TECHNICAL OPERATIONS RESEARCH

PROTECTION FACTORS OF EMERGENCY SHELTERS IN A BRITISH RESIDENCE

By

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ABSTRACT

To check (1) the validity of the fallout protection factor calculations for residential structures given in British Home Office and U.S. OCD Engineering Manuals and (2) the validity of radiation scale modeling, the United States and the United Kingdom in a joint effort tested one full-scale typical residence (100 psf exterior walls) and two models thereof (50 and 100 psf exterior walls). Each house was tested empty and with various shelter configurations installed. Fallout contamination was simulated by pumping a multicurie encapsulated cobalt-60 source through plastic tubing surrounding the houses. The United States calculations agree with measured dose rates in the 50-psf wall house, while British calculations are slightly lower. Agreement between dose rates measured in the 100-psf wall full-scale and model houses was good at locations away from apertures. Full-scale and model experimental results are generally consistent with both British and U.S. calculations, which show a rectangular shelter to offer maximum protection.

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CHAPTER 1

INTRODUCTION

Early in 1962, the Office of Civil Defense (OCD) was approached by the British Home Office (HO) to cooperate in conducting model and full-scale tests to verify the procedure for the computation of fallout protection offered by residential structures containing emergency shelters. The British calculational procedure was based partly on theoretical work and partly on test data on the attenuation of gamma radiation by various types of building material. Since the results of the proposed tests offered an opportunity for further evaluation of the U.S. modeling technique applied to radiation shielding, OCD responded to the British request and the joint effort was undertaken.

The joint effort consisted of three series of tests:

Test Series	Exterior Wall Thickness (psf)	Dates (1963)
Model	50	March 18 - April 4
Full Scale	100	May 9 - June 1
Model	100	August 19 - September 6

The model and full-scale structures were tested empty and with various shelter configurations installed. Fallout contamination was simulated by pumping a cobalt-60 source through plastic tubing surrounding the structures. In this report, the results of tests on both the model and full-scale structures are compared with predictions given by British and by U.S. calculational procedures.

This report is primarily concerned with the results of U.S. measurements on the model structures, but it also gives data obtained in the initial phase of the U.K. full-scale tests at which two U.S. representatives (E. T. Clarke and J. F. Batter) assisted. Further measurements were carried out by the U.K. team later in the summer, details of which are being reported elsewhere.[1] Some preliminary results of these measurements are included here to aid in the overall comparison of the U.S. - U.K. findings.

CHAPTER 2

DESCRIPTION OF EXPERIMENT

THE MODELING TECHNIQUE

Theoretically, the radiation-dose distribution inside a structure due to hard gamma rays from radiation sources located outside the structure will be reproduced in a geometrically similar scale model if the densities of all materials comprising the structure, the surrounding ground, and the atmosphere are increased by the geometric scale factor. In practice, however, the problem of increasing densities by a factor large enough to be useful in reducing building dimensions makes it difficult to achieve the ideal. Steel was substituted for the masonry and other building materials of the full-scale structure to increase the density of the structural material without radically changing the atomic number and the corresponding cross sections of the materials. This gives an increase of approximately 3 in density compared with the required factor of about 12. The remaining factor of 4 was obtained by increasing the relative thickness of the walls, prior modeling experiments having shown that realistic dose rates can be obtained throughout a model if the wall and partition thicknesses do not exceed 10% of average dimensions of a given room.

Since it is impractical to scale the density of the atmosphere surrounding the model, skyshine was not properly reproduced in the experiment. However, since skyshine comprises a maximum of 10% of the dose rate for a zero thickness building and attenuates more rapidly than direct or structure-scattered radiation, the error due to neglect of skyshine should be no greater than this value.

The incomplete scaling of densities raises the additional problem of radiation penetrating the ground and entering the structure through its ground floor. To eliminate this mode of penetration, the model structure was placed on a 2-in.-thick lead slab covered with a 1/2-in.-thick iron plate. The lead reduces the radiation emerging from the ground floor due to gamma rays entering the ground surrounding the model and scattering upward through the base of the model. The iron plate allows radiation entering the structure above ground to rescatter within the structure in a manner similar to that in the full-scale building.

EXPERIMENTAL BUILDINGS

FULL-SCALE STRUCTURE

The structure selected for full-scale test was one located at the U.K.'s Civil Defense Training Center at Falfield, where a mock-up village had been erected primarily for CD rescue exercises. The building not only was representative of British urban construction, but also was situated in an area where experimentation with highly radioactive sources could be safely conducted. It consisted of a standard two-story duplex (two-family) building (Figures 1-5) with 50 psf masonry interior walls; the exterior walls, originally also 50 psf solid concrete block, had been thickened to 100 psf by addition of a course of brick on the inside surfaces. By error the model of this test structure was first constructed with 50 psf exterior and interior walls. This error was not discovered until the full series of tests had been run on the model structure. Thus the first series of model data presented refers to a model with all walls of 50 psf, while the second series was obtained from the model with 100 psf exterior walls.

