction factors at the center detector location within the open concrete basement yields a skyshine exposure rate that is 7.9 percent of the infinite free-field exposure rate at the 3-foot height. This compares favorably with 8.8 percent calculated in the NBS Monograph 42.

(5) The infinite-field exposure rate at the 3-foot height above a graded, rolled, and relatively smooth field was determined as 468 R/h at a source density of 1 Ci/ft² of cobalt-60 radiation simulated with a circulating point source.

FOREWORD

The work described herein was accomplished under OCD Work Order No. OCD-PS-64-91, Subtask No. 1111F, and DASA MWER Subtask No. 11.008.

The authors wish to express their appreciation to Mr. Charles Eisenhower of the National Bureau of Standards for his technical comments and suggestions during the experimental phase of the project.

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SCATTERED RADIATION (SKYSHINE)
CONTRIBUTION TO AN OPEN BASEMENT
LOCATED IN A SIMULATED FALLOUT FIELD

1. INTRODUCTION

This report, fourth in a series (References 1, 2, 3), presents further progress in the US Army Nuclear Defense Laboratory (USANDL) experimental shielding program to test the validity of theoretical calculations for predicting the protection afforded by structures against fallout radiation.

1.1 Objective.

The objective of this subtask was to determine, experimentally, the shielding provided by an open, concrete-walled basement located in a simulated fallout field, and to compare the results of this experiment with theoretical results of National Bureau of Standards (NBS) Monograph 42 (Reference 4).

1.2 Background.

L. V. Spencer of NBS developed a prediction method for determining the shielding effectiveness of structures located in actual or simulated fallout fields. This method, described in Reference 4, became the basis for the engineering manual (Reference 5) published by the Office of Civil Defense (OCD). The manual is used by engineers, architects, and military commanders to predict the protection afforded by existing and proposed structures against fallout gamma radiation.

The information in NBS 42 has been obtained almost completely by machine calculations utilizing basic cross-section data. A number of sources of experimental data are mentioned, but detailed comparisons with such data are not included. This prediction method has been tested experimentally, first with simple structures and then with more complex structures. This Laboratory has conducted experiments with a simple concrete blockhouse, located in a simulated fallout field, to determine the effect of roof thickness and wall thickness on the attenuation of gamma radiation (References 2 and 3). Radiation-penetration measurements for the roof indicated agreement within 20 percent between experimental and theoretical reduction factors determined along the vertical center line of the structure. Experimental and theoretical reduction factors for the wall of the structure agreed within 15 percent at 3 feet and 6 feet above the center of the structure. However, little experimental work has been done on basement structures.

Some experimental work measuring "skyshine" radiation was done by Clifford (Reference 6), who measured the radiation penetration in a circular foxhole from a residual radiation area simulated with cesium-137 sources. Starbird and Batter also measured the radiation penetration in a circular foxhole, but used cobalt-60 sources to simulate the residual radiation area (Reference 7).

More recent work with the circular foxhole and cobalt-60 sources has been performed by Burson and Summers in the Nevada desert (Reference 8). Extensive measurements were made both in the open hole and in the covered hole with various materials.

The work reported here is concerned with measuring air-scattered (skyshine) radiation penetration into what might be considered a full-scale open basement. All experimental data are given in Appendix A.

2. PROCEDURES

2.1 Test Area.

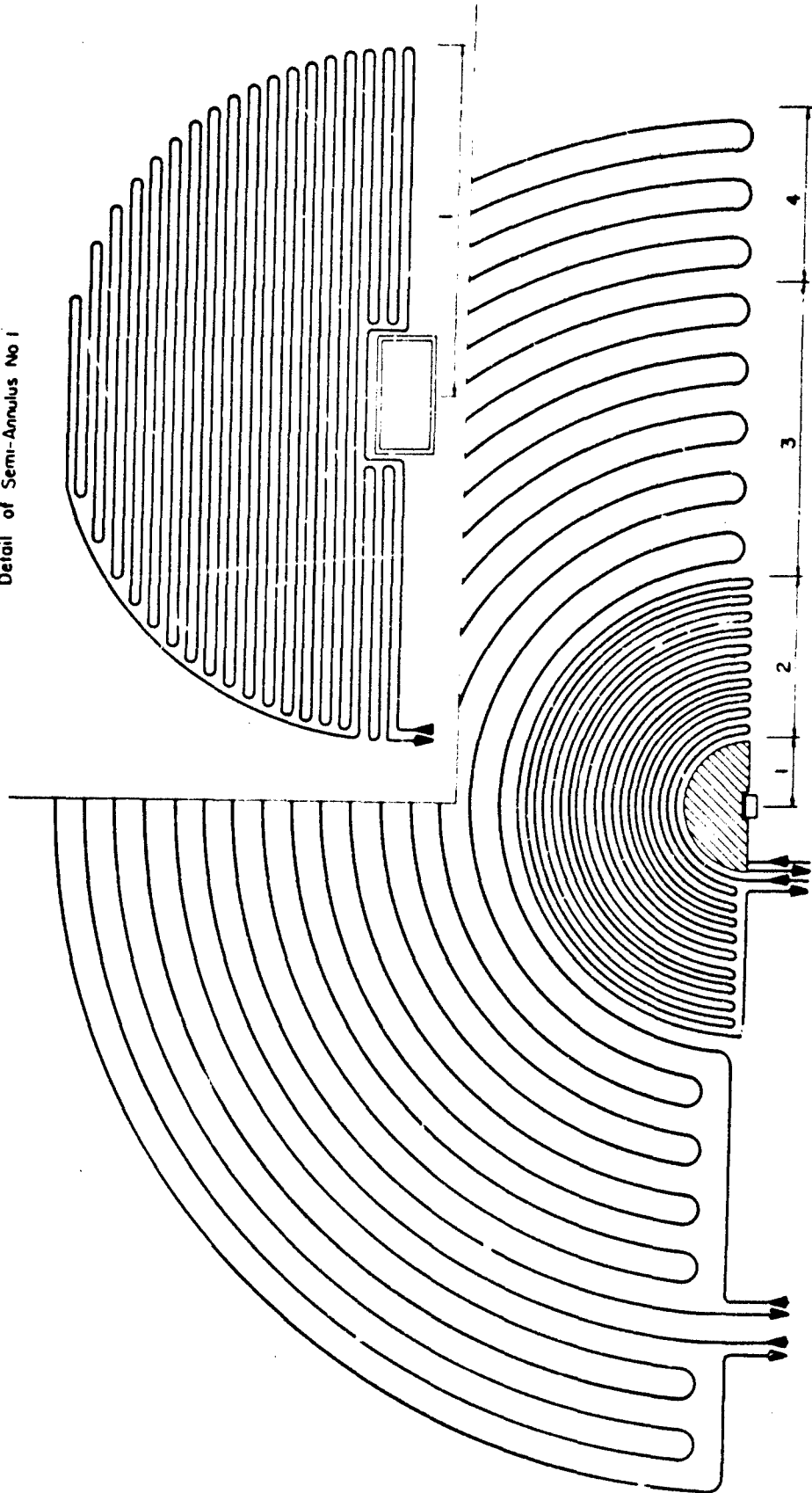
The experiment was conducted at the USANL Westwood test area comprising approximately 60 acres, of which 24 acres have been cleared. The surface of the simulated radiation area was a sandy clay that had been graded, rolled, and treated with a herbicide to prevent the growth of grass. The entire area was enclosed by a 6-foot-high fence equipped with a pressure-sensitive personnel alarm. A field office on the test site provided a place to charge and read dosimeters. The office was shielded from the radiation field by a 32-inch-thick concrete wall. This wall reduced the radiation sufficiently to allow test personnel to remain in the building during testing.

2.2 Source-Handling Facility.

A point-source circulation system was used to simulate fallout radiation (Reference 9). The simulation system involved the placement of nylon tubing, 1/16-inch wall thickness and 3/8-inch diameter, in a uniform pattern on the ground around the structure. A radioactive point source was then propelled by water pressure through the tubing at a constant speed to simulate a uniform distribution of contamination over the area. Since the sources were calibrated within the tubing, no correction was made for energy degradation of the source due to the tubing.

Nylon tubing was placed in a 600-foot-radius semicircular array consisting of four semiannuli (Figure 2.1). The spacing between rows of tubing, inner and outer radial distances of each semiannulus, and area of each semiannulus, are shown in Table 2.1.

Detail of Semi-Annulus No 1



| Semi-Annulus No | Inner and Outer Radius (ft) | Tube Spacing (ft) |
|-----------------|-----------------------------|-------------------|
| 1 | 0 to 60 | 1.67 |
| 2 | 60 to 200 | 7 |
| 3 | 200 to 450 | 25 |
| 4 | 450 to 600 | 25 |

Figure 2.1 Semicircular array of nylon tubing.

TABLE 2.1 DESCRIPTION OF SEMICIRCULAR TUBING ARRAY

| Semiannulus | Tube Spacing | Inner and Outer Radial Distance | Semiannular Area |
|-------------|--------------|---------------------------------|------------------|
| | ft | ft | ft ² |
| 1 | 1.67 | 0 to 60 | 5,499 |
| 2 | 7.0 | 60 to 200 | 57,177 |
| 3 | 25 | 200 to 450 | 255,255 |
| 4 | 25 | 450 to 600 | 247,401 |

2.3 Sources.

Six cobalt-60 sources (18.5 curies, 53.4 curies, 94.5 curies, 185 curies, 332 curies, and 590 curies) were used in this experiment. Calibration date of these sources was 1 March 1962. The choice of a source for a particular test was based upon relative sensitivity of the radiation detectors, source-to-detector distance, and exposure time. All sources were calibrated against a source that had been calibrated in the free air at a height of 11 feet. Victoreen condenser-R-Chambers, calibrated by NBS, were used to obtain three measurements for each source exposure. All readings were within 2 percent of the average for a particular source. Recalibration of these sources was performed 1 September 1964 by the method described in Appendix B. Radioactive decay corrections were made on the experimental data.

Dimensional replicas of the radioactive sources (cobalt-60 pellets doubly encapsulated in stainless steel) are shown on the left side of Figure 2.2. The capsule was crimped to the end of a flexible stainless-steel cable. The leader, connected to the other end of the cable, held a 1/2-inch-diameter leather skirt. The leather skirt acted as a piston by providing a seal between the source assembly and the wall surface of the tubing to permit the propulsion of the source assembly by water pressure.

2.4 Instrumentation.

Radiation-dose measurements were made with the following Victoreen ionization chamber dosimeters: Model 203, 1 mR; Model 239, 10 mR; and Model 332, 200 mR. A Victoreen Model 237 charger-reader was used to charge and read dosimeters. Dosimeter selection was based upon the exposure time, the

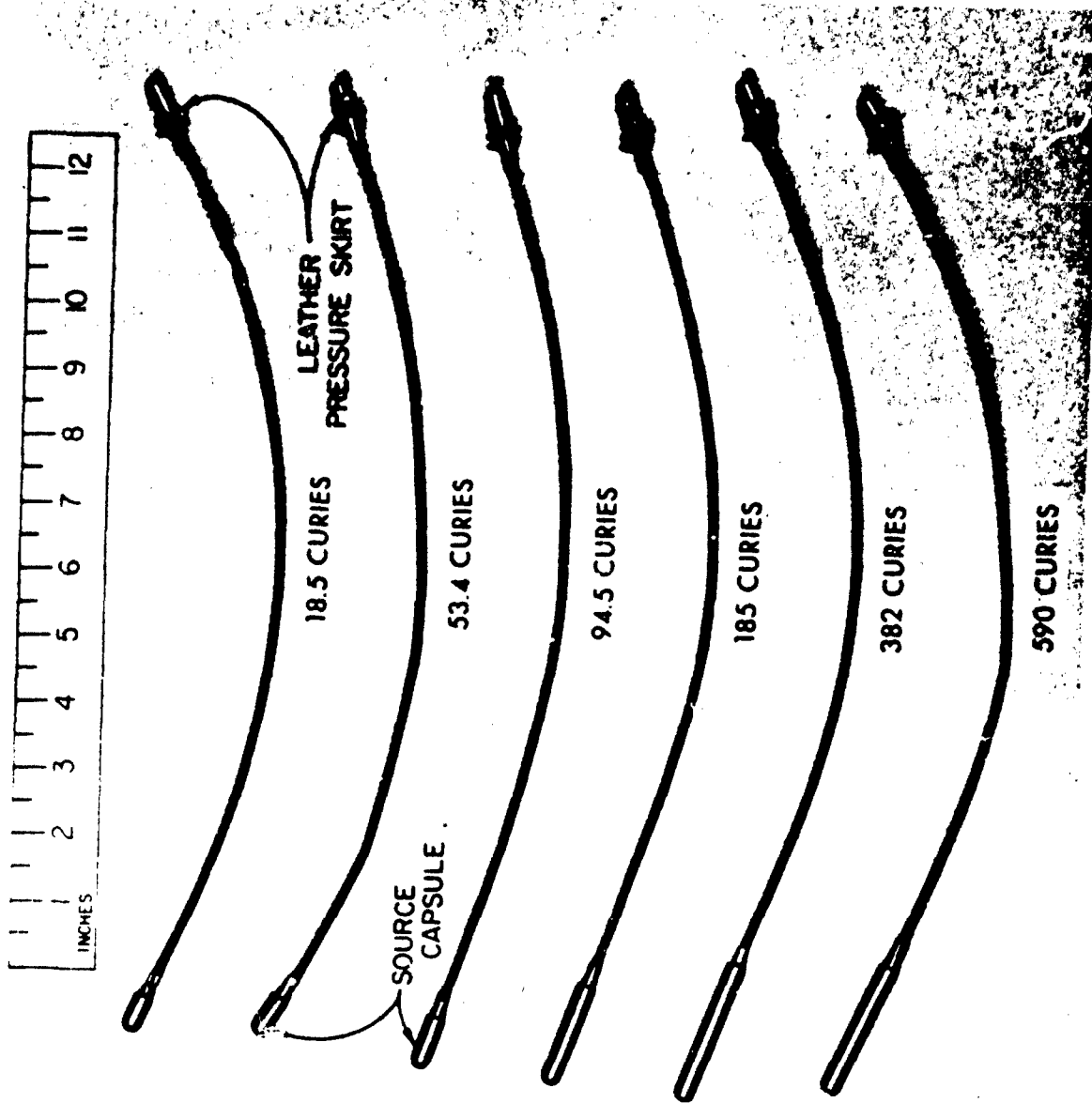


Figure 2.2 Dimensional replicas of cobalt-60 radioactive sources with leaders.

section of the field being simulated, and the location of the dosimeters with respect to the contaminated area. The choice of dosimeters was such that the dose received was about mid-scale on the charger-reader. Experience with the dosimeters indicated that mid-scale deflections could be reproduced within ± 2 percent. Each exposure was timed by a Precision Instrument Company electric timer.

The ionization-chamber dosimeters were calibrated against a Victoreen Model 130 R-Chamber ($0.25R$) and charged and read on a Victoreen Model 70-R meter. The R-meter and n-chamber were calibrated by NBS with a collimated beam of cobalt-60 gamma rays. The estimated accuracy of the NBS calibration was ± 3 percent.

2.5 Description of Experimental Structure.

The rectangular basement, with walls of reinforced concrete, is shown in perspective with tubing layout in Figure 2.3. The inside dimensions of the structure were 20 by 10 by 7 feet. The poured concrete walls were 20 inches thick and the floor was 3 inches thick.

The relatively thick concrete walls were built to serve as a foundation for aboveground walls for future experiments and to prevent any ground direct radiation (lip contribution) from reaching the detectors in the basement. Note the inset in Figure 2.1, an enlargement of semiannulus 1 adjacent to the basement, which shows that the first line of tubing is 10 inches from the concrete wall. In this position direct radiation must penetrate approximately 10 mean free paths of concrete to reach the nearest detector; therefore, it was concluded that the lip contribution was effectively eliminated by the walls.

2.6 Experimental Technique.

Exposure-rate reduction factors within the test structure were obtained by determining the ratio D/D_0 , where D is the exposure rate measured in the structure and D_0 is the exposure rate measured in the free field at 3 feet above the center of a contaminated infinite field.

Free-field radiation exposure measurements were made at heights from 1 to 15 feet above ground at 1-foot intervals. Although only the 3-foot detector height data were required to calculate the experimental reduction factors for comparison with theoretical reduction factors, data for other heights were taken so that comparisons could be made with similar data taken by other investigators (Reference 10), and with the theoretical $L(d)$ curve of Spencer. These comparisons allow some estimate to be made of the ground roughness effects on radiation intensity.