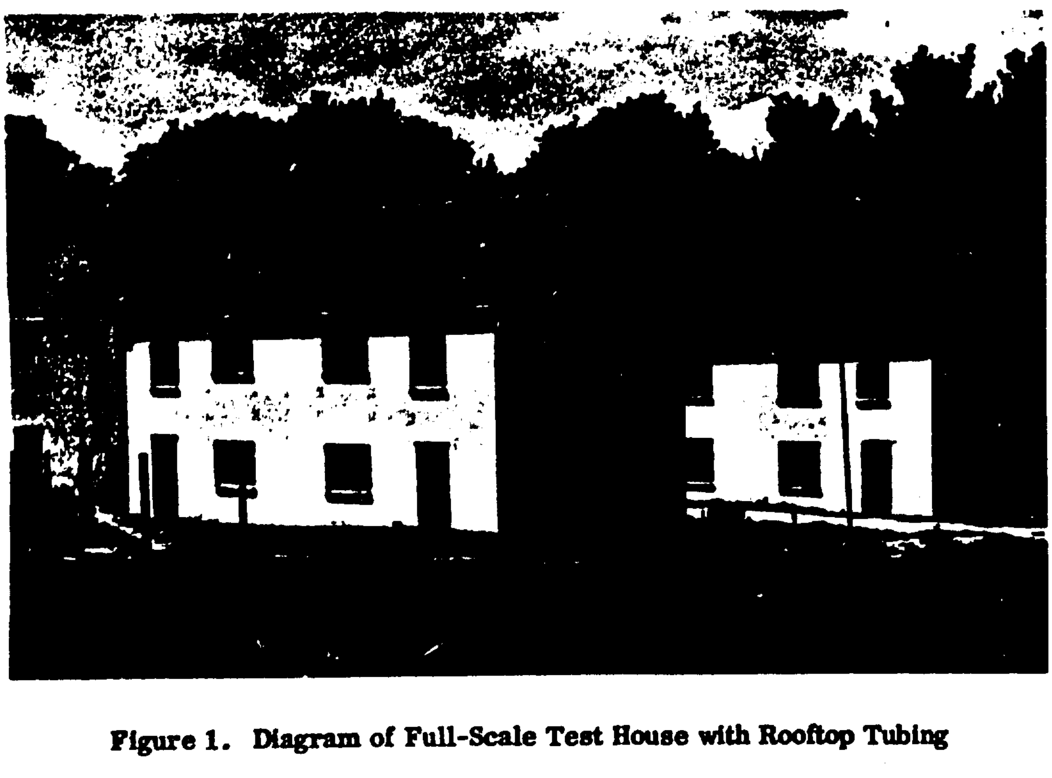


Figure 1. Diagram of Full-Scale Test House with Rooftop Tubing

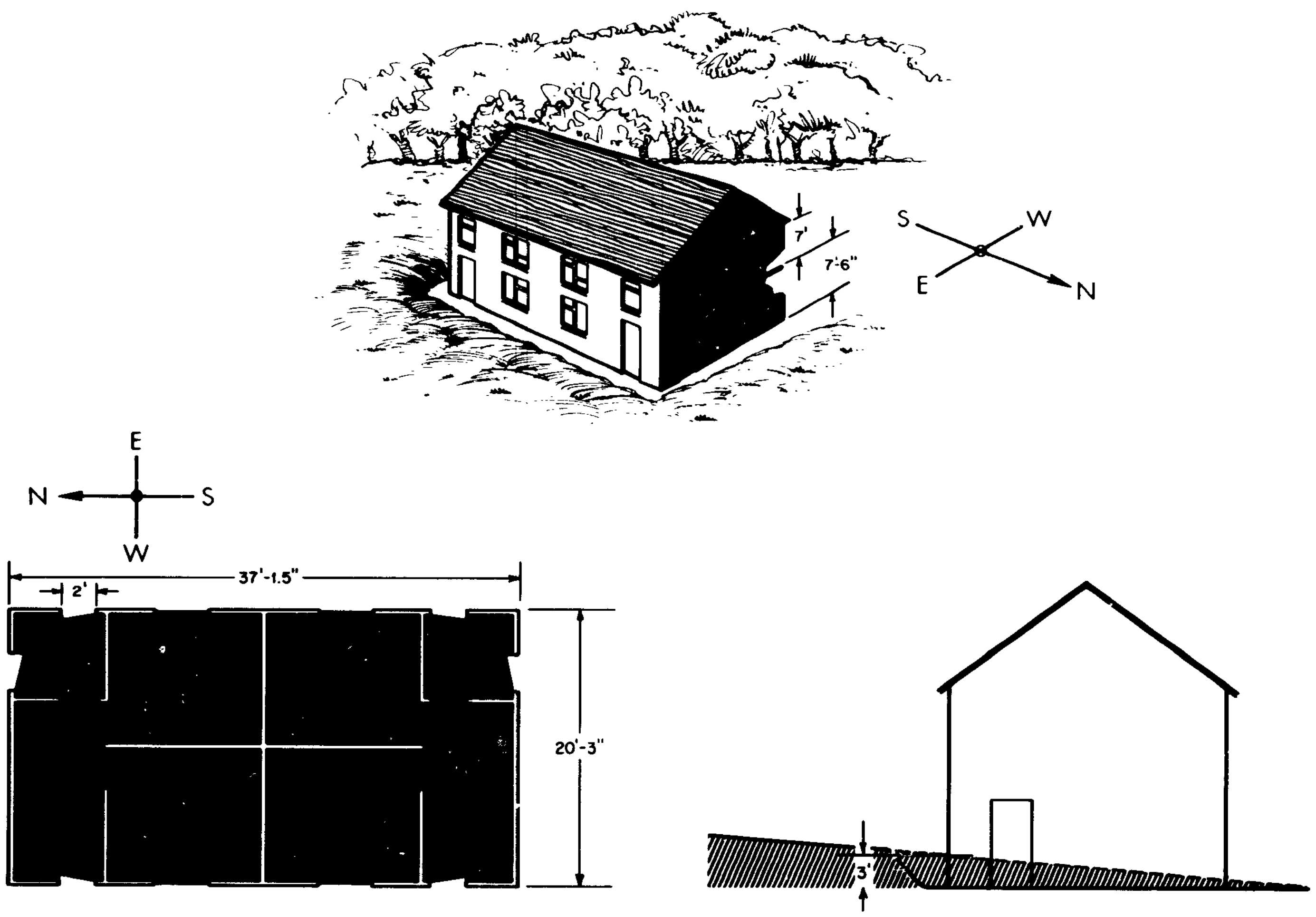


Figure 2. Diagram of Full-Scale Test Structure Showing Dimensions

Figure 3. Close-up of the Area Between the Full-Scale Test Structures

Figure 4. Rectangular Shelter Before Installation Within the Test Structure

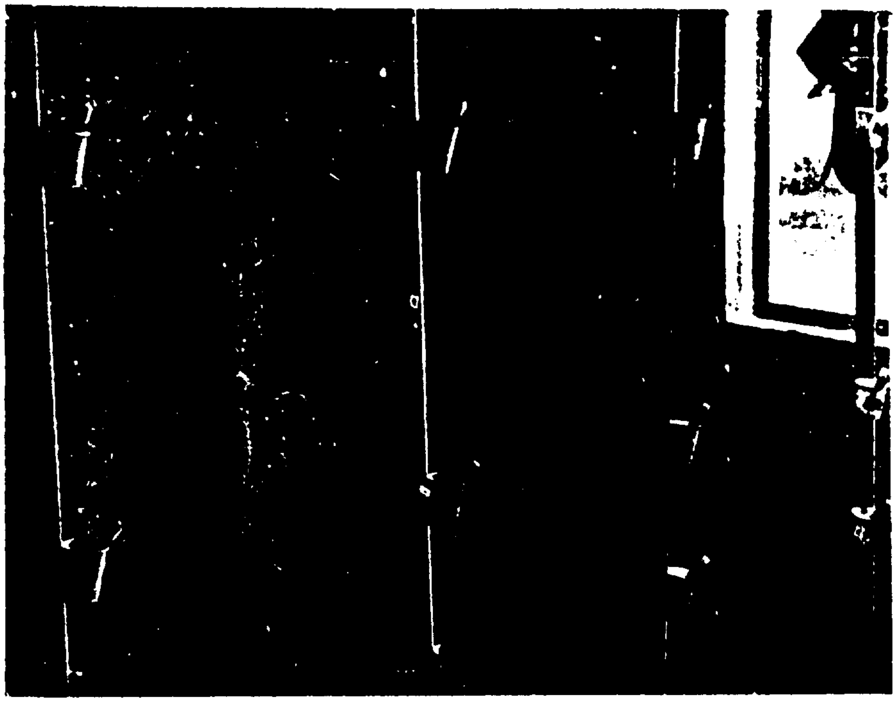


Figure 5. Interior of the Full-Scale Test House With Instrumentation Installed

MODEL STRUCTURE

The 12:1 scale-model experiments on this building were made at the OCD Modeling Facility at Technical Operations Research in Burlington, Massachusetts.[2] The model house was located in the center of the asphalt test area, as shown in Figure 6, together with dummy models of the neighboring houses. Since the ground about the full-scale structure sloped gently upward toward the east behind the house, a foundation was constructed to take this slope into consideration. The 50 psf model was thus tilted 8^{o} to simulate the full-scale house built on an 8^{o} sloping lot. A 1/2-in.-thick steel plate was laid in a sand-filled depression, over which a steel-covered 2-in.-thick lead plate was placed to minimize the radiation penetrating the ground and scattering up into the model. Figure 7 shows the model as it was constructed for the second series of tests; it is a view of the actual test building with the upper floor and roof removed.

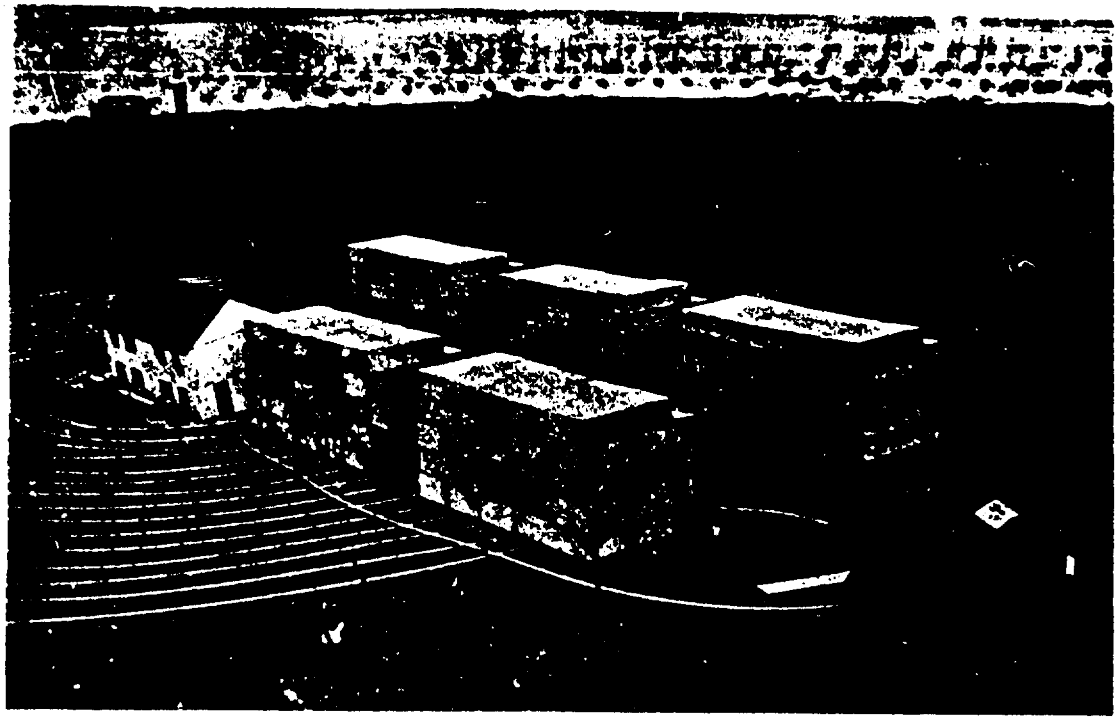
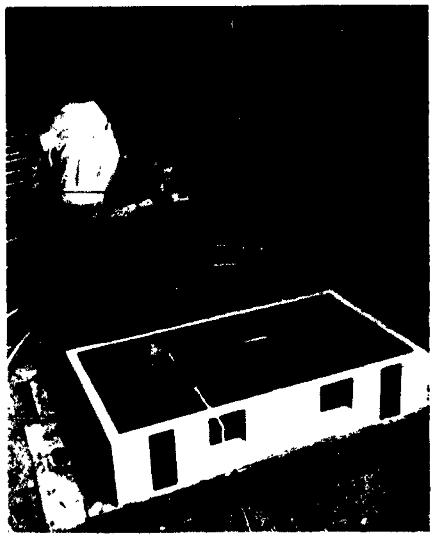


Figure 6. Interior View of Model Test Area

The second series of tests on the model with the 100 psf exterior walls was performed with the tilt reduced to 4^{o}, since the ground to the rear of the full-scale structure had been found to be actually only 18 in. above grade at the rear wall and the smaller angle would better represent the true situation.

Both models were scaled at a 12:1 ratio and constructed from hot rolled steel plates. The exterior walls and interior partitions of the first model were made 1-1/4-in. (50 psf) thick to duplicate the mass thickness of the original building. The second model was then obtained by adding 1-1/4 in. (50 psf) to the external walls and center partition of the north half of the model on the first floor. All second floor walls were identical with those located on the first floor except the additional 50 psf skin was not added. The second floor and roof were constructed separately to make them easily removable for access to the detectors. It was found that the average gross density of the surrounding houses was approximately that of concrete and hence could be modeled by solid concrete blocks stacked to the appropriate size. Figure 8 represents the complete test area.



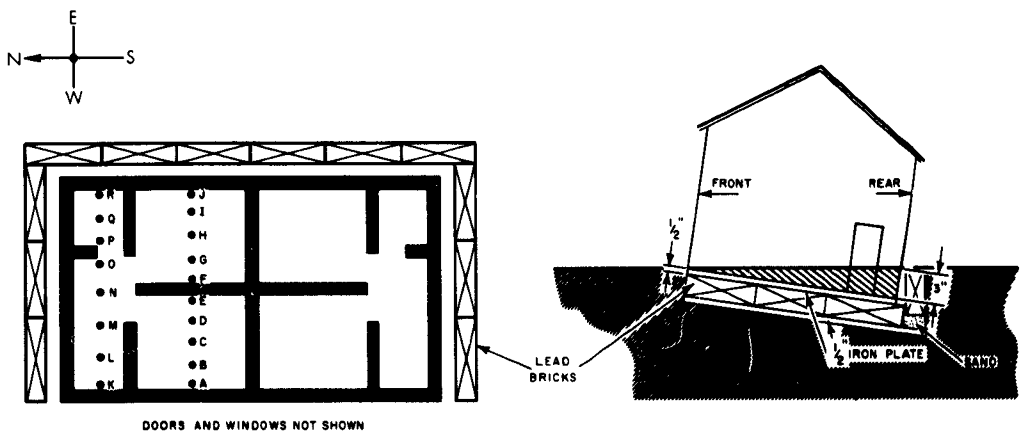


Figure 7. First Floor of Model Showing Dosimeter Locations

SHELTERS

Four "core" shelter designs were installed for attenuation measurements in both the full-scale and model structures. These designs were:

1. A simple lean-to shelter consisting of two ordinary doors (size 6 ft 6 in. x 2 ft 8 in.) leaning against the east wall of the sitting room at an angle of 60^{o} to the ground. Sandbags 4 in. thick were piled on these supports giving a mass thickness for the shelter of 65 psf. The model shelter was machined from 1-5/8-in. thick steel plate. Figure 9 shows the arrangement of this shelter in the model building. (Case 3)

2. A 65 psf A-frame shelter consisting of four doors at angles of 60^{o} to the floor with sandbags piled against them. This shelter as shown in Figure 10 was positioned in the center of the sitting room and was tested both with the shelter ends open and with 65 psf north end baffle. Figure 10 shows the model with 1-5/8-in. thick steel A-frame shelter and baffle. (Cases 4, 5)

3. A rectangular shelter constructed of sandbag walls and roof erected in the center of the sitting room. The roof was supported by two 2 ft 8 in. x 6 ft 6 in. doors. Four rectangular shelter designs were tested both in the model and full-scale structure:

(Case 6) a. 120 psf walls, 25 psf roof (3-in. walls, 5/8-in. roof)

(Case 7) b. 120 psf walls, 50 psf roof (3-in. walls, 1-1/4-in. roof)

(Case 8) c. 75 psf walls, 35 psf roof (1-7/8-in. walls, 7/8-in. roof)

(Case 9) d. 75 psf walls, 70 psf roof (1-7/8-in. walls, 1-3/4-in. roof).

A photograph of one of the full-scale shelters is shown in Figure 4; Figure 11 illustrates the test arrangement.