Free-field measurements were made with the detector stand mounted directly above the center of the basement for semiannuli 2, 3, and 4. Free-field measurements for semiannulus 1 (see inset Figure 2.1) were made over a

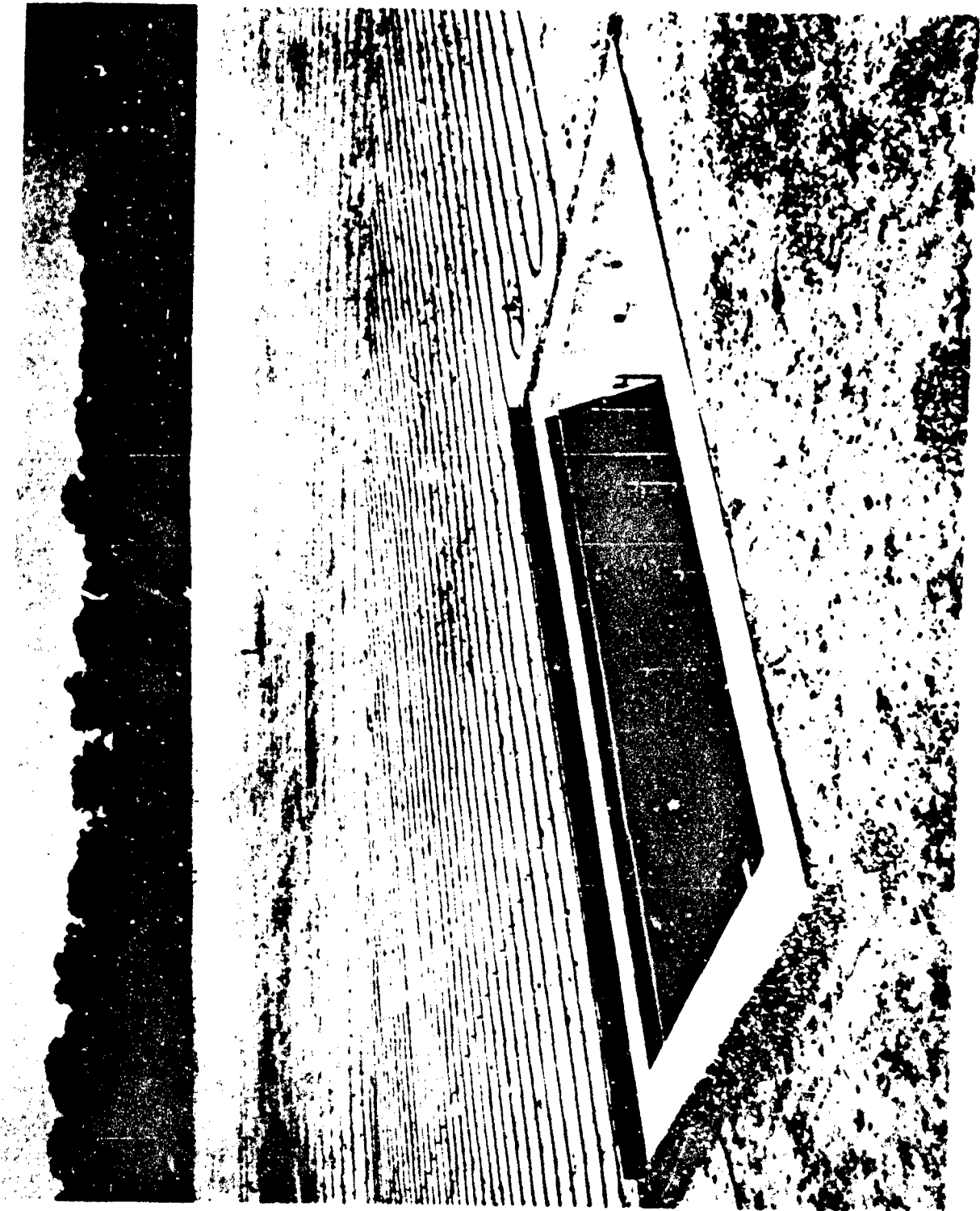


Figure 2.3 Basement structure showing tubing layout and masonite water deflector.

separate semiannulus with tubing laid out to cover the entire radius of the semiannulus, which was offset 300 feet from the basement over graded, level terrain. The total free-field measurements listed in Table 3.1 are for the entire field and not for an area with a portion of the contamination cleared away at the center.

The detector stand resembled a gibbet with a 2 1/2-foot long horizontal arm braced at the top of an 18-foot high vertical support (wooden four-by-four). The detector holders were paper cups taped to two parallel 1/16-inch diameter stainless steel wires attached at the end of the horizontal arm and anchored at the base of the gibbet by a 30-pound lead brick. The entire assembly was supported by three guy wires and adjusted so that the line of detectors was perpendicular to the center point of the diameter of the semiannulus. Ten source runs were made for each semiannular area and the exposure measurements were checked for reproducibility.

The detector layout inside the basement structure is shown in Figure 2.4, a cross-section view of the detector positions with respect to the floor, and in Figure 2.5, a plan view of the location of the detectors with respect to the walls of the building. Primary detectors (capital letters) and image detectors (small letters) were placed within the structure as shown in Figure 2.5. To obtain the total radiation exposure from the simulated fallout area for detector locations A, B, and E, the exposure rate at the primary positions A, B, and E were added to the exposure rate at the image positions a, b, and e, respectively. At each detector height for detector locations C and D, the exposures were doubled.

All exposure measurements were converted to milliroentgens per hour for a source density of 1 Ci/ft² by use of the following equation:

$$D = D_x A \frac{\rho \lambda C}{S}, \quad (2.1)$$

where

D = the corrected exposure rate in (mR/h)/(Ci/ft²),

D_x = the uncorrected exposure rate in (mR/h),

A = the area of the semiannulus in ft²

ρ = the atmospheric correction factor at standard conditions (described below),

λ = decay factor for cobalt 60 used to correct the exposure reading to a reference time,

C = the calibration factor of a given detector, and

S = the strength in curies.

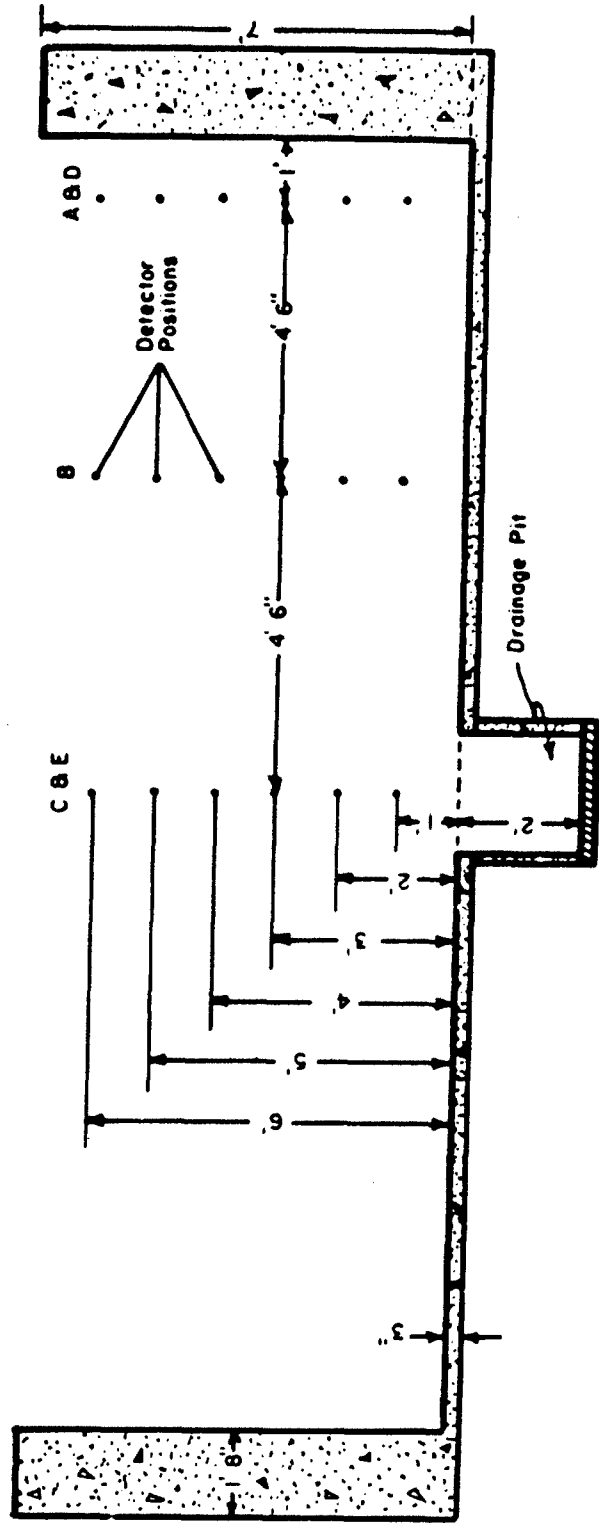


Figure 2.4 Basement section showing elevation of detector locations.

SOURCE FIELD 180°

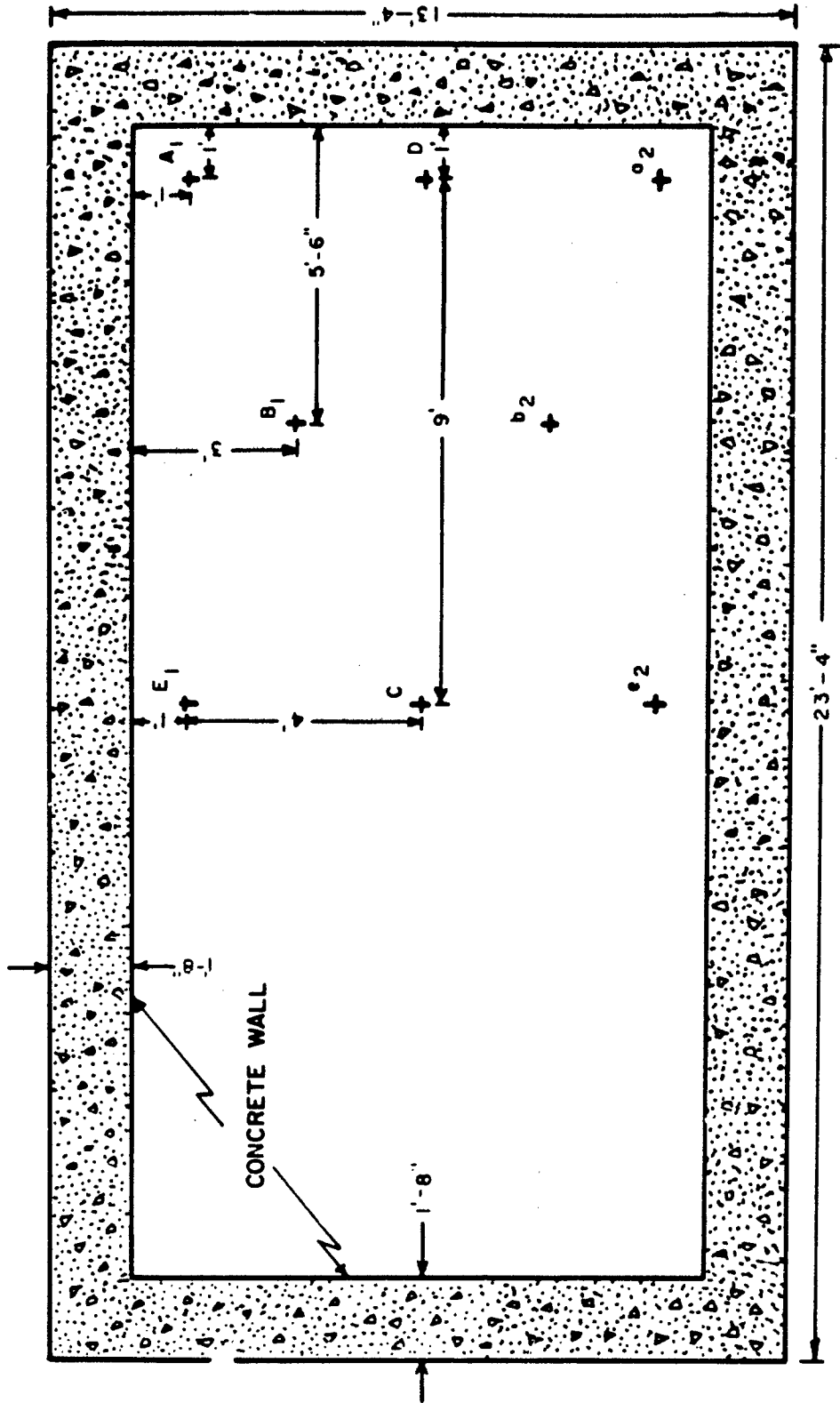


Figure 2.5 Basement plan of primary and image detector locations.

2.7 Discussion of Errors.

To estimate the error in most laboratory-type experiments, a large number of experimental runs are usually made, from which the standard deviation, σ , is calculated. The reliability of the estimated error is dependent on the number of experimental runs, N . However, in a field-type experiment this is usually not possible nor practical. In this experiment, the time required to make a large number of runs on each semiannulus would have been excessive. To compensate for this, attempts were made to carefully control the factors that could produce experimental variation and to analyze the systematic errors which are inherent when different personnel charge and read the ionization chamber dosimeters.

A point-source circulation system, in which a source of cobalt 60 was propelled through plastic tubing at a constant rate, was used to simulate residual radiation. Since the system depends on the source remaining the same amount of time in a given area of the field, an error could result if there were lack of uniformity of movement of the source through the tubing. To minimize this possibility, a "dummy source," an exact replica of the actual source, was propelled through the tubing prior to the "hot" run. The movement of the dummy source was observed to determine whether any imperfections in the tubing or any variations in the pumping system were present to cause irregular flow of the source. Any delay in the flow would increase the total time of a run. Results of this pre-testing showed that the variation in the times for the experimental runs would never be greater than 0.5 percent for a given semiannulus. Since all measurements were normalized to milliroentgens per hour, the error in timing would be averaged out in the normalization.

Further experimental error could be caused by errors in source calibration. All sources were calibrated on the USANDL calibration range, as described in Appendix B. The calibration error, σ_1 , calculated from five repetitive measurements for each source was no greater than ± 2 percent.

The ionization chamber dosimeters that were used to make the exposure measurements are the most sensitive to possible error. Error could result from variations in temperature, pressure, leakage, and reading. Since the ionization chambers were not hermetically sealed and the ionization of the air within the chambers is dependent to some extent on the air density, the chambers are sensitive to change in temperature and atmospheric pressure. This error was effectively eliminated by the use of an atmospheric correction factor, ρ , to correct the detector reading from experimental conditions to standard conditions of temperature and pressure. This was calculated as follows:

$$\rho = \frac{P_1 T_2}{T_1 P_2}, \quad (2.2)$$

where

P_1 = 760 mm of mercury, atmospheric pressure at standard conditions,

T_1 = 273° Kelvin, temperature at standard conditions,

P_2 = pressure at experimental conditions in millimeters of mercury, and

T_2 = temperature at experimental conditions in degrees Kelvin.

Leakage of the charge from the ionization chambers will occur as a result of background radiation and, in some instances, because of dirt on the insulator. Normally this leakage is not large, and for exposures of 1 hour the effect will be approximately 1.4 percent of full scale for the 1-mR chambers and about 0.2 percent for the 10-mR chambers. Obviously, for exposure of several hours duration this effect could be significant, especially with the 1-mR chambers. However, this effect was eliminated by establishing a leakage rate for each chamber. This leakage rate was rechecked weekly and detectors with excessive leakage rates were set aside for cleaning. The leakage value was subtracted from the detector reading in the data normalization process.

All belowground radiation measurements were made with either the 1-mR dosimeters or the 10-mR dosimeters and calibrated as described in Section 2.4. The estimated error, σ_2 , in the calibration of the 1-mR and 10-mR chambers against the secondary standard, was ± 3.6 percent.

To estimate the error, σ_3 , that may occur in the experiment as a result of different persons reading the charger reader, a test was conducted during which seventy measurements were read at various positions on the scale by nine people. The resultant standard deviation indicated a maximum error of ± 1.4 percent.

Since the systematic errors of temperature, pressure, and leakage have been either eliminated or corrected, the remaining contributors to the errors of a single measurement are the source calibration error, the detector calibration error, and possible errors caused by different persons reading the minometer. The total error for a given measurement, σ_z , is calculated as follows:

$$\sigma_z = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} = \sqrt{2^2 + 3.6^2 + 1.4^2} = 4.4\% \quad (2.3)$$

The total experimental measurement at a given detector position consisted of the sum of four separate semiannular measurements. Since repetitive exposure-rate measurements were made for each semiannular area,

there was also a standard deviation from the mean of each semiannulus. In most cases the error was small (1 percent in semiannulus 1 for detector location C at the detector position 1 foot above the basement floor), although, in some instances for the same detector position, the standard deviation was as large as 7 percent, as in semiannulus 3. Since each semiannulus contributes only a certain percent to the total exposure, the effect of a large error in any single semiannulus would depend upon the percent contribution to the total exposure rate of that semiannulus. For example, the standard deviation for semiannulus 3 at detector position C-1 is 7 percent; however, the percent error for the sum of four semiannuli is 4.5 percent.