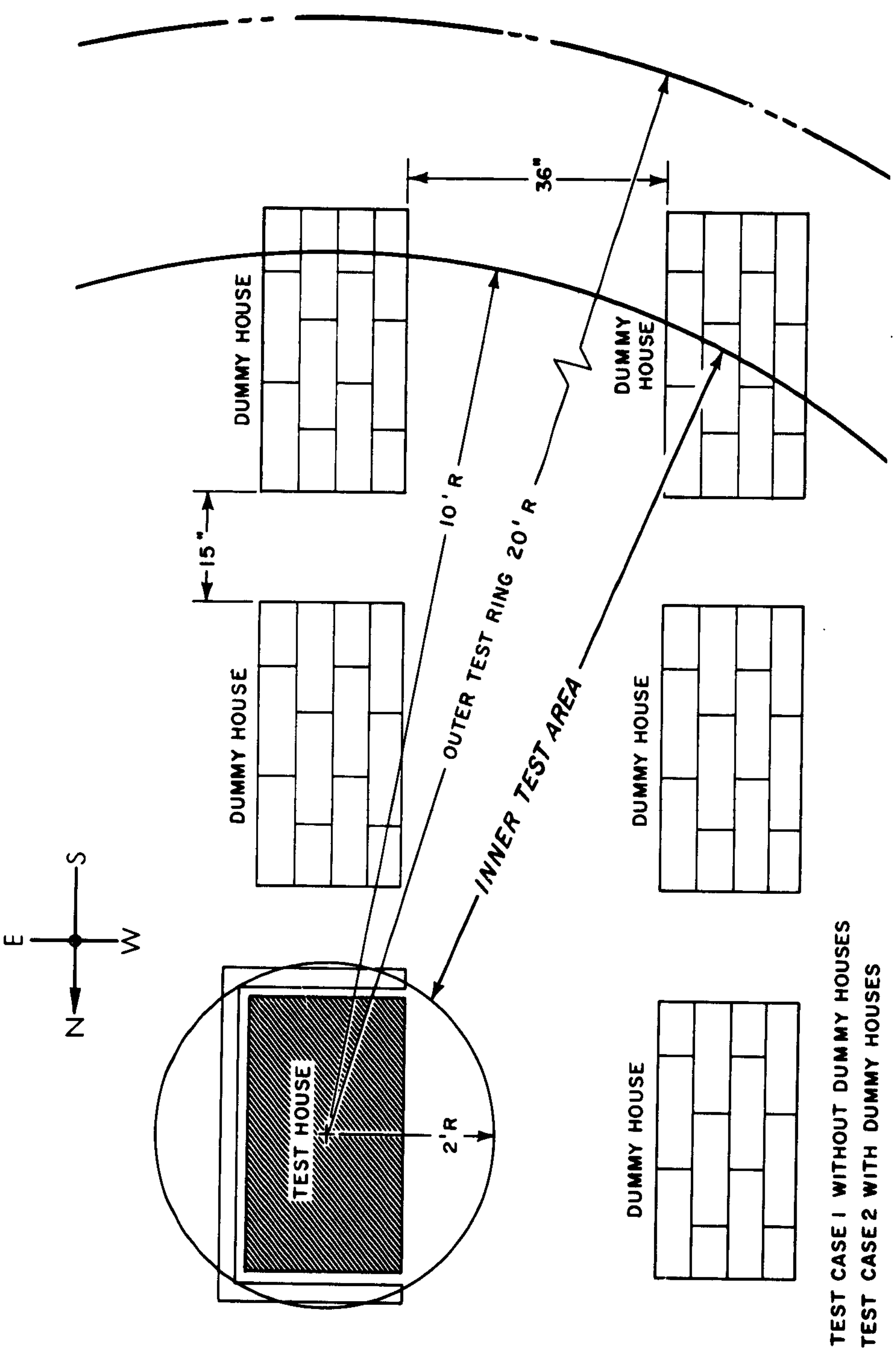


Figure 8. Diagram of Model Test Area

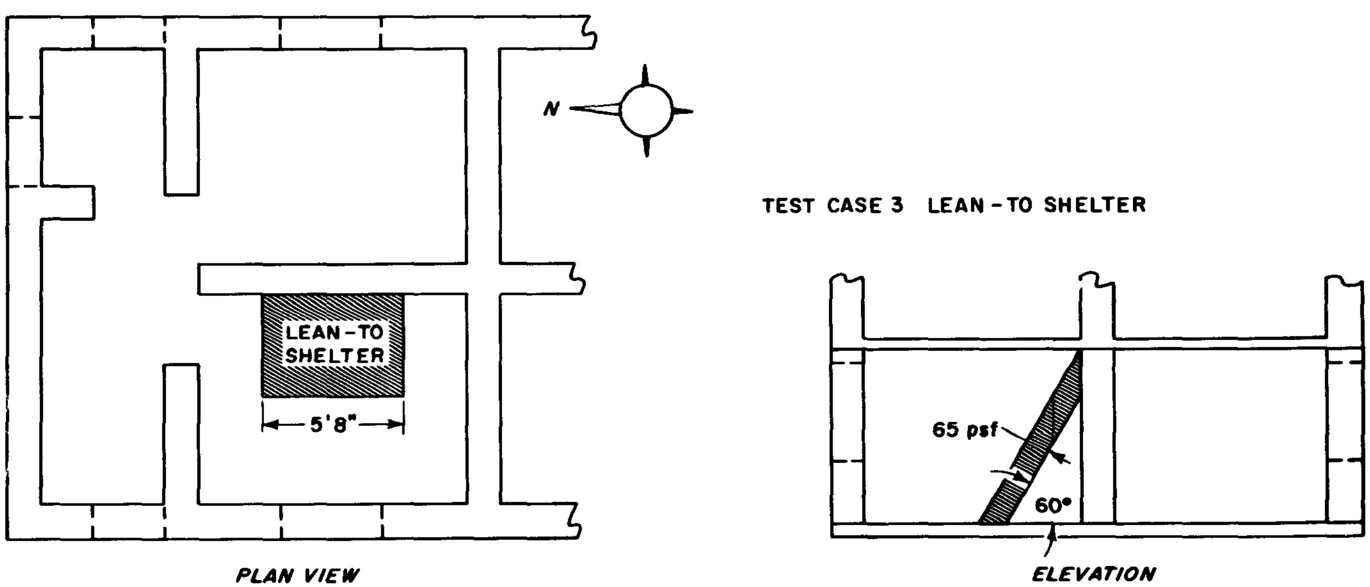


Figure 9. Diagram of Model Structure With Lean-To Shelter

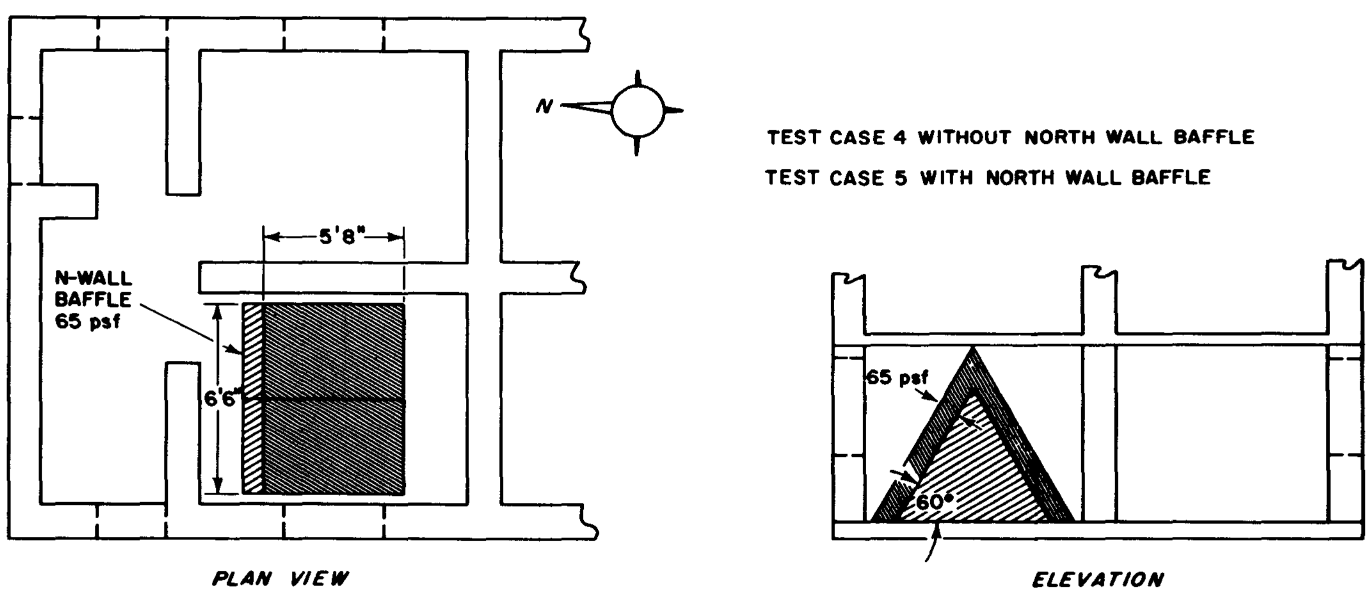
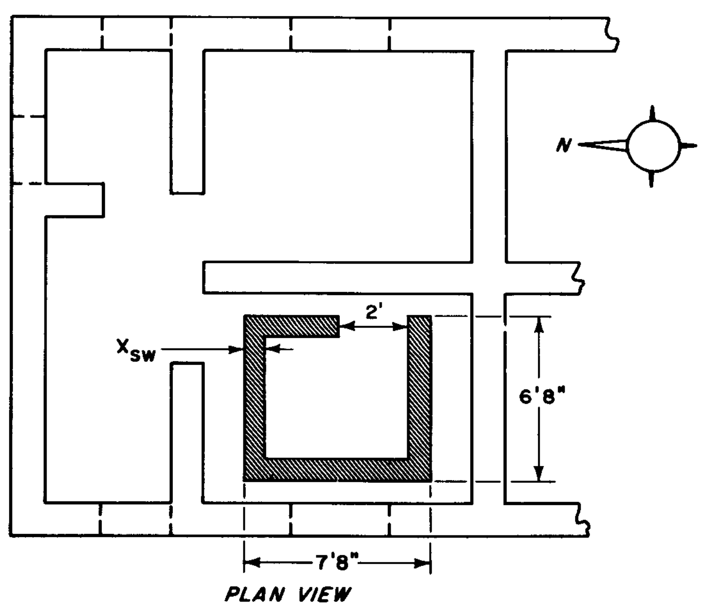


Figure 10. Diagram of Model Structure With A-Frame Shelter



TEST CASE	psf X_{SW}	psf X_{SC}
6	120	25
7	120	50
8	75	35
9	75	70

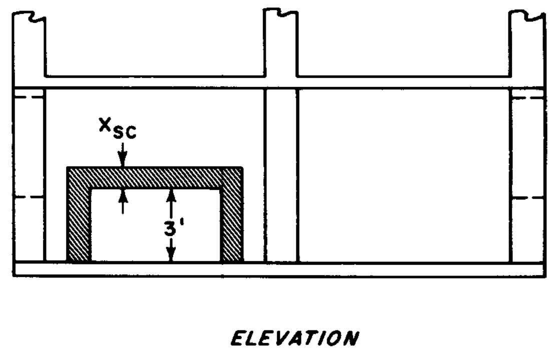


Figure 11. Diagram of Model Structure With Rectangular Shelter

4. An under-the-stairs shelter with the following arrangements of sandbags (Figure 12):

(Case 10) a. With the stairs and top landing sandbagged to a mass thickness of 64 psf

(Case 11) b. As in (a) but with the north wall of the building sandbagged to 76 psf adjacent to the shelter

(Case 12) c. As in (b) above but with passage wall (south wall of the shelter) sandbagged to 76 psf except for a 2-ft-wide shelter entrance

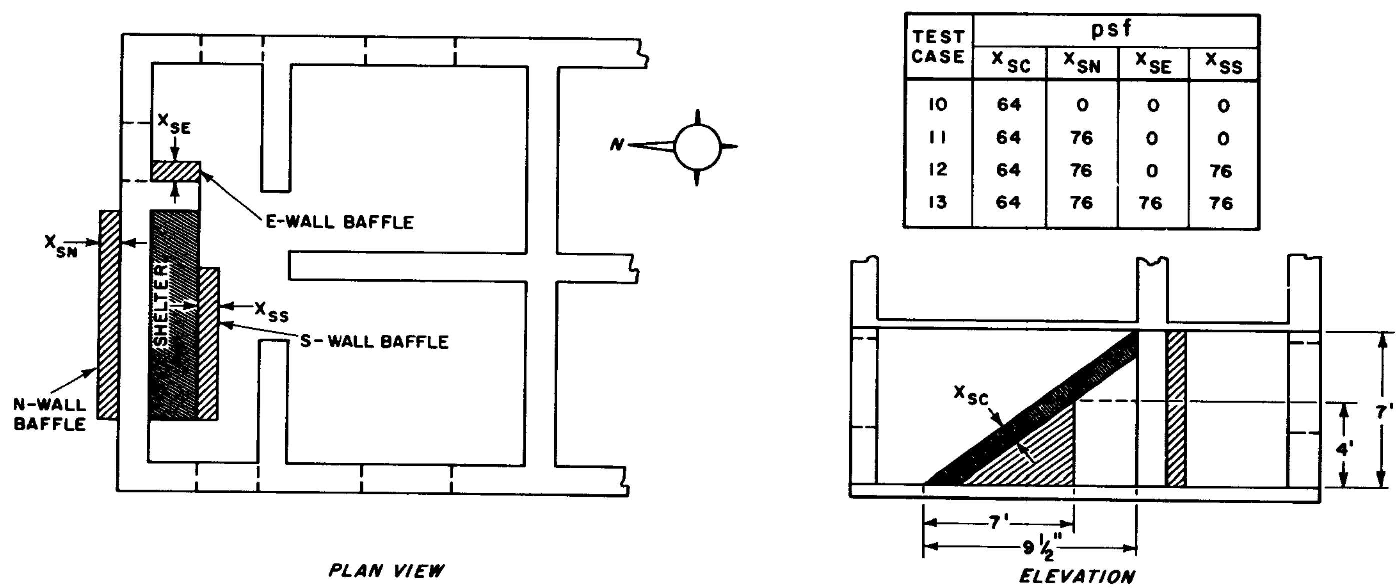
(Case 13) d. As in (c) above but with east shelter wall also sandbagged to 76 psf.

For the model under-the-stairs shelter, the roof mass thickness was simulated with 1-5/8 in. of steel and the 76 psf wall sandbagging with 1-7/8-in.-thick steel plate.

SIMULATION OF FALLOUT-CONTAMINATED AREAS

MODEL STRUCTURE

A uniform density of contamination surrounding the model house was simulated by pumping a 20-curie cobalt-60 source through properly arranged polyethylene tubing. Tubing was placed around the model in a spiral configuration with a 6-in. spacing. The spiral started 2 ft from the center of the model and extended to a