The total error of the measurements would be a total of the variance from systematic errors connected with the detector measurement, σ_s^2 , plus the variance due to difference in the total measurements, σ_i^2 or

$$\sigma \text{ total} = \sqrt{\sigma_s^2 + \sigma_i^2} \quad (2.4)$$

The maximum total error expected at any detector position would not exceed 6.3 percent.

3. RESULTS

3.1 Free-Field Exposure Rates.

Table 3.1 shows the results of the free-field measurements. The table shows the cumulative exposure rate as a function of radius of the field in 1-foot intervals for heights of 1 to 15 feet. The exposure rates listed in Table 3.1 have been converted from semiannular to annular by multiplying by a factor of two.

According to free-field experiments reported in NDL-TR-2 (Reference 1), the exposure measurements at 3 feet above the center of a simulated fallout field of 600-foot radius constituted approximately 95 percent of the infinite-field exposure rate. For calculations necessary to determine the shielding effectiveness of structures, however, the infinite-field exposure rate is required. Since it is clearly impractical to measure the exposure rates to infinity, the free-field contribution was estimated analytically as shown in Section 4.1. The cumulative free-field exposure rates for an infinite field are shown in the last column in Table 3.1.

3.2 Open-Basement Exposure Rates.

The exposure rates measured in the open basement are shown in Table 3.2. The exposure rates are listed according to detector location (A, B, C, etc.) and to height above the basement floor. The contribution

for each annulus is listed along with the far-field contribution and the total exposure rate at each dosimeter position. The method used to determine the far-field exposure rates is explained in Section 4.2.

TABLE 3.1 CUMULATIVE FREE-FIELD EXPOSURE RATES ABOVE A RADIATION AREA AS A FUNCTION OF RADIUS AND HEIGHT

Note: Data normalized to R/h at a source density of 1 Ci/ft².

| Detector Height Above Ground | Exposure Rates For A Radiation Area With a Radius of | | | | Infinite* Field Exposure Rate |
|------------------------------|--|--------|--------|--------|-------------------------------|
| | 60 ft | 200 ft | 450 ft | 600 ft | |
| ft | | | R/h | | R/h |
| 1 | 370 | 463 | 496 | 502 | 548 |
| 2 | 320 | 419 | 464 | 472 | 500 |
| 3 | 285 | 388 | 438 | 447 | 468 |
| 4 | 260 | 366 | 417 | 428 | 444 |
| 5 | 239 | 343 | 397 | 409 | 424 |
| 6 | 220 | 324 | 377 | 387 | 403 |
| 7 | 206 | 310 | 365 | 377 | 391 |
| 8 | 206 | 313 | 369 | 382 | 387 |
| 9 | 190 | 288 | 343 | 357 | 369 |
| 10 | 178 | 276 | 331 | 344 | 357 |
| 11 | 169 | 263 | 324 | 337 | 349 |
| 12 | 161 | 258 | 316 | 330 | 341 |
| 13 | 153 | 249 | 308 | 322 | 333 |
| 14 | 146 | 244 | 300 | 313 | 325 |
| 15 | 136 | 235 | 292 | 306 | 318 |

*Far-field contribution beyond 600 feet was calculated - See Section 4.1.

TABLE 3.2 EXPOSURE RATES TO DETECTORS AT VARIOUS LOCATIONS IN AN OPEN CONCRETE BASEMENT LOCATED IN A RESIDUAL RADIATION AREA SIMULATED BY COBALT 60

Note: Exposure rates are in (mR/h)/(Ci/ft²).
For detector locations, see Figure 2.5.

| Detector Height Above Floor (ft) | Exposure Rates for Annulus | | | | Far-Field Exposure Rate | Total Exposure Rate |
|----------------------------------|----------------------------|------|------|-------|-------------------------|---------------------|
| | 1 | 2 | 3 | 4 | | |
| Detector Location-A | | | | | | |
| 1 | 666 | 1560 | 2120 | 842 | 1970 | 7160 |
| 2 | 781 | 1650 | 2320 | 995 | 2330 | 8080 |
| 3 | 826 | 2000 | 2560 | 1080 | 2530 | 9100 |
| 4 | 1010 | 2410 | 3090 | 1280 | 3000 | 10800 |
| 5 | 1320 | 3120 | 4240 | 1590 | 3720 | 14000 |
| 6 | 2340 | 4750 | 5850 | 2270 | 5310 | 20500 |
| Detector Location-B | | | | | | |
| 1 | 880 | 2000 | 2670 | 1020* | 2390 | 8960 |
| 2 | 1050 | 2230 | 2920 | 1290 | 3020 | 10500 |
| 3 | 1240 | 2790 | 3390 | 1510 | 3530 | 12500 |
| 4 | 1450 | 3480 | 4320 | 1870 | 4380 | 15500 |
| 5 | 1960 | 4490 | 5450 | 2320 | 5430 | 19700 |
| 6 | 3360 | 6560 | 8020 | 3160 | 7390 | 28500 |
| Detector Location-C | | | | | | |
| 1 | 950 | 2060 | 2860 | 1210 | 2830 | 9910 |
| 2 | 1090 | 2460 | 3200 | 1380 | 3230 | 11400 |
| 3 | 1320 | 2920 | 3560 | 1640 | 3840 | 13300 |
| 4 | 1560 | 3860 | 4480 | 1950 | 4560 | 16400 |
| 5 | 2000 | 5140 | 5680 | 2500 | 5850 | 21200 |
| 6 | 3900 | 6960 | 8380 | 3260 | 7630 | 30100 |

See footnote at end of table.

TABLE 3.2 CONTINUED

| Detector Height Above Floor (ft) | Exposure Rates for Annulus | | | | Far-Field Exposure Rate | Total Exposure Rate |
|----------------------------------|----------------------------|------|------|------|-------------------------|---------------------|
| | 1 | 2 | 3 | 4 | | |
| Detector Location-D | | | | | | |
| 1 | 754 | 1720 | 2400 | 992 | 2320 | 8180 |
| 2 | 920 | 1900 | 2480 | 1130 | 2640 | 9070 |
| 3 | 992 | 2240 | 2940 | 1250 | 2930 | 10400 |
| 4 | 1170 | 2800 | 3520 | 1550 | 3630 | 12700 |
| 5 | 1700 | 3740 | 5120 | 1910 | 4470 | 16900 |
| 6 | 2820 | 5520 | 6840 | 2680 | 6270 | 24100 |
| Detector Location-E | | | | | | |
| 1 | 864 | 1940 | 2610 | 1040 | 2430 | 8880 |
| 2 | 976 | 2160 | 2850 | 1250 | 2930 | 10200 |
| 3 | 1160 | 2660 | 3330 | 1440 | 3370 | 12000 |
| 4 | 1310 | 3270 | 4030 | 1700 | 3980 | 14300 |
| 5 | 1750 | 4220 | 5310 | 2150 | 5030 | 18500 |
| 6 | 3700 | 5520 | 6480 | 2780 | 6510 | 25000 |

*Based on Estimated Value.

3.3 Reduction Factors, Experimental and Theoretical.

The reduction factor, R , is defined as the ratio of the shielded exposure rate, D , to the free-field exposure rate at a 3-foot height above an infinitely contaminated field, D_0 , i.e.,

$$R = D/D_0 \quad (3.1)$$

The experimentally determined value for the free-field exposure rate at the 3-foot height, D_0 , is $463 (R/h)/(Ci/ft^2)$, Table 3.1. Therefore, the experimentally determined reduction factors, R_e , as shown in Table 3.3, were calculated by Equation 3.1 with the measured exposure rate at a given detector position and the experimentally determined D_0 .

The theoretical reduction factors, R_t , were calculated by Spencer's method, as explained in Section 4.3.

TABLE 3.3 EXPERIMENTAL AND THEORETICAL REDUCTION FACTORS IN AN OPEN BASEMENT

| Detector Height Above Floor | Location A | | Location B | | Location C | | Location D | | Location E | |
|-----------------------------|------------|--------|------------|-------|------------|-------|------------|-------|------------|-------|
| | Exp. | Theo. | Exp. | Theo. | Exp. | Theo. | Exp. | Theo. | Exp. | Theo. |
| ft | | | | | | | | | | |
| 1 | 0.015 | 0.0079 | 0.019 | 0.015 | 0.021 | 0.018 | 0.017 | 0.010 | 0.019 | 0.013 |
| 2 | 0.017 | 0.0092 | 0.022 | 0.019 | 0.024 | 0.022 | 0.019 | 0.012 | 0.022 | 0.016 |
| 3 | 0.019 | 0.011 | 0.027 | 0.024 | 0.028 | 0.028 | 0.022 | 0.016 | 0.026 | 0.019 |
| 4 | 0.023 | 0.014 | 0.033 | 0.032 | 0.035 | 0.038 | 0.027 | 0.020 | 0.031 | 0.024 |
| 5 | 0.030 | 0.019 | 0.042 | 0.044 | 0.047 | 0.051 | 0.036 | 0.028 | 0.040 | 0.031 |
| 6 | 0.044 | 0.032 | 0.061 | 0.066 | 0.064 | 0.072 | 0.051 | 0.045 | 0.053 | 0.047 |

4. DISCUSSION

4.1 Estimate of Far-Field Exposure Rate Aboveground.

The exposure rate at height h along the centerline of a uniformly contaminated annulus, Figure 4.1, is given by

$$\begin{aligned} D(h; \rho_1, \rho_0) &= D_1 \int_0^{2\pi} d\varphi \int_{r_1}^{r_0} B(h, \rho) \frac{e^{-\mu\rho}}{\rho^2} r dr \\ &= 2\pi D_1 \int_{\rho_1}^{\rho_0} B(h, \rho) \frac{e^{-\mu\rho}}{\rho} d\rho, \end{aligned} \quad (4.1)$$

where

D_1 = source strength expressed as exposure rate at unit distance from a unit area of source distributed at unit density. For cobalt 60, this value is $14.3 (R/h)/(Ci/ft^2)$,

$B(h, \rho)$ = buildup factor at detector height, h ,

$\rho_1 = \sqrt{r_1^2 + h^2}$ slant radius from the detector to the inner circle of radius r_1 of the annulus,

$\rho_0 = \sqrt{r_0^2 + h^2}$ slant radius from the detector to the outer circle of radius r_0 of the annulus, and

μ = total linear absorption coefficient of air for the source radiation.

It is assumed that $B(h, \rho)$ is independent of h and linear in ρ ; i.e.,

$$B(\rho) = \alpha + \beta \mu \rho, \quad (4.2)$$

where α and β are constants. Then (4.1) becomes

$$D(h; \rho_1, \rho_0) = 2\pi D_1 \left\{ \alpha \left[E_1(\mu \rho_1) - E_1(\mu \rho_0) \right] + \beta \left[e^{-\mu \rho_1} - e^{-\mu \rho_0} \right] \right\}, \quad (4.3)$$

where $E_1(x)$ denotes the exponential integral,

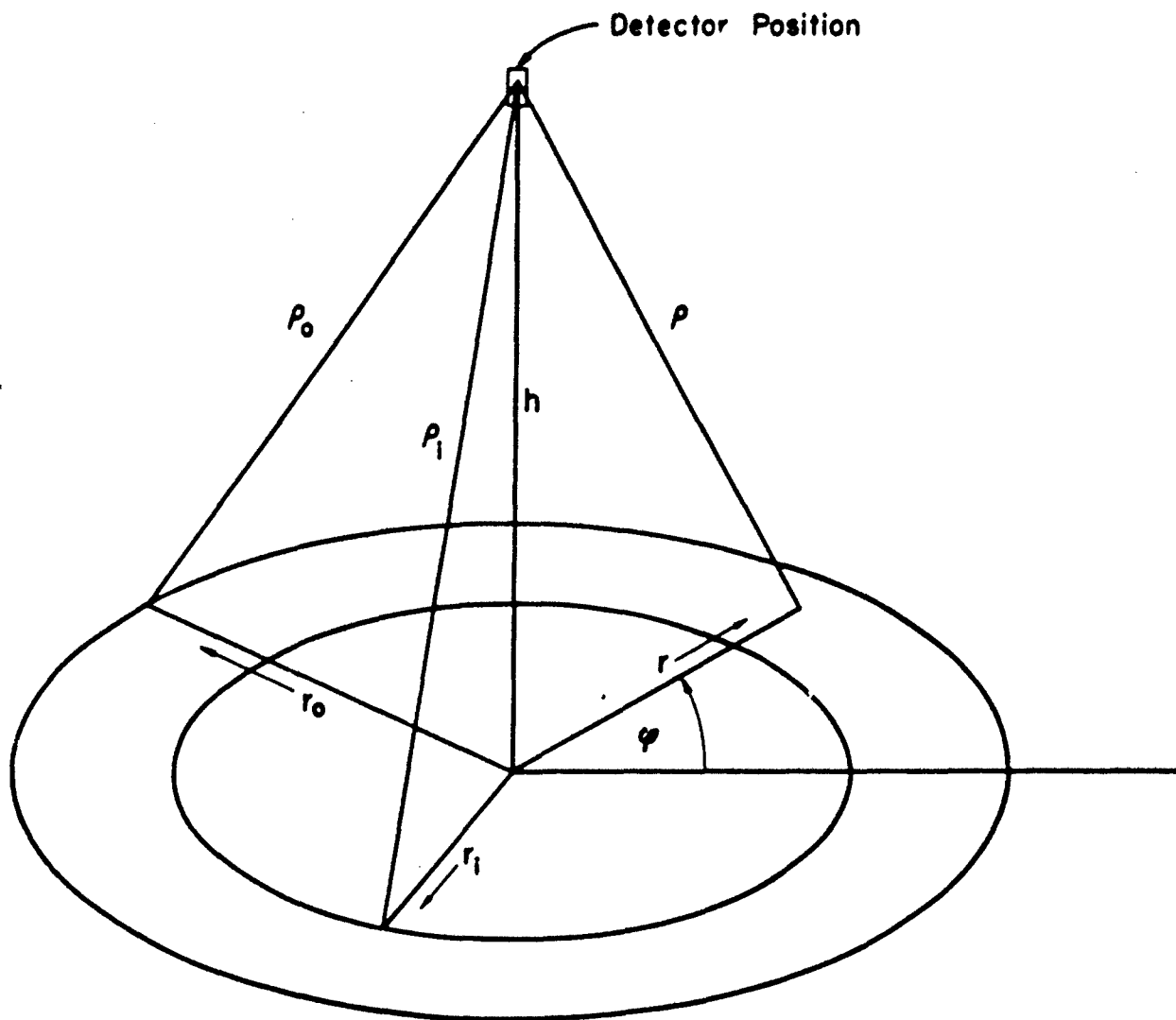


Figure 4.1 Annulus - Detector Geometry.

$$E_1(x) = \int_x^{\infty} \frac{e^{-t}}{t} dt \quad (4.4)$$

If α , β , and μ are specified in (4.3), theoretical exposure rates for various detector positions and annuli can readily be calculated by means of tables.

The exposure rate, $D(h; \rho_1, \infty)$, is called the theoretical far-field contribution of the exposure rate at height h . The particular case $h=3$, i.e., the theoretical far-field contribution of the exposure rate for the standard position, is especially important. For every ρ_1

$$D(h; h, \infty) = D(h; h, \rho_1) + D(h; \rho_1, \infty) \quad (4.5)$$

In an experiment covering a slant range, ρ_1 , it is necessary to obtain an estimate for the experimental far-field contribution $D_m(h; \rho_1, \infty)$, the subscript m standing for measured.

In the experimental analogue of (4.5),

$$D_m(h; h, \infty) = D_m(h; h, \rho_1) + D_m(h; \rho_1, \infty) \quad (4.6)$$

Only $D_m(h; h, \rho_1)$ is known and all respective quantities in (4.6) are smaller than in (4.5) because of such factors as ground roughness, deviation of the field from a smooth plane, etc. The fact that

$$D_m(h, \rho_1) < D_m(h, \infty) < D(h, \infty) \quad (4.7)$$

suggests to approximate $D_m(h, \infty)$ by a weighted mean

$$M = \frac{\lambda_1 D_m(h, \rho_1) + \lambda_2 D(h, \infty)}{\lambda_1 + \lambda_2} \quad (4.8)$$

The weight of the experimental value $D_m(h, \rho_1)$ is favored over $D(h, \infty)$ because the computation of $D(h, \infty)$ assumes the validity of a buildup factor for unrestricted slant ranges. In (4.7) and (4.8) the first argument, h , denoting the detector position, has been omitted. Thus, $D_m(h, \rho_1) = D_m(h; h, \rho_1)$ and similarly for the other quantities.