radius of 10 ft representing a limited field of 120 ft diameter full scale. The source was pumped at a uniform velocity through the tubing, thus spending an equal amount of time in each square foot of the simulated area. Integrating radiation detectors used within the model accumulated the radiation effects from each increment of the tubing as the source passed through it. The dose accumulated at the end of an exposure was thus essentially equivalent to that which would have been received if the source were uniformly smeared over the entire simulated area.



TEST CASE	psf			
	X_{SC}	X_{SN}	X_{SE}	X_{SS}
10	64	0	0	0
11	64	76	0	0
12	64	76	0	76
13	64	76	76	76

Figure 12. Diagram of Model Structure With Stairway Shelter

Since it was not possible to place the tubing uniformly about the five duplex houses neighboring the test model (because of the minimum required bend radius of the tubing), the tubing was placed uniformly over the area with the surrounding houses removed. One-half in. thick steel plates were then laid between each row of tubing where the structures were to be located and the structures (represented by appropriately sized stacks of solid concrete block) placed upon these spacers. It was judged that the attenuation afforded by the structure while the source traveled under it was great enough to represent the real case of no fallout on the ground under the surrounding structures. Preliminary measurements with a detector at the center of the test house indicated a drop in radiation intensity by a factor of about 25 when the source passed under the "dummy" houses.

In addition to the inner test area a source ring 20 ft in radius was placed around the 50 psf test model to obtain data necessary for analytically estimating far-field dose rate effects. For the 100 psf model, the ring source radius was reduced to 10 ft since the full-scale tests had been conducted with a ring at 120 ft radius.

FULL-SCALE STRUCTURE

The experiments on the full-scale structure were performed with simulated areas of fallout contamination similar to those used in the model tests. However, in the full-scale structure the contamination was simulated up to the building walls (it was not possible to simulate contamination at locations very near the structure walls in the model because of the minimum-bend radius of the tubing); also, the contaminated area to a radius of 120 ft from the center of the structure was divided into an inner annulus with 4-ft tube spacing extending from the structure to a radius of 80 ft, and an outer annulus from 80 to 120 ft radius with 10-ft tube spacing.

RADIATION SOURCE CIRCULATION SYSTEM

Figure 13 shows the schematic diagram of the pumped source system used in both the model and full-scale tests to circulate the source through the polyethylene tubing of the simulated source fields. The output of the metering pumps forces the source assembly out of its container, through the area spread or ring of tubing at constant velocity, and back to the container. These pumps are valved in parallel

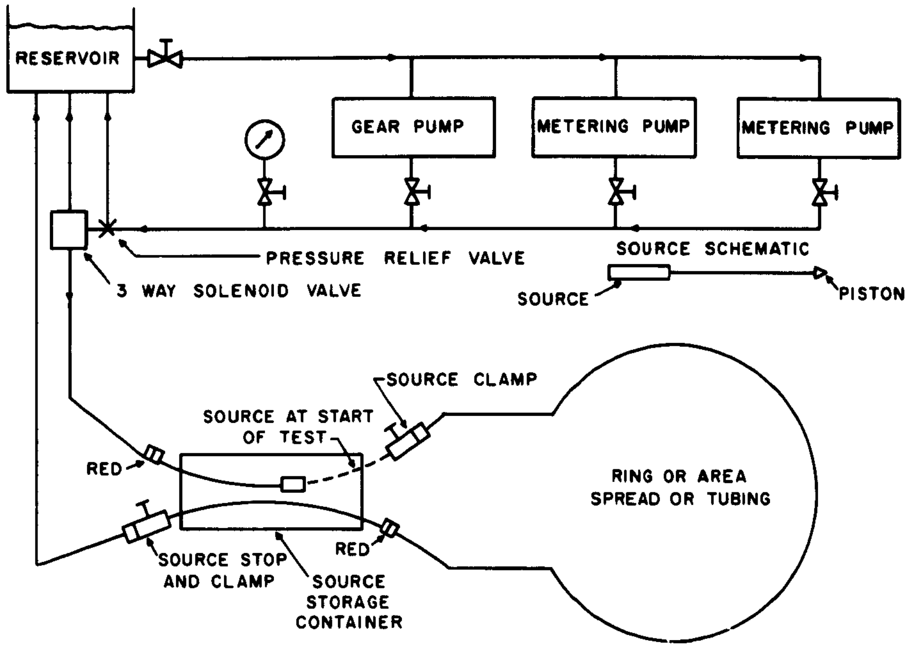


Figure 13. Diagram of Source Circulation System

to provide a versatile range of source velocities. A 3-way solenoid valve wired for remote operation permits either bypassing the pump output directly to the reservoir or diverting the flow to the source storage container and subsequently into the area spread of tubing. The gear pump is used for initially filling tubing with water and for rapid source movement where accurate velocity control is not required.

Each source assembly pumped through the polyethylene tubing consisted of an encapsulated cobalt-60 source attached by a stainless steel flexible leader to a piston with a leather hydraulic seal. The 20-curie cobalt-60 source used for the model experiments was pumped through 0.267-in. I.D. polyethylene tubing; the 93-curie source capsule used for the full-scale tests required 3/8-in. I.D. tubing.

Each 20-curie and 93-curie source storage container consisted of a lead-filled steel shell with two stainless steel tubes of the same internal diameter as the matching polyethylene tubing. These tubes were formed with a radius to prevent gamma ray streaming from the container and were equipped with special fittings to hold the source in a safe position within the container, to positively stop the source within the container on its return from the source field, and to enable the operator to easily hook up the pumping system and source area spread to the source container.

INSTRUMENTATION AND DOSIMETER CALIBRATION

The majority of the measurements in both the 50 and 100 psf model structures were made with Landsverk 2-roentgen L-81 dosimeters. These dosimeters were used wherever possible because of their relatively small size—1-5/8-in. long by 1/2-in. in diameter. Each instrument thus represented a cylinder 6 in. in diameter and 20 in. long in the full-scale structure. These instruments were read and charged using the compact portable dosimeter reader-charger instruments developed by Technical Operations, Inc. for field experimentation.[3,4] The principle of operation of this unit is to measure the charge required to restore the voltage across the ionization chamber terminals to its original value. The actual reading, proportional to the total electronic charge, must then be calibrated in terms of roentgens. The chamber-reader-charger combination was calibrated by measuring known doses from a cobalt-60 source standardized by the National Bureau of Standards. This was done on an essentially massless calibration range using source-to-detector distances less than one-fourth of the source and detector-to-ground distances to keep ground scattering effects to less than 1% of free air value.[5] The L-81 dosimeters were found to have a rather large amount of scatter in repeated identical experiments. Detectors were thus hand-selected for matched calibration characteristics to give dose rate characteristics with ± 5% full-scale accuracy.

The doses accumulated at the test locations in the full-scale British house were measured in a fashion similar to that used in the model tests. The detectors used, however, were self-reading dosimeters of three ranges: 0-20 mr, 0-200 mr, and 0-5 r. Since only two of the 0-20 mr chambers were available, their use was restricted to the most sheltered positions in each experiment. The 0-200 mr detectors were placed in all other positions (all positions were identical with those in the model structure) except where it was believed they would go off scale. In these few positions, 0-5 r detectors were used. Readings were obtained from these detectors by charging them to approximately zero dose, recording this zero reading, and subtracting it from the first reading at the conclusion of the exposure.

Each of the detectors used was calibrated by the U.K. AERE at Harwell. There was no opportunity during the full-scale trials to calibrate these detectors for direct comparison with the detectors used for the model studies. A secondary calibration was obtained by placing the 93-curie test source on the ground at a distance of 40 and 50 ft from detectors at 1-, 3-, and 6-ft heights, and combining these measurements with the known properties of the air-ground buildup factor.[6] A total of twenty-four data points were accumulated in this geometry. Analysis of these data showed the indicated doses averaged 1.05 times the calculated doses, with over 80% of the data falling within ± 3% of this value. This discrepancy between instruments calibrated at Harwell and doses produced by a National Bureau of Standards calibrated source is at present unexplained. Since this discrepancy is small and within the estimated error for the entire experiment, it is neglected in the presentation of full-scale results in the experimental section, i.e., the British dosimeters were assumed to be identical in response with those used in the model tests.

CHAPTER 3

EXPERIMENTAL DATA

The structure selected for experimentation by the British Home Office as typical of those in Great Britain was a duplex residential structure, symmetrical to the right and left of the center wall (see Figure 1, p. 3).