If one chooses $\lambda_1 = D(h, \rho_1)$ and $\lambda_2 = D_m(h, \rho_1)$, $D_m(h, \infty)$ is approximated by

$$D_m^*(h, \infty) = D_m(h, \rho_1) \frac{D(h, \rho_1) + D(h, \infty)}{D(h, \rho_1) + D_m(h, \rho_1)} \quad (4.9)$$

Then the relative error of $D_{\infty}(h, \infty)$ is given by

$$\left| \frac{D_{\infty}(h, \infty) - \hat{D}_{\infty}(h, \infty)}{D_{\infty}(h, \infty)} \right| = \frac{1}{D_{\infty}(h, \infty)} \left| L_{\infty}(h, \rho_1) \gamma - D_{\infty}(\rho_1, \infty) \right|, \quad (4.10)$$

where

$$\gamma = \frac{D(h, \infty) - E_{\infty}(h, \rho_1)}{D(h, \rho_1) + D_{\infty}(h, \rho_1)}. \quad (4.11)$$

Since $2 D_{\infty}(h, \rho_1) > D_{\infty}(\rho_1, \infty)$,

$$\left| \frac{D_{\infty}(h, \infty) - \hat{D}_{\infty}(h, \infty)}{D_{\infty}(h, \infty)} \right| < \gamma, \quad \text{and} \quad (4.12)$$

one obtains the following result: For experiments such that the measured contribution from the finite part of the field exceeds 50 percent of the far-field contribution, the total exposure rate $D_{\infty}(h, \infty)$ can be approximated by $\hat{D}_{\infty}(h, \infty)$ with a relative error considerably less than γ .

The mild condition stated is always satisfied in elaborate experiments. That the relative error is in fact considerably less than γ follows from the details of removing the unknowns $D_{\infty}(\rho_1, \infty)$ and $D_{\infty}(h, \infty)$ from the right side of (4.10). From Reference 1 the values $\alpha = 1.11$, $\beta = 0.529$ are used; i.e.,

$$B(\rho) = 1.11 + 0.529 \mu \rho. \quad (4.13)$$

One obtains with $\mu = 2.24 \cdot 10^{-3} \text{ ft}^{-1}$, $\rho_1 = 600 \text{ ft}$, for the standard position $h = 3$ from (4.13), (4.9), and (4.11),

$$D_{\infty}(3; 3, \infty) \approx \hat{D}_{\infty}(3; 3, \infty) = 468 \text{ R/h} \quad (4.14)$$

with % Error $\left[\frac{D_{\infty}(3; 3, \infty) - \hat{D}_{\infty}(3; 3, \infty)}{D_{\infty}(3; 3, \infty)} \right] < 5\%$. As shown in Reference 1, the buildup factor (4.13) is valid for slant ranges up to 800 feet. It is assumed that its use for unrestricted slant ranges introduces only negligible error. Similarly, it is expected that all constants in the pertinent equations do not change appreciably up to heights of 15 feet (Reference 10). Far-field corrections for other heights have accordingly been made, as shown above for the standard position.

4.2 Experimental Exposure Rates in Basement.

If in (4.1) β is replaced by $(\beta-1)$, the exposure rate $D^{(s)}(h; \rho_1, \rho_0) = D^{(s)}(\rho_1, \rho_0)$ due to skyshine only is obtained. $D^{(s)}(\rho_1, \rho_0)$ also represents the theoretical skyshine contribution in an open structure below ground.

From (4.3) it follows that

$$(2\pi D_1)^{-1} D^{(s)}(\rho_1, \rho_0) = (\alpha-1) [E_1(\mu\rho_1) - E_1(\mu\rho_0)] + \beta [e^{-\mu\rho_1} - e^{-\mu\rho_0}] \quad (4.15)$$

With the method below, an estimate for the experimental far-field contribution $D_n^{(s)}(\rho_1, \infty)$ is obtained. Since

$$(2\pi D_1)^{-1} D^{(s)}(h, \infty) = (\alpha-1) E_1(\mu h) + \beta e^{-\mu h},$$

$$(2\pi D_1)^{-1} D^{(s)}(h, \rho_0) = (\alpha-1) [E_1(\mu h) - E_1(\mu\rho_0)] + \beta [e^{-\mu h} - e^{-\mu\rho_0}], \text{ and}$$

$$(2\pi D_1)^{-1} D^{(s)}(\rho_0, \infty) = (\alpha-1) E_1(\mu\rho_0) + \beta e^{-\mu\rho_0},$$

$$D^{(s)}(h, \infty) = D^{(s)}(h, \rho_0) + C(\rho_1, \rho_0) D^{(s)}(\rho_1, \rho_0), \quad (4.16)$$

where

$$C(\rho_1, \rho_0) = \frac{(\alpha-1) E_1(\mu\rho_0) + \beta e^{-\mu\rho_0}}{(\alpha-1) [E_1(\mu\rho_1) - E_1(\mu\rho_0)] + \beta [e^{-\mu\rho_1} - e^{-\mu\rho_0}]} \quad (4.17)$$

In (4.16) the theoretical far-field contribution is represented as the product of the ring contribution $D_n^{(s)}(\rho_1, \rho_0)$ and the correction factor $C(\rho_1, \rho_0)$. It is assumed now that the correction factor $C(\rho_1, \rho_0)$ can be applied to the experimental value $D_n^{(s)}(\rho_1, \rho_0)$; that is, for the experimental case

$$D_n^{(s)}(h, \infty) \approx D_n^{(s)}(h, \rho_0) + C(\rho_1, \rho_0) D_n^{(s)}(\rho_1, \rho_0), \quad (4.18)$$

where $D_n^{(s)}(\rho_1, \rho_0)$, the contribution from the outermost annulus, is taken since it is expected that skyshine contributions from the far field and the last annulus behave similarly. Although the method is widely adopted, it is difficult to find an error estimate in terms of readily computed quantities. None has been offered so far. Because of the differences in the denominator of (4.17), the small value of μ , and the behavior of $E_1(x)$, the method should never be applied to small outer annuli. An attempt to adapt the method of (4.1) to the present skyshine case is not very promising. Since the far-field contribution can easily amount to 30 to 40 percent of the contribution from the finite part of the field even in elaborate experiments, it is difficult to find close lower and upper bounds for $D_n^{(s)}(h, \infty)$ that allow a general error estimate of practical value.

The far-field exposure rates presented in Table 3.2 were obtained by the above method applied to the fourth annulus.

4.3 Reduction Factors.

The various detector positions in the basement at which measurements were taken, along with the solid angle fractions subtended at them by the rectangular opening of the basement, are listed in Table 4.1. A rectangular coordinate system centered at the middle of the basement floor with the positive x-direction CD, positive y-direction CE, and positive h-direction pointing towards the opening has been introduced. The ω -values were calculated as outlined in Section 41 of NBS 42 (Reference 4).

TABLE 4.1 DETECTOR POSITIONS WITH CORRESPONDING SOLID-ANGLE FRACTIONS

| ω \ h | 1 | 2 | 3 | 4 | 5 | 6 |
|--------------|-------|-------|-------|-------|-------|-------|
| A(9,4,h) | 0.197 | 0.224 | 0.259 | 0.308 | 0.389 | 0.563 |
| B(4.5,2,h) | 0.326 | 0.386 | 0.461 | 0.556 | 0.677 | 0.828 |
| C(0,0,h) | 0.370 | 0.436 | 0.516 | 0.614 | 0.729 | 0.859 |
| D(9,0,h) | 0.243 | 0.284 | 0.337 | 0.409 | 0.511 | 0.679 |
| E(0,4,h) | 0.298 | 0.342 | 0.395 | 0.461 | 0.551 | 0.701 |

Theoretically, detector positions with equal ω -values should yield similar exposure rates. A comparison of exposure rates measured at detector positions with nearly equal ω -values shows that they are appreciably influenced by radiation backscattering from the floor and walls. It is not possible to dispose of the backscattering component with a flat percentage (20 percent or so). It would appear, therefore, that inaccuracies will result from using a single factor (1.2) to account for the backscattering component in a concrete basement. A clear separation of the sky-shine component from the backscattering component calls for future experimentation, possibly with leaded and unleaded walls.

Ideally, theoretical reduction factors, R, should take the following form:

$$R = \frac{D}{D_0} = \frac{D}{D(3;3,\infty)} = f(h,\omega) S_A(d=0,\omega) \quad (4.19)$$

where the function $S_{\bullet}(d = 0, \omega)$ is the geometry function defined by formula (27.13) of NBS 42, and $f(h, \omega)$ is the position function. The position function includes the skyshine detector response at ground level $S(d = 0)$ and the response to radiation backscattered from the side walls and floor, which is a function of height, h , above the basement floor and the solid-angle fraction, ω , subtended at the detector. However, the only theoretical formulation available for calculating reduction factors for a case which resembles closely the open-basement situation is the approximate skyshine response formula for a foxhole [formula (31.1), NBS 42].

$$\frac{D}{D_0} = 1.2 S(d = 0) S_{\bullet}(d = 0, \omega) . \quad (4.20)$$

Reduction factors computed from (4.20) are listed in Table 3.3, along with those found experimentally at corresponding detector positions A through E. At positions along the centerline, relatively good agreement is observed. Note that the theoretical and experimental reduction factors are not directly comparable since the far-field correction factor $C(\rho_1, \rho_0)$ should be applied only to the skyshine contribution and not to the sum of the skyshine and backscattering component.

Figure 4.2 describes the nature of the experimental position function $f(h, \omega)$ for the open basement. This figure shows the experimental position function $f(h, \omega)$ plotted against the solid-angle fraction, ω , for detector height, h , where R is the experimental reduction factor. The detector location for each point of the height curves may be found by matching the points with the solid-angle fractions shown in Table 4.1. For comparison the corresponding theoretical representation (4.20) is included and is described by the line $1.2 S(d = 0)$, parallel to the ω -axis.

Figure 4.2 shows that, in a concrete basement, detector response to skyshine radiation depends upon position in the basement and height above the floor. Indications are that in a rectangular basement the theoretical calculation as given in Equation (4.20) will only approximate the center or near-center detector locations but is not good for eccentric off-center detector locations. According to Equation (4.20) the quantity $1.2 S(d = 0)$ should be constant for all solid angles. Figure 4.2 shows that this does not hold throughout the basement but varies according to horizontal and vertical positions. Since the function $S(d = 0)$, which describes the amount of skyshine radiation entering the basement at ground level, should not vary according to detector location, then the difference would be caused by the inaccurate estimation of the contribution due to backscattering from the side walls and the floor, or the 1.2 factor. For any detector position in the basement an approximate reduction factor can be interpolated by means of Figure 4.2.

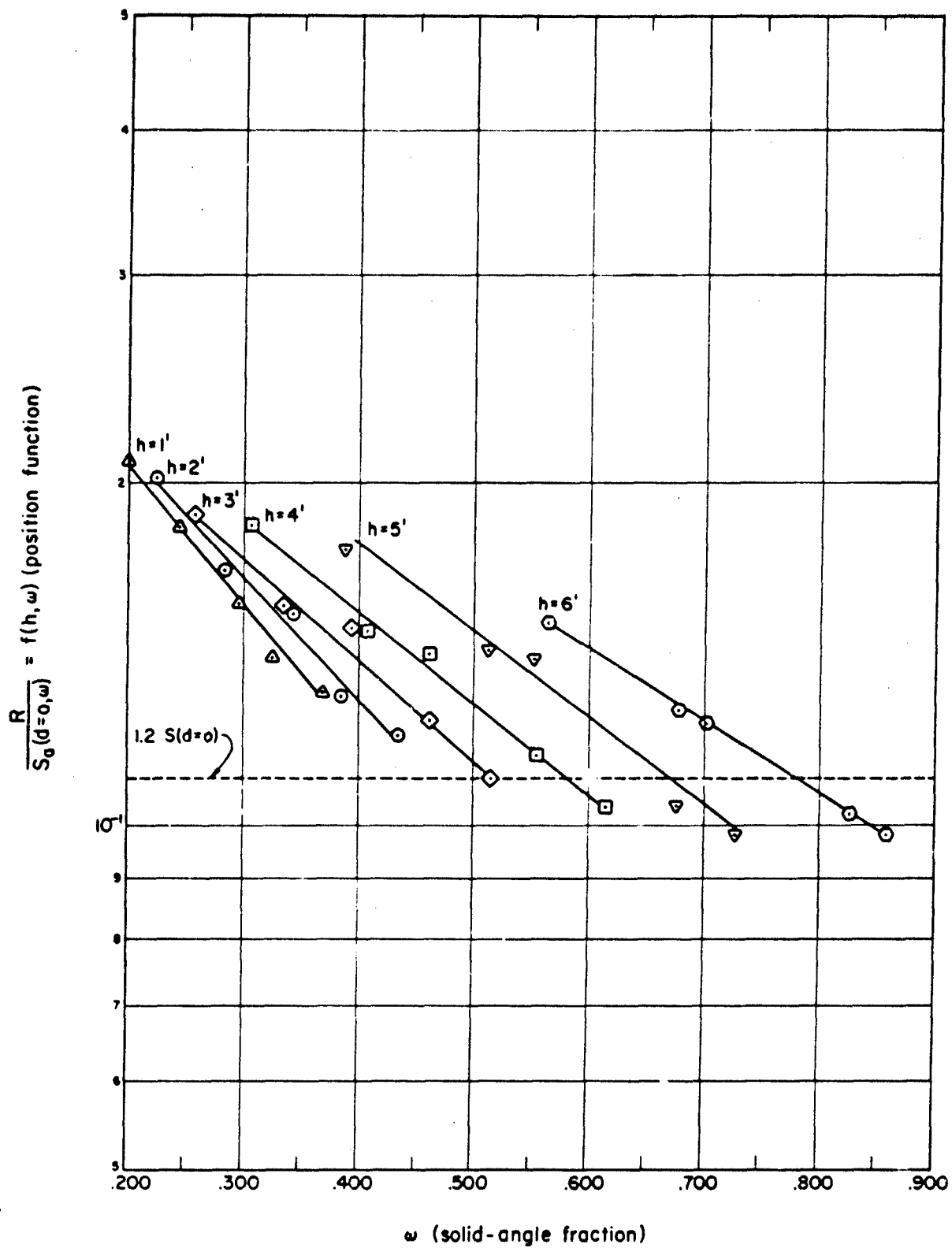


Figure 4.2 Graph showing the experimental position function $f(h, \omega) = \frac{R}{S_0(d=0, \omega)}$ versus the solid-angle fraction, ω , for various heights above the basement floor.

4.4 Comparison of Experimental and Theoretical Reduction Factors.

The difference between experimental and theoretical reduction factors at various detector locations and positions within a concrete basement are shown in Table 4.2 and plotted in Figures 4.3 through 4.7.

TABLE 4.2 COMPARISON OF EXPERIMENTAL AND THEORETICAL REDUCTION FACTORS

| Detector Height Above Floor | Percent Differences at Detector Locations* | | | | |
|-----------------------------------|--|----|------|----|----|
| | A | B | C | D | E |
| ft | percent | | | | |
| 1 | 47 | 21 | 14 | 41 | 32 |
| 2 | 46 | 14 | 8 | 37 | 27 |
| 3 | 42 | 11 | 0 | 27 | 27 |
| 4 | 39 | 3 | -9 | 26 | 23 |
| 5 | 37 | -5 | -8.5 | 22 | 23 |
| 6 | 27 | -8 | -13 | 12 | 11 |

$$*\text{Percent Difference} = \frac{\text{Experimental} - \text{Theoretical}}{\text{Experimental}} \times 100$$

The largest range of differences is seen at all heights of detector location A, Figure 4.3. For all heights at this detector location, the experimental values ranged from 27 to 47 percent higher than the theoretical values. These rather large differences are due in part to the error caused by using a single correction for backscattered radiation and partly to the fact that the detector location A is in a highly eccentric position with respect to the overhead opening. The theoretical calculations are best suited for a detector location in the center of the basement. Spencer states that calculated results under highly eccentric geometries (i.e., the value of the length-to-width ratio, e , greater than 3) would greatly underestimate the experimental results (Reference 4).