Dosimeters were arranged in two vertical planes across the width of the first floor of one half of the structure, both model and full-scale, as shown in Figures 7 and 14. One series of dosimeters provided horizontal traverses through the center of the living room and sitting room at heights of 1, 2, and 4 ft above the floor. A similar set of horizontal traverses extended across the kitchen and the stairwell at a full-scale distance of 18 in. from the outside north walls of these rooms. Dosimeters for each horizontal traverse were evenly spaced, starting at 6 in. from the east and west walls. All fallout shelters installed in the structure were centered on one of these two dosimeter planes. The physical size of the shelters sometimes restricted the actual number of dosimeter positions that could be used during a particular experiment, especially in the model structures.

MODEL AND FULL-SCALE TEST DATA

Experiments on both model and full-scale structures were conducted both with and without shelters installed. Dose rate measurements were made for the annular contaminated fields previously described. Also, measurements with the five surrounding model houses removed were made to determine their effect on dose rates within the test building. All dosimeter readings were normalized to a roentgen-per-hour basis from a source density of either 1 curie/ft^{2*} for annular areas or to 1 curie/ft of circumference for ring sources.

Additional tests on the full-scale structure determined the effects of roof contamination.

The data obtained in these tests series are summarized in Tables 2 through 17, while Table 1 provides a brief description of each table.

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*This source density produces a field of 497 r/hr at 3 ft above an infinite, smooth, uniformly-contaminated plane.[7]

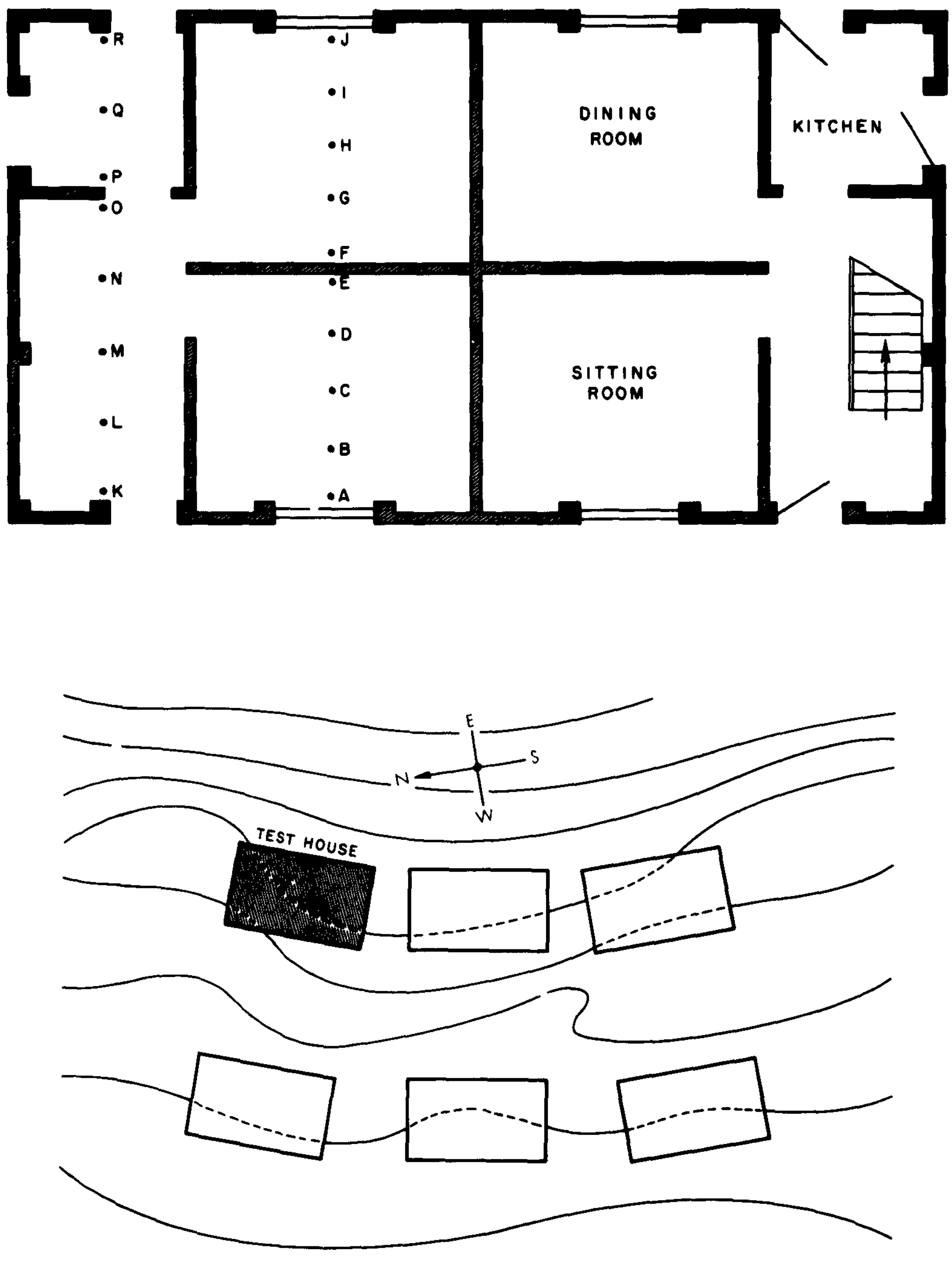

Figure 14. Detector Positions

TABLE 1

DATA TABLES

Test	Exterior Wall Thickness (psf)	Detector Position (See Figure 14)	Radius of Simulated Area (full-scale) (ft)	Table No.
Model	50	A-J	24 → 120	2
Model	50	A-J	Ring 240	3
Model	50	K-R	24 → 120	4
Model	50	K-R	Ring 240	5
Model	100	A-J	24 → 120	6
Model	100	A-J	Ring 120	7
Model	100	K-R	24 → 120	8
Model	100	K-R	Ring 120	9
Full Scale	100	A-J	16.1 → 80	10
Full Scale	100	A-J	80 → 120	11
Full Scale	100	A-J	Ring 120	12*
Full Scale	100	K-R	16.1 → 80	13
Full Scale	100	K-R	80 → 120	14
Full Scale	100	K-R	Ring 120	15*
Full Scale	100	A-J	Roof	16
Full Scale	100	K-R	Roof	17

*Note that the data for the full scale ring source measurements have been converted to far-field dose rates (see Chapter 4).

TABLE 2

MODEL SITTING AND DINING ROOM TRAVERSE, 50-PSF EXTERNAL WALLS — DOSE RATE FROM INNER CONTAMINATED AREA FROM 2- TO 10-FT RADIUS