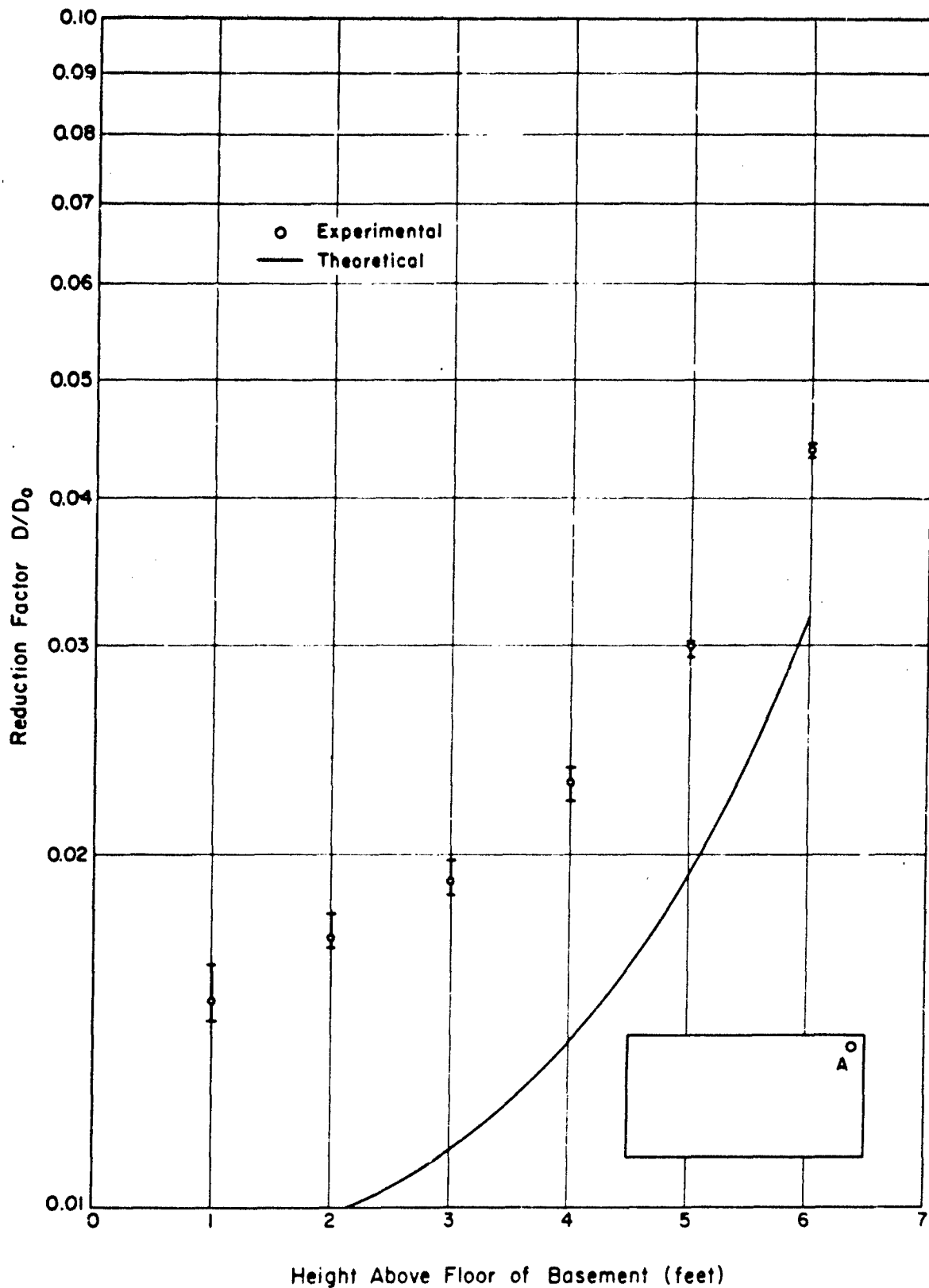


Figure 4.3 Experimental and theoretical reduction factors versus height above an open basement floor, detector location A.

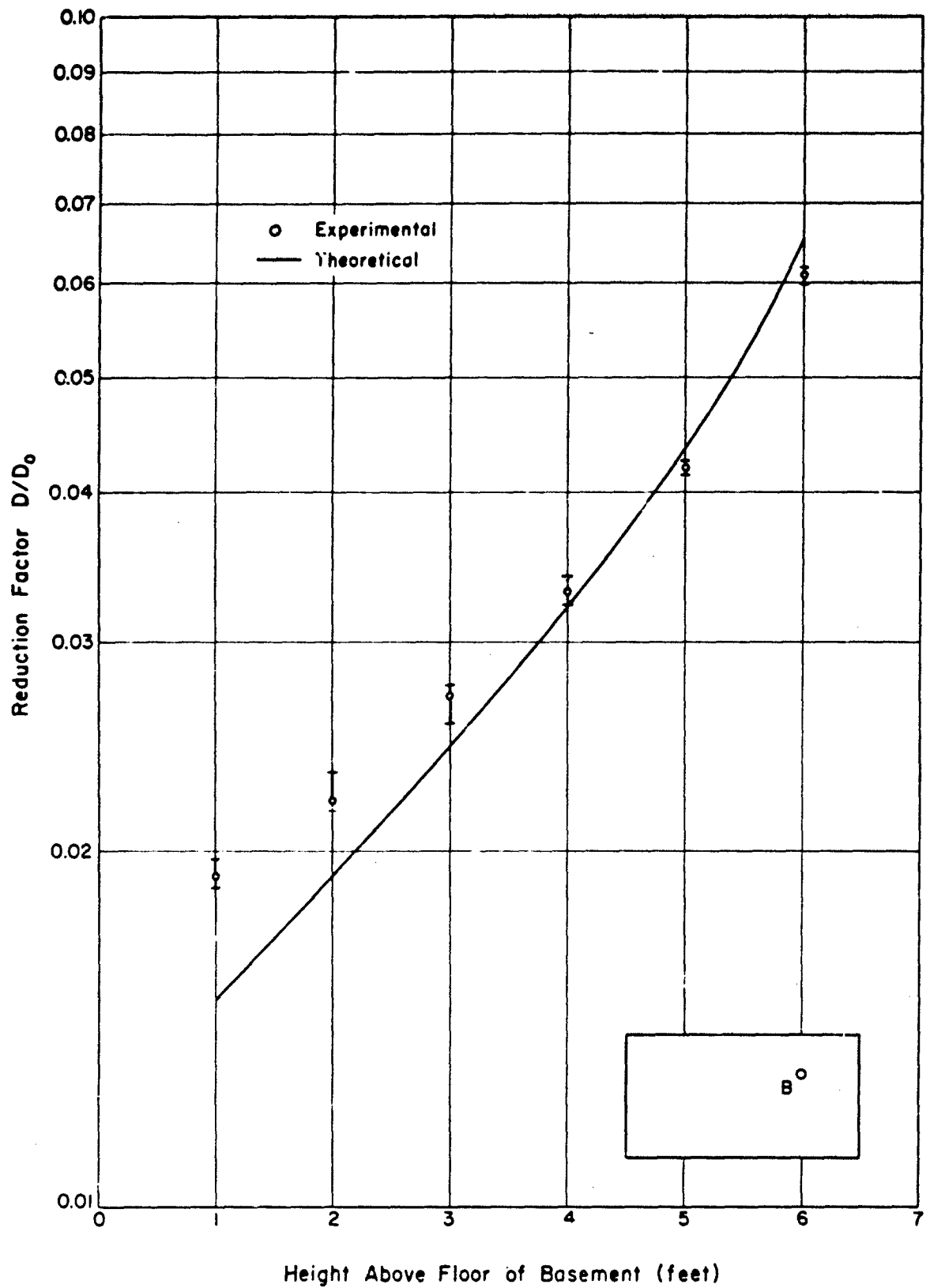


Figure 4.4 Experimental and theoretical reduction factors versus height above an open basement floor, detector location B.

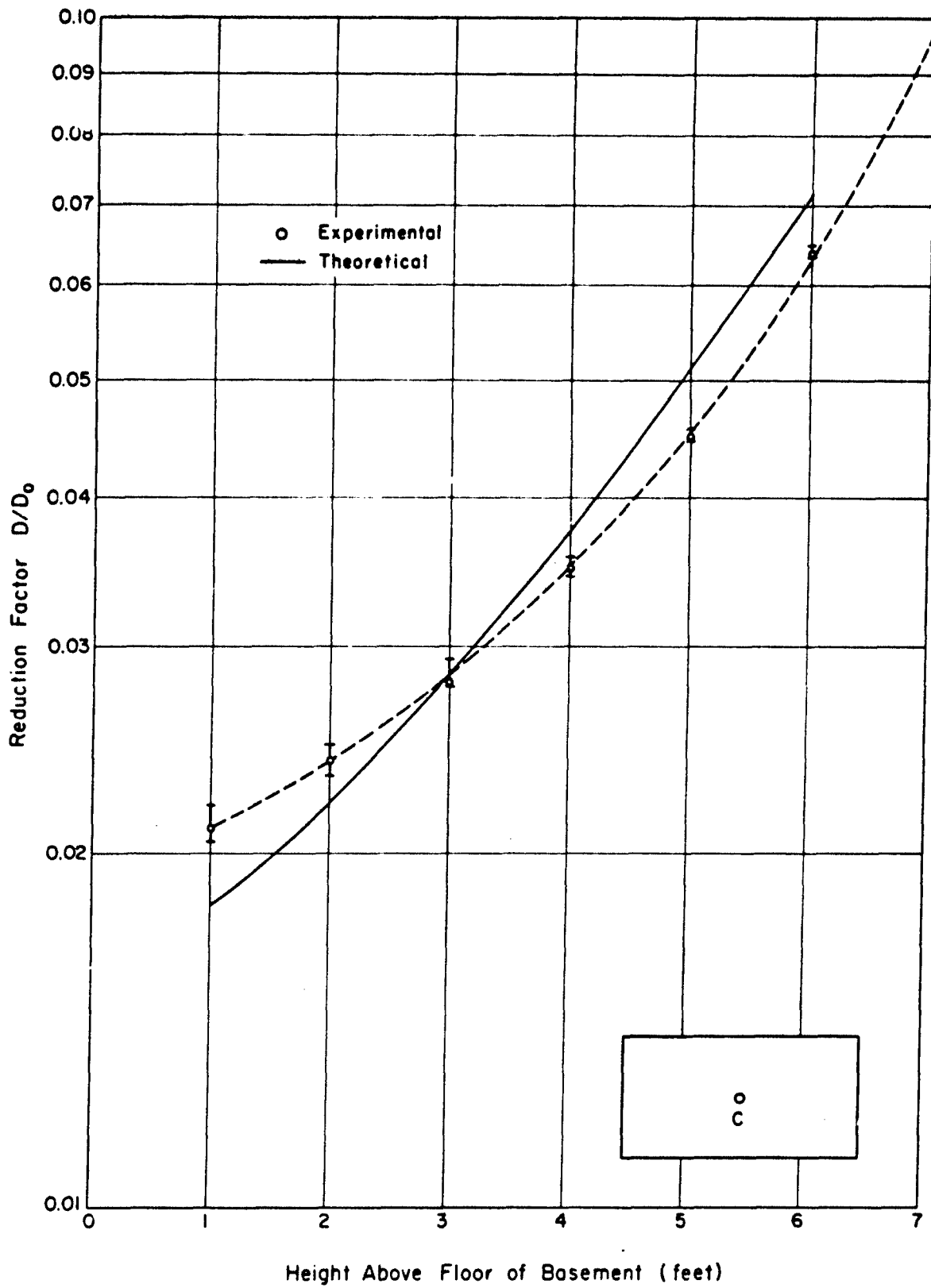


Figure 4.5 Experimental and theoretical reduction factors versus height above an open basement floor, detector location C.

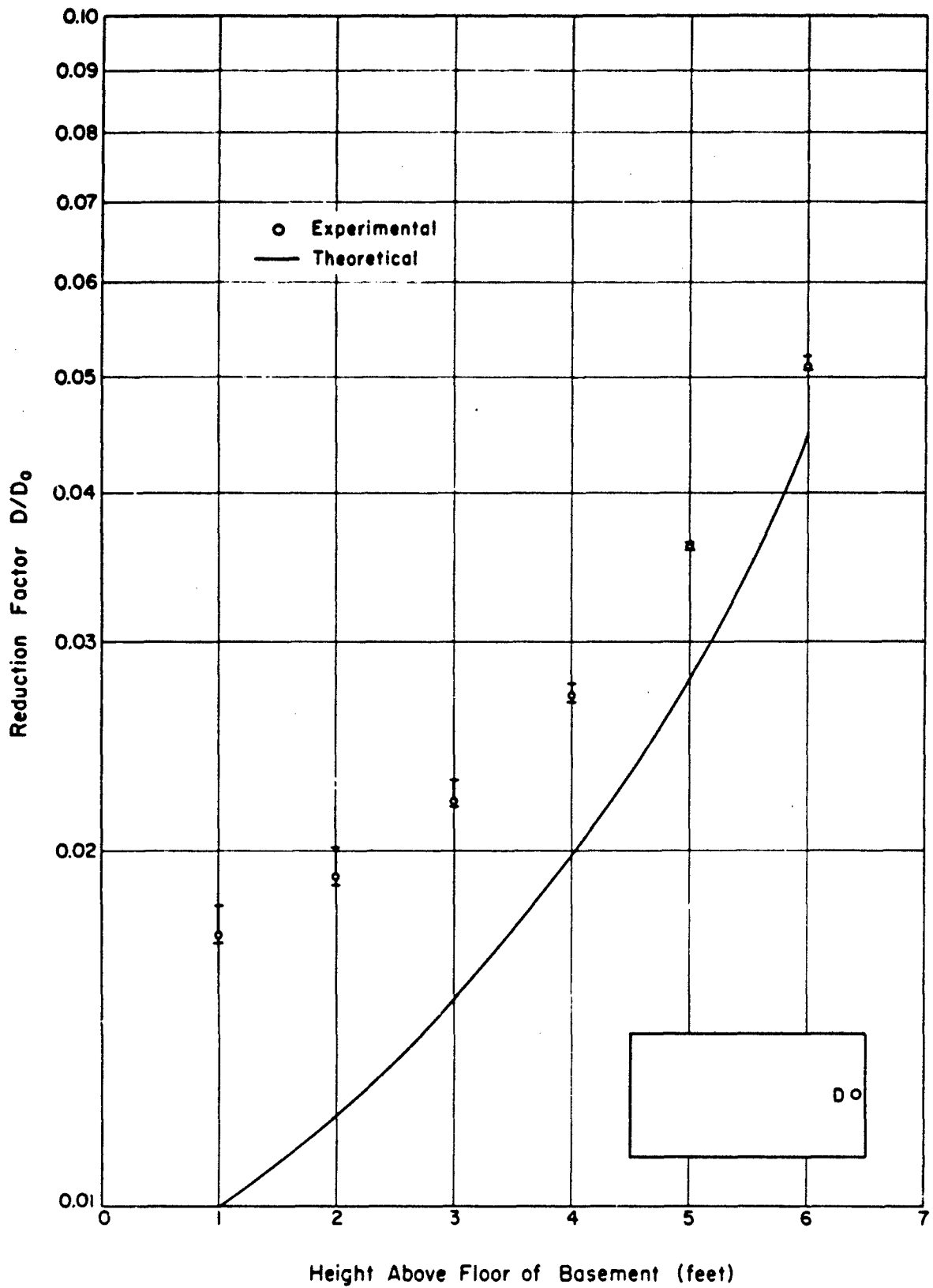


Figure 4.6 Experimental and theoretical reduction factors versus height above an open basement floor, detector location D.

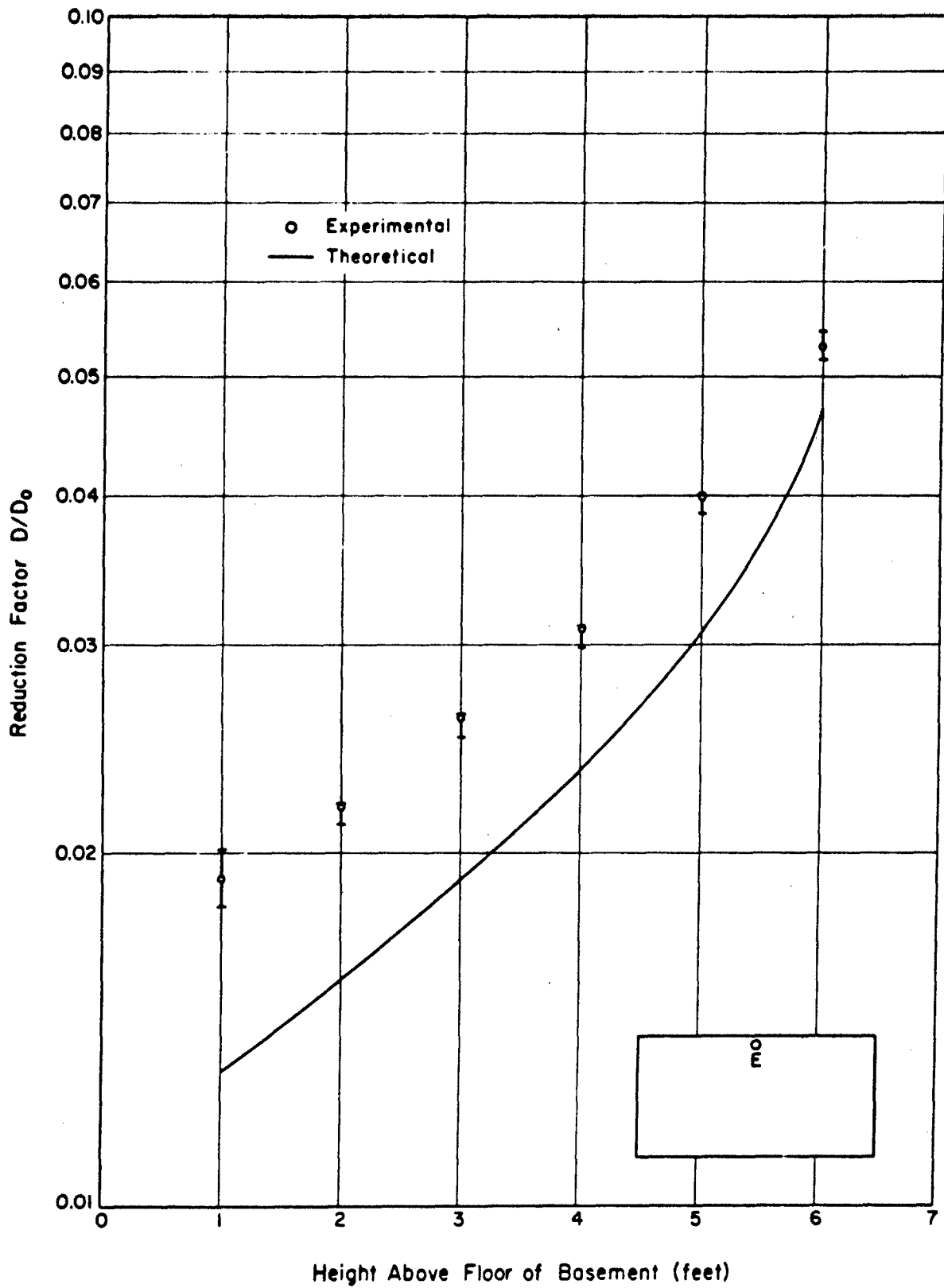


Figure 4.7 Experimental and theoretical reduction factors versus height above an open basement floor, detector location E.

A similar explanation pertaining to eccentric detector geometries can be made for the differences in experiment and theory at detector location D, Figure 4.6, although the difference is not as large as that at detector location A. The reason for this was that detector location D was oriented along the centerline of the width of the basement and was less eccentric than detector location A.

Note that the larger percent differences (Table 4.2) between experiment and theory, probably due to backscattered radiation, occur at all detector positions next to the walls and floor, e.g., corner detector location A, and wall detector locations D and E. The radiation backscatter contribution is emphasized in comparing the percent differences for detector locations A, D, and E. Here, the percent differences between experiment and theory are largest for those detector positions that are next to the larger wall-surface areas.

Agreement between experimental and theoretical reduction factors was good at detector locations B and C, Figures 4.4 and 4.5. This would be expected at the C detectors located at the center of the basement. However, in view of the results from the other detector locations (A, D, and E), the close agreement at detector location B is somewhat surprising. Again, the explanation appears to be that detector location B, although off-center, was somewhat nearer the center than the other detector locations.

It was noted that, at all detector locations, the agreement between experiment and theory was best at the detector positions near the top of the basement. In Figures 4.3 through 4.7, the experimental data taken near the basement floor curves upward, whereas the theoretical curve continues to fall off approximately exponentially. This again indicates that in a large open basement there may be the additional buildup of radiation due to backscatter from the floor that is not accounted for with the 1.2 factor recommended in NBS Monograph 42.

Figure 4.5 shows the exposure rate plotted versus the height above the basement floor at the center detector location. The experimental curve was extrapolated to the 7-foot height (ground level) or $w=1$. The extrapolated value 0.0987 , from Figure 4.5, times the free-field exposure rate, $468,000$ $(\text{mR/h})/(\text{Ci/ft}^2)$ at the 3-foot height, yields an exposure rate of $46,500$ $(\text{mR/h})/(\text{Ci/ft}^2)$ at ground level. This value, of course, would include any backscatter from the walls and the floor. If a backscatter of 20 percent is assumed and subtracted, then the total exposure rate due to skyshine at the surface of the basement would be $37,200$ $(\text{mR/h})/(\text{Ci/ft}^2)$. This is 7.9 percent of the infinite free-field exposure rate at the 3-foot height above ground. This compares favorably with 8.8 percent calculated by Spencer (Reference 4) and 10 percent measured by Burson and Summers (Reference 8).

5. CONCLUSIONS

Analysis of the position function $f(h,\omega)$ at various detector levels above the basement floor indicates the presence of a backscattering contribution that is dependent on height above the floor and solid-angle fraction and is not adequately estimated by a single correction factor (1.2 suggested in NBS Monograph 42).

Agreement within 21 percent was obtained between experimental and theoretical reduction factors calculated by Formula (31.1) of NBS Monograph 42 for detector locations in the center or near the center of the basement (detector locations C and B).

Theoretical reduction factors underestimate experimental reduction factors at the off-center detector locations close to the basement wall (detector locations A, D, and E) by as much as 47 percent. The differences appear to be caused by radiation scattered from the walls and floor of the basement; this scattering is not completely accounted for in the theoretical calculations.

Extrapolation to the ground surface ($\omega = 1$) of the experimentally measured reduction factors at the center detector location within the open concrete basement yields an exposure rate that is 7.9 percent of the infinite free-field exposure rate at the 3-foot height. This compares favorably with 8.8 percent calculated in the NBS Monograph 42.

The infinite-field exposure rate at the 3-foot height above a graded, rolled, and relatively smooth field was measured as 468 R/h at a source density of 1 Ci/ft² of cobalt-60 radiation simulated with a circulating point source.

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APPENDIX A

EXPERIMENTAL DATA

Tables A.1 through A.8 contain the data for each detector position at the various locations within a concrete basement. The exposure-rate contributions are given for all four semiannuli of the radiation area with the sum of the four semiannuli shown in the column to the right.

To obtain the total exposure rate from the simulated fallout field for detectors at locations, A, B, and E, the exposure rate of the primary positions A, B, and E are added to the exposure rate of the image positions a, b, and e, respectively. At each height for detector locations C and D, the exposure rates are doubled.

TABLE A.1 EXPOSURE RATE CONTRIBUTION TO PRIMARY DETECTORS AT LOCATION (A)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 |
|---|--|------|------|------|------------------|
| | 1 | 2 | 3 | 4 | |
| 1 | 262 | 600 | 777 | 363 | |
| | 261 | 696 | 794 | 321 | |
| | | 532 | | 362 | |
| | | | | 303 | |
| | Average | 262 | 609 | 786 | 337 |
| 2 | 302 | 627 | 971 | 426 | |
| | 283 | 618 | 975 | 400 | |
| | | 597 | | 381 | |
| | | | | 381 | |
| | Average | 293 | 614 | 973 | 388 |
| 3 | 350 | 714 | 943 | 446 | |
| | 318 | 682 | 956 | 418 | |
| | | 694 | | 375 | |
| | | | | 433 | |
| | Average | 334 | 697 | 950 | 408 |
| 4 | 380 | 851 | 1110 | 460 | |
| | 362 | 862 | 1170 | 442 | |
| | 370 | 865 | | 468 | |
| | | 813 | | 453 | |
| | Average | 371 | 848 | 1140 | 456 |
| 5 | 467 | 1050 | 1390 | 535 | |
| | 483 | 962 | 1460 | 522 | |
| | 507 | 1020 | | 528 | |
| | | 1110 | | 537 | |
| | Average | 486 | 1030 | 1430 | 531 |
| 6 | 802 | 1650 | 2100 | 852 | |
| | 813 | 1690 | 2170 | 859 | |
| | | 1760 | | 866 | |
| | | | | | |
| | Average | 808 | 1700 | 2140 | 859 |

TABLE A.2 EXPOSURE RATE CONTRIBUTION TO IMAGE DETECTORS AT LOCATION (a)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 | |
|---|--|------|------|------|------------------|------|
| | 1 | 2 | 3 | 4 | | |
| 1 | 434 | 941 | 1450 | 516 | | |
| | 372 | 945 | 1200 | 487 | | |
| | | 963 | | 512 | | |
| | | | | 504 | | |
| | Average | 404 | 950 | 1330 | 505 | 3190 |
| 2 | 490 | 969 | 1360 | 596 | | |
| | 485 | 1110 | 1340 | 617 | | |
| | | 1050 | | | | |
| | Average | 488 | 1040 | 1350 | 607 | 3490 |
| | 3 | 500 | 1280 | 1630 | 673 | |
| 483 | | 1300 | 1580 | 677 | | |
| | | 1260 | | 651 | | |
| | | 1360 | | | | |
| Average | | 492 | 1300 | 1610 | 667 | 4070 |
| 4 | 637 | 1590 | 2040 | 852 | | |
| | 634 | 1550 | 1860 | 801 | | |
| | | 1520 | | 814 | | |
| | | 1510 | | | | |
| | | 1610 | | | | |
| | | 1550 | | | | |
| | | 1590 | | | | |
| | Average | 636 | 1560 | 1950 | 822 | 4970 |
| 5 | 826 | 2070 | 2810 | 1030 | | |
| | 837 | 2110 | | 1080 | | |
| | | 2100 | | | | |
| | Average | 832 | 2090 | 2810 | 1060 | 6790 |
| | 6 | 1530 | 3080 | 3710 | 1370 | |
| 1530 | | 3040 | | 1440 | | |
| | | 3040 | | | | |
| Average | | 1530 | 3050 | 3710 | 1410 | 9700 |

TABLE A.3 EXPOSURE RATE CONTRIBUTION TO PRIMARY DETECTORS AT LOCATION (B)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 |
|---|--|------------------------------|------|---------------------------------|------------------|
| | 1 | 2 | 3 | 4 | |
| 1 | 426 | 899 | 1110 | | |
| | 374 | 886 | 1100 | | |
| Average | 400 | 902 896 | 1110 | 390* | 2800 |
| 2 | 484 | 919 | 1260 | 600 | |
| | 411 | 936 | 1240 | 648 | |
| Average | 463 | 928 | 1250 | 547 520 573 600 581 | 3220 |
| 3 | 561 | 1220 | 1550 | 597 | |
| | 529 | 1140 | 1500 | 698 | |
| Average | 545 | 1180 1180 | 1530 | 648 | 3900 |
| 4 | 652 | 1500 | 1790 | 772 | |
| | 649 | 1450 | 1860 | 806 | |
| Average | 651 | 1430 1550 1560 1500 | 1830 | 866 815 | 4800 |
| 5 | 902 | 1910 | 2340 | 989 | |
| | 915 | 1940 | | 1040 | |
| Average | 915 910 | 2050 1970 | 2340 | 1010 | 6230 |
| 6 | 1710 | 2930 | 3680 | 1360 | |
| | 1670 | 2980 | | 1480 | |
| Average | 1740 1610 1680 | 2960 | 3680 | 1420 | 9740 |

*Graphically interpolated.

TABLE A.4 EXPOSURE RATE CONTRIBUTION TO IMAGE DETECTORS AT LOCATION (b)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 | |
|---|--|------|------|------|------------------|-------|
| | 1 | 2 | 3 | 4 | | |
| 1 | 479 | 1090 | 1510 | 623 | 3770 | |
| | | 1110 | 1600 | 666 | | |
| | | 1090 | | 617 | | |
| | | | | 669 | | |
| | | | | 590 | | |
| Average | 479 | 1100 | 1560 | 633 | 3770 | |
| 2 | 584 | 601 | 1310 | 1710 | 682 | 4270 |
| | | 567 | 1280 | 1620 | 727 | |
| | | | 1300 | | 724 | |
| | | | 1300 | 1670 | 711 | |
| | | | | | | |
| Average | 584 | 1300 | 1670 | 711 | 4270 | |
| 3 | 695 | 700 | 1660 | 1860 | 818 | 5030 |
| | | 690 | 1580 | | 891 | |
| | | | 1520 | | 872 | |
| | | | 1690 | | | |
| | | | 1610 | 1860 | 360 | |
| Average | 695 | 1610 | 1860 | 360 | 5030 | |
| 4 | 799 | 790 | 1910 | 2490 | 1110 | 6320 |
| | | 801 | 1940 | | 1000 | |
| | | 805 | 2060 | | 1040 | |
| | | | 2000 | | | |
| | | | 1980 | 2490 | 1050 | |
| Average | 799 | 1980 | 2490 | 1050 | 6320 | |
| 5 | 1050 | 1060 | 2450 | 3110 | 1310 | 7990 |
| | | 1020 | 2440 | | 1300 | |
| | | 1070 | 2590 | | | |
| | | | 2520 | 3110 | 1310 | |
| | | | | | | |
| Average | 1050 | 2520 | 3110 | 1310 | 7990 | |
| 6 | 1680 | 1630 | 3620 | 4340 | 1740 | 11400 |
| | | 1670 | 3630 | | 1740 | |
| | | 1730 | 3560 | | | |
| | | 1690 | | | | |
| | | | 3600 | 4340 | 1740 | |
| Average | 1680 | 3600 | 4340 | 1740 | 11400 | |

TABLE A.5 EXPOSURE RATE CONTRIBUTION TO DETECTORS AT LOCATION (C)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 |
|---|--|------|------|------|-------------------------|
| | 1 | 2 | 3 | 4 | |
| 1 | 470 | 1060 | 1530 | 601 | |
| | 481 | 1010 | 1410 | 609 | |
| | | 1030 | 1340 | 625 | |
| | | | | 594 | |
| | Average | 475 | 1030 | 1430 | 607 |
| 2 | 560 | 1240 | 1650 | 712 | |
| | 534 | 1210 | 1610 | 699 | |
| | | 1230 | 1550 | 672 | |
| | | | | 707 | |
| | Average | 547 | 1230 | 1600 | 688 |
| 3 | 675 | 1450 | 1800 | 801 | |
| | 640 | 1470 | 1750 | 788 | |
| | | | | 867 | |
| | Average | 658 | 1460 | 1780 | 819 |
| 4 | 767 | 1880 | 2310 | 982 | |
| | 790 | 1960 | 2240 | 958 | |
| | 790 | 1940 | 2180 | 988 | |
| | Average | 782 | 1930 | 2240 | 976 |
| 5 | 995 | 2570 | 2840 | 1250 | |
| | 1010 | 2580 | | 1220 | |
| | 1000 | 2560 | | 1270 | |
| | Average | 1000 | 2570 | 2840 | 1250 |
| 6 | 1970 | 3550 | 4190 | 1620 | |
| | 1930 | 3410 | | 1650 | |
| | 1960 | 3470 | | 1620 | |
| | 1930 | | | | |
| | Average | 1950 | 3480 | 4190 | 1630 |

TABLE A.6 EXPOSURE RATE CONTRIBUTION TO DETECTORS AT LOCATION (D)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 |
|---|--|------|------|------|------------------|
| | 1 | 2 | 3 | 4 | |
| 1 | 380 | 876 | 1180 | 511 | |
| | 372 | 849 | 1220 | 522 | |
| | | 854 | | 459 | |
| | | | | 506 | |
| | | | | 481 | |
| Average | 376 | 860 | 1200 | 496 | 2930 |
| 2 | 437 | 944 | 1260 | 577 | |
| | 483 | 949 | 1210 | 600 | |
| | | 958 | | 562 | |
| | | | | 560 | |
| | | | | 537 | |
| Average | 460 | 950 | 1240 | 567 | 3220 |
| 3 | 496 | 1150 | 1480 | 628 | |
| | | 1090 | 1460 | 609 | |
| | | 1120 | | 625 | |
| | | | | 658 | |
| | | | | 610 | |
| Average | 496 | 1120 | 1470 | 624 | 3710 |
| 4 | 581 | 1430 | 1790 | 767 | |
| | 589 | 1380 | 1730 | 783 | |
| | | 1360 | | | |
| | | 1380 | | | |
| | | 1390 | | | |
| Average | 585 | 1400 | 1760 | 775 | 4520 |
| 5 | 850 | 1860 | 2560 | 958 | |
| | 850 | 1870 | | 953 | |
| | Average | 850 | 1870 | 956 | 6240 |
| 6 | 1410 | 2740 | 3420 | 1300 | |
| | 1410 | 2770 | | 1370 | |
| | 1410 | | | | |
| | Average | 1410 | 2760 | 3420 | 1340 |

TABLE A.7 EXPOSURE RATE CONTRIBUTION TO PRIMARY DETECTORS AT LOCATION (E)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 |
|---|--|------|------|------|------------------|
| | 1 | 2 | 3 | 4 | |
| 1 | 348 | 714 | 1080 | 419 | |
| | 314 | 779 | 944 | 435 | |
| | | | 852 | 389 | |
| | | | | 394 | |
| Average | 331 | 747 | 959 | 409 | 2450 |
| 2 | 394 | 809 | 1090 | 494 | |
| | 358 | 806 | 1080 | 456 | |
| | | 809 | 1020 | 486 | |
| | | | | 485 | |
| | | | | 468 | |
| Average | 376 | 808 | 1060 | 478 | 2720 |
| 3 | 424 | 933 | 1170 | 505 | |
| | 428 | 933 | 1220 | 511 | |
| | | 948 | 1160 | 516 | |
| | | | | 485 | |
| | | | | 524 | |
| Average | 426 | 938 | 1180 | 508 | 3050 |
| 4 | 467 | 1050 | 1360 | 562 | |
| | 473 | 1020 | 1370 | 610 | |
| | 465 | 1040 | | 564 | |
| | | 1070 | | | |
| Average | 468 | 1050 | 1370 | 579 | 3470 |
| 5 | 695 | 1390 | 1810 | 767 | |
| | 657 | 1400 | 1740 | 730 | |
| | 637 | 1410 | 1680 | 769 | |
| | | 1400 | | | |
| Average | 663 | 1400 | 1740 | 755 | 4560 |
| 6 | 2190 | 2010 | 2240 | 1020 | |
| | 2150 | 1990 | | 1040 | |
| | 1710 | 2080 | | | |
| | 2190 | | | | |
| Average | 2060 | 2030 | 2240 | 1030 | 7360 |

TABLE A.8 EXPOSURE RATE CONTRIBUTION TO IMAGE DETECTORS AT LOCATION (e)
FROM VARIOUS SEMIANNULI OF A SIMULATED FALLOUT FIELD

Note: Exposure rates are in (mR/h)/(Ci/ft²)

| Detector Height Above Floor (ft) | Exposure Rate Contribution From Semiannulus | | | | Σ 1 through 4 |
|---|--|------|------|------|------------------|
| | 1 | 2 | 3 | 4 | |
| 1 | 542 | 1170 | 1790 | 659 | |
| | 523 | 1200 | 1500 | 633 | |
| | | 1210 | | 610 | |
| | | | | 630 | |
| Average | 533 | 1190 | 1650 | 633 | 4010 |
| 2 | 618 | 1330 | 1790 | 784 | |
| | 582 | 1360 | 1780 | 783 | |
| | | | | 745 | |
| | | | | 771 | |
| Average | 600 | 1350 | 1790 | 771 | 4510 |
| 3 | 738 | 1690 | 2200 | 909 | |
| | 722 | 1740 | 2100 | 959 | |
| | | 1720 | | | |
| | | | | | |
| Average | 730 | 1720 | 2150 | 934 | 5530 |
| 4 | 821 | 2230 | 2570 | 1100 | |
| | 863 | 2210 | 2750 | 1130 | |
| | | 2210 | | 1130 | |
| | | | | 1130 | |
| Average | 842 | 2220 | 2660 | 1120 | 6840 |
| 5 | 1080 | 2840 | 3560 | 1410 | |
| | 1080 | 2810 | 3570 | 1340 | |
| | 1110 | 2800 | | 1410 | |
| | | | | | |
| Average | 1090 | 2820 | 3570 | 1390 | 8870 |
| 6 | 1620 | 3470 | 4190 | 1710 | |
| | 1650 | 3490 | 4280 | 1740 | |
| | 1650 | 3520 | | 1810 | |
| | | | | | |
| Average | 1640 | 3490 | 4240 | 1750 | 11100 |

APPENDIX B
SOURCE CALIBRATION

All circulating point sources used in the experiment were carefully calibrated to determine the radiation output (effective curie strength) of the source. In addition, to determine the validity of previous calibrations (Reference 1), all stationary point sources used in previous experimental work were recalibrated by a different geometrical arrangement.

The stationary point source and detector were supported at a height of 12.5 feet above ground. The source shield rested on a 10-foot-high platform and the detector was held in a holder fastened to a 12-foot-high ladder, Figure B.1. Exposure-rate measurements were made at horizontal source-to-detector distances of 2 feet, 4 feet, and 6.23 feet. At least 5 exposures were made at each separation distance with all measurements falling within 2 percent of the average.

To obtain an accurate estimate of the effective curie strength of the radiation source, a measurement must be made of the uncollided (narrow-beam) exposure rate at a known distance between the source and the detector. A direct measurement of this uncollided beam is complicated by the presence of air-scattered radiation and in some instances ground-scattered radiation. Therefore, the contribution from these two effects must be either eliminated or accurately estimated. The air-scattered component was estimated by using the infinite air-medium buildup factor $B(\mu x)$ of Berger (Reference 11). The air-ground interface buildup factor, as measured by Batter and Clark (Reference 12), was used to account for ground-scattered radiation.

The corrected exposure rate at 1 foot was obtained by the following formula:

$$D_1 = D_x \frac{x^2}{B(\mu x) K e^{-\mu x}}, \quad (B.1)$$

where

D_1 = corrected exposure rate at 1 foot, R/h,

D_x = measured exposure rate at standard atmospheric conditions, R/h,

x = distance from source to detector, feet,

$B(\mu x)$ = infinite air-medium buildup factor,

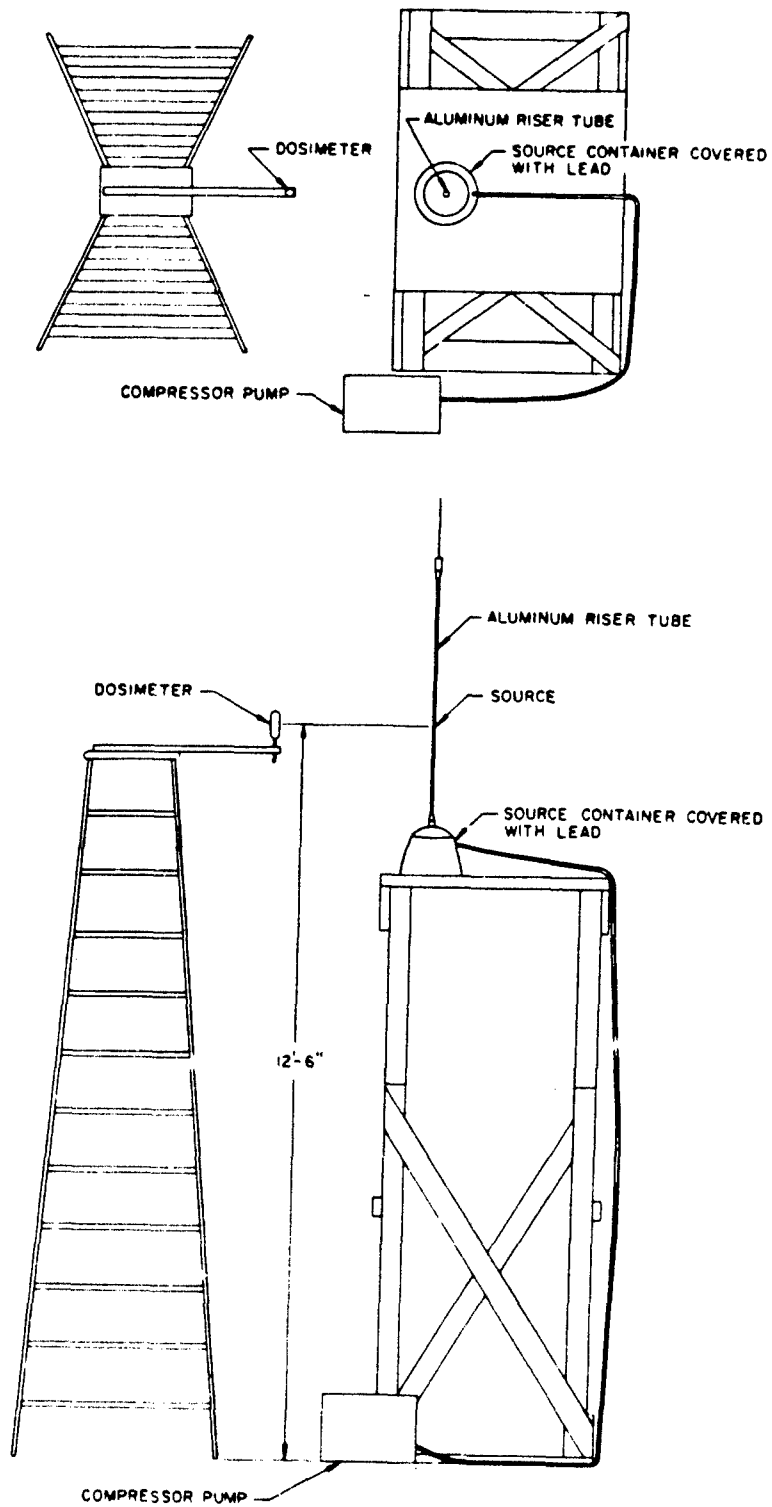


Figure B.1 Experimental set-up for calibration of stationary point sources.

K = air-ground interface buildup factor, and

μ = linear absorption coefficient in air at standard atmospheric conditions, $2.24 \times 10^{-3} \text{ ft}^{-1}$ for cobalt 60.

The effective curie strength of each source was determined by dividing the corrected exposure rate by the standard exposure rate for cobalt 60 (14.3 R/h per curie at a distance of 1 foot).

Table B.1 shows the effective curie strengths of the sources used in earlier experimentation as determined by the new method (C_N), along with the source strengths determined by the old method (C_o), corrected for radioactive decay. The maximum difference between the two is 1.6 percent, which is well within the error of ± 3 percent inherent in the NBS calibrated standard.

Circulating point sources were calibrated similarly except that the plastic tubing was suspended above ground between two 12-foot-high step-ladders spaced 6 feet apart (Figure B.2). A positive source stop was placed in the tubing line in a position that would stop the source halfway between the ladders. Radiation measurements were made with calibrated R chambers and the exposure rates were corrected to 1 foot by use of Equation B.1.

TABLE B.1 COMPARISON OF STATIONARY POINT SOURCE CALIBRATION DATA

| Source Strength ^a | Distance x | B ^b | K ^b | D _x ^b | E ₁ ^b | Method | | Percent Difference |
|------------------------------|---------------|----------------|----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------|
| | | | | | | C _N ^c | C _O ^c | |
| CI | ft | | | R/h | R/h | CI | CI | |
| 3.25 | 2 | 1.0039 | 1.0 | 5.37 | 21.39 | 1.50 | 1.509 | 0.53 |
| 3.25 | 4 | 1.0078 | 1.005 | 1.36 | 21.48 | 1.502 | 1.509 | 0.46 |
| 3.25 | 6.23 | 1.012 | 1.007 | 0.505 | 21.52 | 1.504 | 1.509 | 0.33 |
| 0.346 | 6.23 | 1.012 | 1.007 | 0.0612 | 2.33 | 0.163 | 0.161 | 0.62 |
| 94.5 | 2 | 1.0039 | 1.0 | 662 | 2638 | 186 | 183 | 1.6 |
| 94.5 | 4 | 1.0078 | 1.005 | 167 | 2631 | 184 | 183 | 0.5 |
| 94.5 | 6.23 | 1.012 | 1.007 | 71.4 | 2665 | 185 | 183 | 0.8 |

^a Calibrated 1 September 1958.

^b See Equation (B.1).

^c Calibrated 1 September 1964.

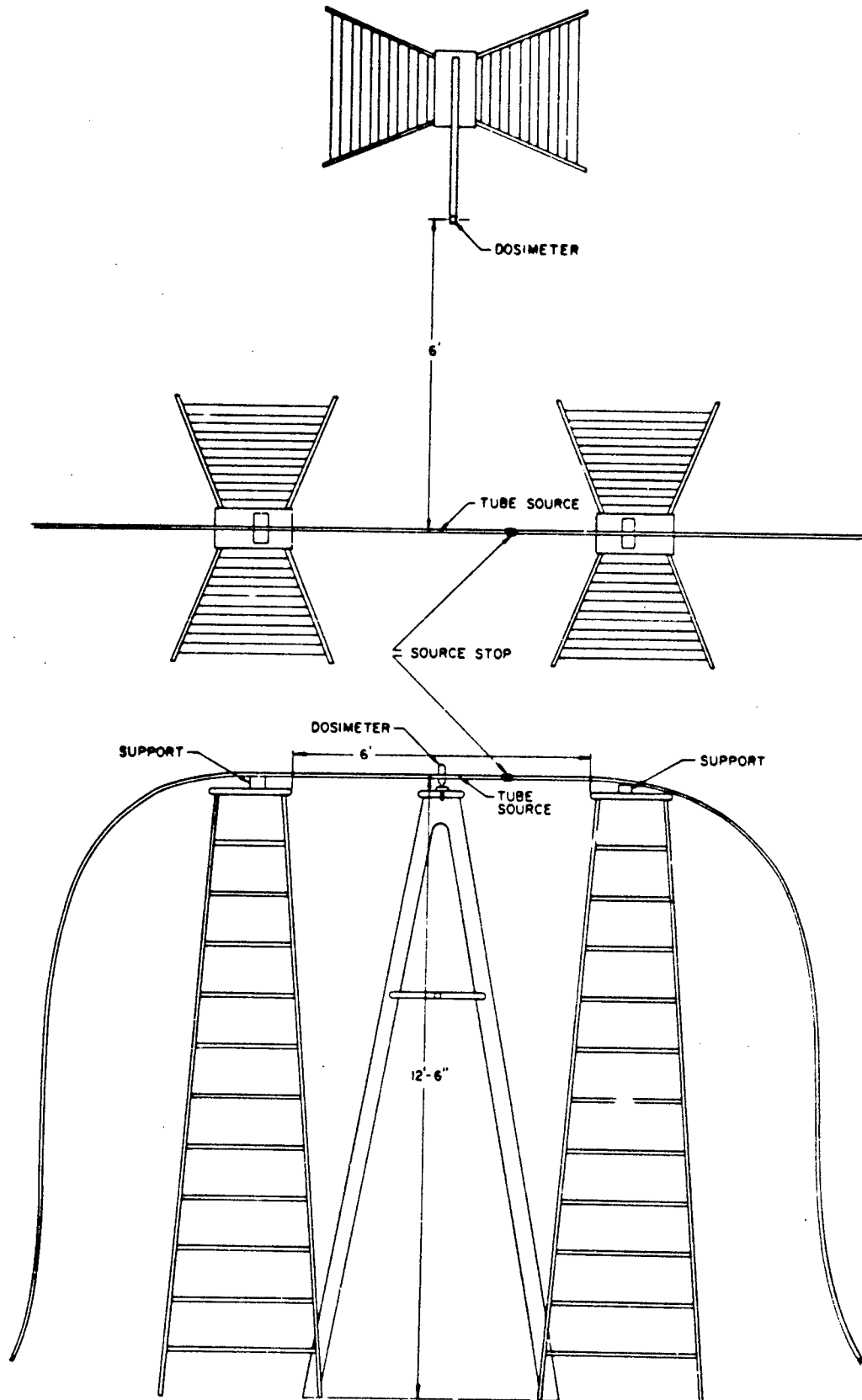


Figure B.2 Experimental set-up for calibration of circulating point sources.

APPENDIX C

FREE-FIELD EXPOSURE RATES MEASURED BY US ARMY NUCLEAR DEFENSE LABORATORY AND BY PROTECTIVE STRUCTURES DEVELOPMENT CENTER

One of the problems attendant with simulating a fallout field is that theoretically the fallout field is considered smooth and infinite in extent, a condition that is impractical to simulate. Therefore, the simulation of the field will be at best an approximation of the actual situation. This involves experimental measurements for a finite distance plus an analytical extrapolation for the far-field contribution. Earlier experiments measured the free-field exposure rates at the air-ground interface; cobalt-60 and cesium-137 sources were used to simulate the residual radiation (Reference 1). The site of these previous experiments was a relatively smooth, grassy field; however, the measurements were made with the source raised approximately 3-1/2 inches above the ground to ensure line-of-sight between source and detector and to reduce the effects of ground roughness in the measurements. These measurements were converted to ring-source data and the results were graphically integrated over the 800 feet covered by the measurements. An analytical estimate was made of the far-field contribution. The resultant infinite-field exposure rate at a 3-foot height was determined to be 497 R/h at a contamination density of 1 Ci/ft².

The 497 R/h compares favorably to the theoretical infinite-field exposure rate, 500 R/h, calculated by Eisenhower (Reference 13). However, it was higher than the experimental infinite-field exposure rate, 464 R/h, determined by McDonnell, et al., at the Protective Structures Development Center (PSDC), (Reference 10). Possible contributors to the difference in the above experimental exposure rates are (1) the method used to determine effective curie strengths of the sources and (2) ground roughness effects.

For the experiment in Reference 1, the sources were calibrated at a height of 11 feet above ground and at a horizontal distance of 6 feet from the detector. Measurements were made with and without an 8-inch-thick lead shield between the source and detector; the shield was designed to eliminate the direct radiation and to measure only the scattered radiation. These measurements resulted in a 5.1 percent correction for radiation-scatter contribution from the air-ground interface; this correction was applied in calculating the effective curie strengths of the sources. An objection to this method of source calibration was that the radiation scatter from the edges of the lead shield could be greater than the air-scattered radiation one is trying to measure. Subsequent measurements at a similar geometry indicated that the correction for the radiation scatter at the air-ground interface could be about 4.5 percent too high.

To determine the validity of these source strengths, all the sources used in the previous experiment (Reference 1) were recalibrated under conditions closely approximating free-air conditions. Details of this recalibration are given in Appendix B. The recalibration indicated that the effective curie strengths of all sources were almost exactly as previously reported after corrections were made for decay.

Since the present measurements were being made with the point-source circulation system, which presented a different source geometry, a remeasurement of the free-field exposure rate was required. Because the surface had been graded and rolled, for practical purposes the field was considered a smooth, level plane. The free-field exposure rates at various heights above the field are shown in Table 3.1 and are presented graphically in Figure C.1. Curves showing the cumulative exposure rate for each annulus are plotted. These curves indicate the relative contribution for each annulus with increasing distance from the center of the field.

To compare the free-field data reported in Reference 1 with the free-field data obtained with the point-source circulation system (in this report), the cumulative exposure rates at the 3-foot height were plotted versus the distance from the center of the field in Figure C.2. Also shown in Figure C.2 are data measured at the 15-foot height (this report) and data at the 3-foot and 15-foot heights taken at PSDC (Reference 10). The curves at the 3-foot height show a definite difference between the previously taken MDL data (Reference 1) and the measured data in this report. The latter measurements were 5 percent lower than the previous measurements. The PSDC measurements were also lower (12 percent) at the 452-foot radius. The fact that the curves are very nearly parallel indicates that the difference in the exposure rates was probably due to differences in terrain (ground roughness) between the sites of the experiment. During the initial work (Reference 1), the source was exposed just above the surface of the field to decrease ground-roughness effects. However, the source was near enough to the ground to be considered at the air-ground interface without being extremely affected by the variations in the terrain. The circulating point source, on the other hand, travelled through plastic tubing that was laid directly on the ground. Although the surface had been graded and rolled, the field was only an approximation of a smooth field. That only an approximation of a smooth field can be achieved may be inferred from data obtained by Huddleston, et.al., (Reference 14) who, under somewhat similar conditions, made measurements of fallout radiation on a flat, dry lake bed at the Nevada Test Site. Angular distribution measurements 3 feet above ground resembled the theoretical curve at the 20-foot height above ground, or schematically as if the fallout on the ground has been covered with a mass thickness of material equivalent to 20 feet of air. This indicated that there are ground-roughness effects even on ground which appears to approach the ideal in smoothness in an infinite terrain.

Ordinarily it might be expected that the PSDC measurements in the free-field would be in closer agreement with the NDL measurements since similar systems were used to simulate the fallout areas. However, at the PSDC test site, washed gravel had produced a rolling terrain which introduced shadowing effects to the lower detectors; these were not present in the NDL measurements. This is substantiated in the close agreement of NDL and PSDC data at the 15-foot height.

The infinite-field exposure rate at a 3-foot height for this experiment was 468 R/h at unit curie density. This is approximately 5 percent lower than the exposure rate measured previously (Reference 1), a difference believed to be due primarily to ground roughness.

The experimental infinite-field exposure rates at heights to 15 feet taken at NDL and at PSDC are plotted in Figure C.3, along with the theoretical curve. The theoretical curve was calculated from Spencer's $L(d)$ curve and a value of 468 R/h was assumed as the infinite-field value for a relatively smooth plane. The $L(d)$ function is the total detector response at a distance d (in air) from an infinite, plane, isotropic source, divided by the total detector response at 3 feet in air from the same source. In general, the experimental free-field measurements of NDL and of PSDC agree very well with Spencer's theoretical values. Good agreement exists between the NDL measurements and the theoretical values near the ground, and the measurements above 5 feet agree within 3.8 percent; however, the PSDC measurements were low at the 1-foot and 3-foot detector heights. If it is assumed that the difference between the measurements at these low detector heights is due to ground roughness, a correction factor may be calculated for each height by obtaining a ratio of the theoretical-to-experimental exposure rate. When these ratios are applied for ground roughness correction to the PSDC cumulative results shown in Figure C.2, the agreement between NDL measurements and PSDC measurements becomes quite good. This is shown by the 3-foot height data in Table C.1.

TABLE C.1 COMPARISON OF THE PSDC FREE-FIELD EXPOSURE RATES CORRECTED FOR GROUND ROUGHNESS WITH NDL FREE-FIELD EXPOSURE RATES MEASURED AT THE 3-FOOT HEIGHT ABOVE AN INFINITE RADIATION FIELD SIMULATED BY COBALT 60

| Outer Radius of Radiation Area | Cumulative Exposure Rates | | | Difference ^c |
|--------------------------------------|-----------------------------|--------------------------------|------------------------------|-------------------------|
| | Measured PSDC | Corrected ^a PSDC | Measured ^b NDL | |
| ft | (R/h)/(Ci/ft ²) | | | pct |
| 17.9 | 159.4 | 174.9 | - | - |
| 32 | 213.4 | 234.1 | - | - |
| 68 | 279.1 | 306.2 | 297 | 3.1 |
| 164 | 344.6 | 378.0 | 370 | 2.2 |
| 452 | 398.6 | 437.3 | 438 | 0.2 |
| ∞ | 429.3 | 470.9 | 468 | 0.6 |

^a Ground roughness correction factor = 1.097.

^b Data at the indicated radii interpolated from Figure 4.2.

^c Percent Difference = $\frac{\text{Corrected Exp Rate (PSDC)} - \text{Measured Exp Rate (NDL)}}{\text{Measured Exp Rate (NDL)}}$

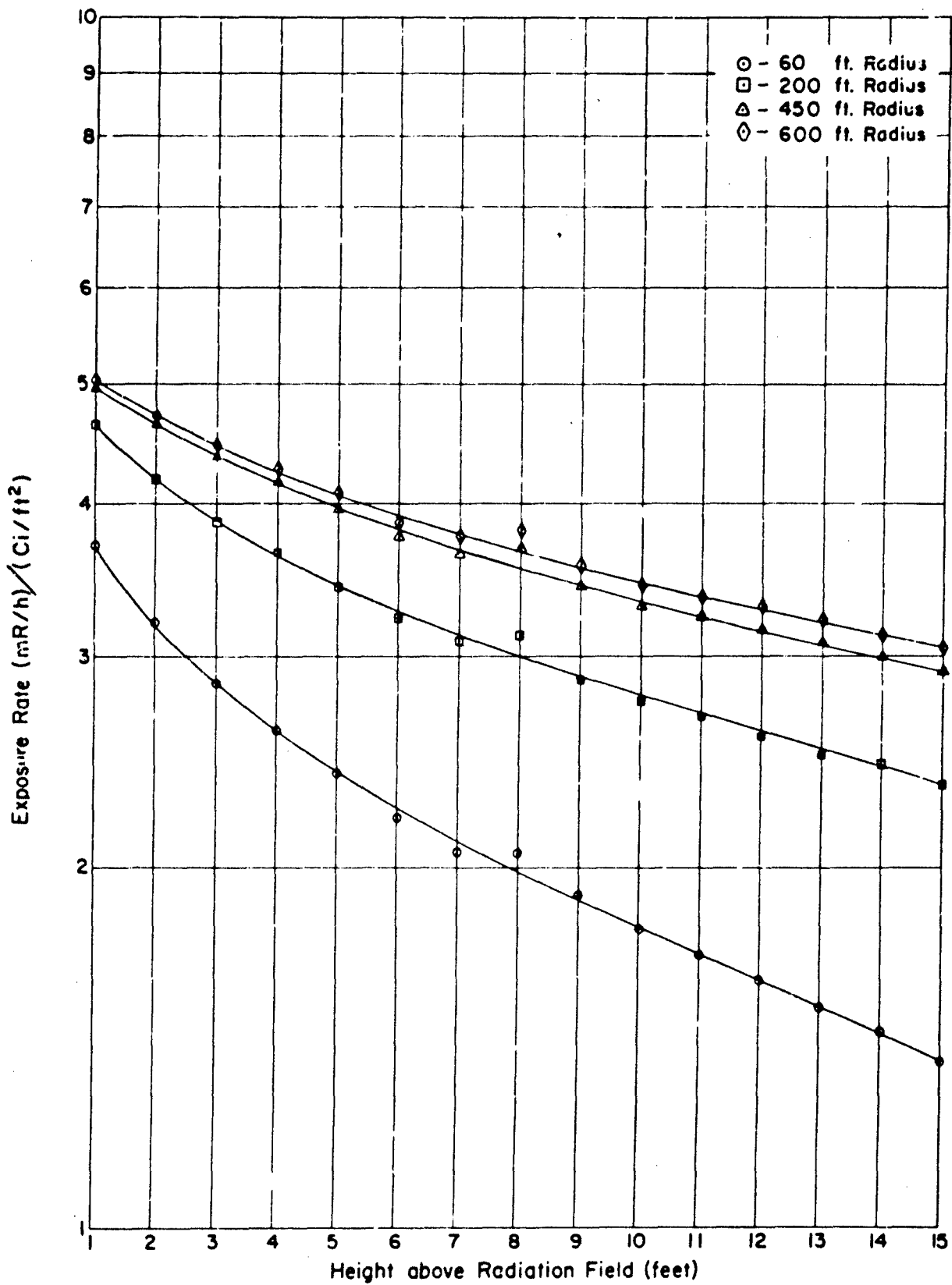


Figure C.1 Experimental exposure rates versus height above contaminated field.

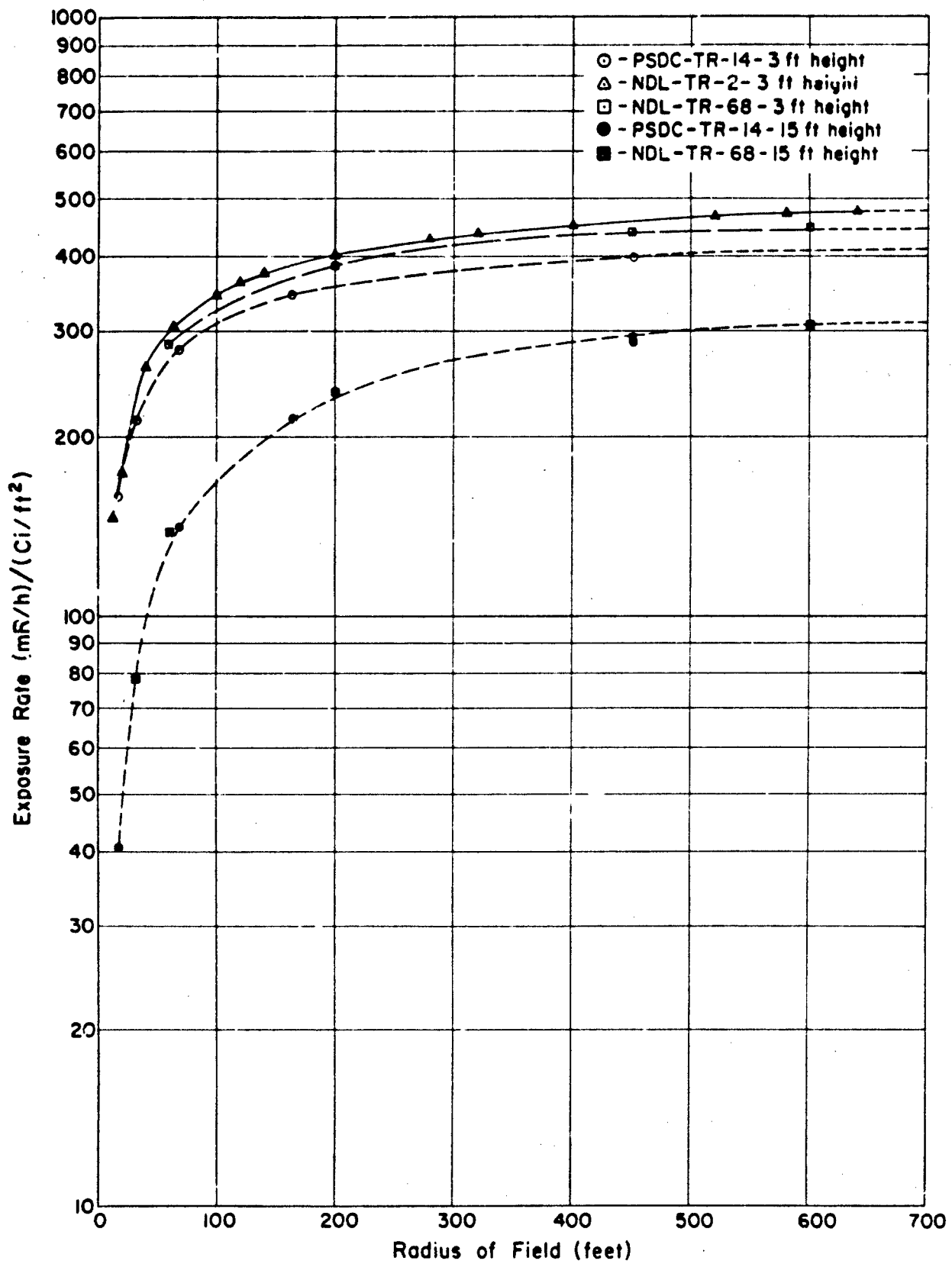


Figure C.2 Cumulative exposure rates versus radius of contaminated field as measured by NDL and PSDC.

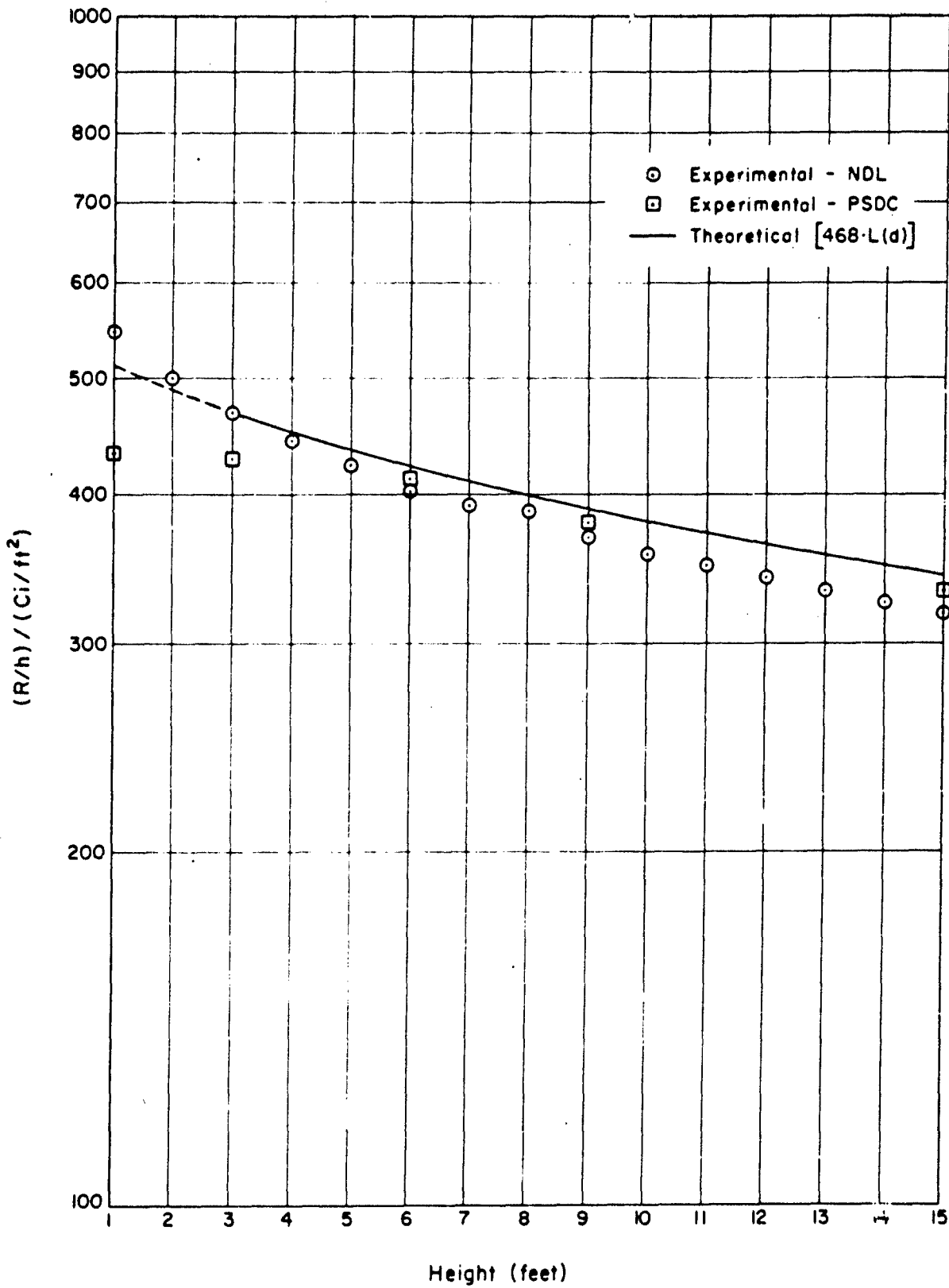


Figure C.3 Experimental and theoretical exposure rate versus height, d , above a radiation field.

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|--|--------|----|--------|----|--------|----|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Fallout, Simulated Free-Field Exposure Rates Far-Field Exposure Rates Gamma Radiation Radiation, Gamma Radiation, Scattered Point-Source Circulation Cobalt-60 Skyshine Reduction Factors Basement, Open, Concrete | | | | | | |

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