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (in.)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
1	Surrounding houses removed	1	23	23	26	22	14	9.9	7.2	5.8	3.9	2.2
		2	32	30	26	23	22	22	20	17	8.7	4.7
		4	86	59	49	34	23	29	40	42	51	75
2	With surrounding houses	1	22	20	20	19	9.9	7.7	8.3	9.0	6.1	1.7
		2	23	23	23	21	18	22	23	15	11	5.5
		4	61	44	37	28	24	29	33	40	52	73
3	65-psf lean-to shelter at position E	1	27	23	22	--	7.7	8.4	7.7	7.1	5.4	2.6
		2	27	27	25	--	13	23	16	13	11	5.9
		4	59	47	39	31	--	32	43	50	50	67
4	65-psf "A" frame shelter at position C	1	23	--	8.2	--	14	9.0	9.0	7.5	6.2	4.5
		2	27	--	9.9	--	19	24	27	18	9.9	6.2
		4	62	41	--	17	26	32	41	43	43	56
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	18	--	5.0	--	8.2	8.2	9.9	8.9	5.5	4.1
		2	20	--	5.7	--	14	21	19	14	9.9	6.8
		4	60	35	--	13	16	31	34	41	50	68
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	--	--	1.8	--	--	9.0	9.9	8.6	65	4.5
		2	--	--	2.9	--	--	20	23	15	12	6.7
		4	--	--	--	--	--	31	34	39	50	68
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	--	--	1.5	--	--	11	9.0	11	6.7	4.9
		2	--	--	2.4	--	--	22	24	19	9.0	7.3
		4	--	--	--	--	--	34	37	41	50	67
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	--	--	4.3	--	--	6.3	5.0	7.6	5.7	3.8
		2	--	--	4.8	--	--	20	23	15	11	5.7
		4	--	--	--	--	--	31	36	40	49	66
9	Rectangular shelter of 75-psf walls, 70-psf ceiling located at position C	1	--	--	3.6	--	--	9.9	13	7.8	6.5	3.9
		2	--	--	4.8	--	--	20	23	18	13	5.9
		4	--	--	--	--	--	31	38	41	50	68
10	Stairway shelter of 64 psf located at position N	1	23	20	20	14	9.9	8.1	9.9	8.5	6.0	4.2
		2	25	23	23	20	18	24	23	18	9.0	6.0
		4	60	47	32	22	21	32	38	40	49	68
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	22	20	19	15	12	9.9	5.6	6.3	5.9	4.9
		2	29	22	24	18	13	20	22	21	8.7	7.7
		4	62	47	29	19	14	26	33	41	49	66
12	Same as 11 plus south wall baffle of 76 psf	1	22	20	17	13	7.2	8.6	7.3	6.5	5.9	4.5
		2	27	23	24	19	15	22	21	14	9.0	6.2
		4	64	45	32	22	22	28	31	37	45	53
13	Same as 12 plus east wall baffle of 76 psf	1	23	21	18	14	9.9	9.0	8.3	7.6	5.9	4.1
		2	26	22	24	18	16	19	19	11	9.9	7.2
		4	63	45	33	25	23	29	40	41	50	65

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TABLE 3

MODEL SITTING AND DINING ROOM TRAVERSE, 50-PSF EXTERNAL WALLS – DOSE RATE FROM OUTER CONTAMINATED RING OF 20-FT RADIUS

Data normalized to (r/hr)/(curie/ft)

Test Case	Structure	Detector Height (in.)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
1	Surrounding houses removed	1	0.83	0.72	0.57	0.48	0.35	0.22	0.19	0.13	0.17	0.077
		2	0.89	0.82	0.90	0.68	0.64	0.55	0.49	0.31	0.31	0.18
		4	2.0	1.7	1.3	1.4	0.99	0.89	1.1	1.2	1.5	2.3
2	With surrounding houses	1	0.27	0.38	0.41	0.41	0.32	0.19	0.32	0.21	0.18	0.14
		2	0.50	0.45	0.51	0.50	0.59	0.50	0.45	0.33	0.27	0.18
		4	1.2	0.76	0.59	0.59	0.59	0.90	1.1	1.2	1.4	1.9
3	65-psf lean-to shelter at position E	1	0.28	0.24	0.28	--	0.11	0.15	0.19	0.17	0.14	0.046
		2	0.32	0.31	0.31	--	0.30	0.23	0.31	0.26	0.17	0.13
		4	0.69	0.49	0.41	0.33	--	1.2	1.5	1.2	1.4	2.3
4	65-psf "A" frame shelter at position C	1	0.30	--	0.12	--	--	0.21	0.16	0.16	0.14	0.075
		2	0.27	--	0.11	--	0.32	1.2	0.38	0.23	0.21	0.14
		4	0.71	2.0	--	0.99	0.38	1.9	0.99	1.1	1.4	2.2
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	0.19	--	0.062	--	0.15	0.19	0.19	0.19	0.13	0.072
		2	0.26	--	0.079	--	0.24	0.37	0.30	0.19	0.19	0.15
		4	0.53	0.45	--	0.33	0.33	0.77	0.83	0.99	1.1	1.8
6	Rectangular shelter of 120-psf walls, 25-psf ceiling at position C	1	--	--	0.042	--	--	0.24	0.26	0.25	0.17	0.031
		2	--	--	0.063	--	--	0.57	0.36	0.37	0.28	0.19
		4	--	--	--	--	--	0.99	1.1	1.2	1.4	1.5
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	--	--	0.038	--	--	0.16	0.18	0.099	0.11	0.14
		2	--	--	0.063	--	--	0.36	0.29	0.25	0.15	0.15
		4	--	--	--	--	--	0.74	0.90	0.99	1.4	1.4
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	--	--	0.097	--	--	0.16	0.23	0.20	0.14	0.12
		2	--	--	0.15	--	--	0.35	0.32	0.27	0.23	--
		4	--	--	--	--	--	0.69	0.84	0.99	1.2	1.4
9	Rectangular shelter of 75-psf walls, 70-psf ceiling located at position C	1	--	--	0.083	--	--	0.17	0.18	0.15	0.12	0.063
		2	--	--	0.12	--	--	0.32	0.31	0.25	0.22	0.13
		4	--	--	--	--	--	0.73	0.78	0.90	1.1	1.4
10	Stairway shelter of 64 psf located at position N	1	0.37	0.32	0.27	0.29	0.16	0.22	0.16	0.27	0.19	0.14
		2	0.43	0.48	0.40	0.46	0.35	0.50	0.30	0.29	0.19	0.14
		4	0.99	0.76	0.50	0.34	0.41	0.87	0.81	0.99	1.1	1.6
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	0.33	0.37	0.32	0.23	0.17	0.15	0.13	0.26	0.15	0.13
		2	0.38	0.38	0.37	0.33	0.37	0.37	0.29	0.26	0.17	0.15
		4	0.80	0.65	0.53	0.35	0.42	0.65	0.83	0.89	1.2	1.7
12	Same as 11 plus south wall baffle of 76 psf	1	0.30	0.24	0.30	0.23	0.18	0.14	0.12	0.16	0.14	0.090
		2	0.36	0.36	0.32	0.39	0.32	0.39	0.30	0.20	0.18	--
		4	0.64	0.59	0.63	0.60	0.54	0.77	0.90	0.99	1.2	1.5
13	Same as 12 plus east wall baffle of 76 psf	1	0.38	0.35	0.27	0.22	0.16	--	0.14	0.18	0.24	0.081
		2	0.40	0.38	0.38	0.29	0.33	0.49	--	0.20	0.24	0.16
		4	0.90	0.75	--	0.41	0.50	9.90	--	--	1.4	1.6

TABLE 4

MODEL KITCHEN AND STAIRWAY TRAVERSE, 50-PSF EXTERNAL WALLS — DOSE RATE FROM INNER CONTAMINATED AREA FROM 2- TO 10-FT RADIUS

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (in.)	Detector Positions							
			K	L	M	N	O	P	Q	R
1	Surrounding houses removed	1	61	55	38	19	12	6.0	3.1	3.2
		2	65	58	51	40	31	49	35	11
		4	68	61	59	51	50	69	77	66
2	With surrounding houses	1	49	47	32	24	14	6.7	6.6	4.4
		2	52	47	42	32	24	36	30	14
		4	62	50	44	49	43	59	61	69
3	65-psf lean-to shelter at position E	1	53	49	32	17	11	5.9	5.4	3.8
		2	56	50	46	35	28	52	36	9.0
		4	57	53	59	50	47	74	69	65
4	65-psf "A" frame shelter at position C	1	53	45	40	23	12	5.7	5.0	4.5
		2	61	58	49	40	34	50	34	9.9
		4	69	62	64	50	42	77	77	69
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	37	43	31	19	9.9	8.9	6.2	6.8
		2	56	54	41	37	30	49	35	11
		4	59	63	49	42	39	72	73	59
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	51	44	36	20	12	6.9	5.9	4.0
		2	61	54	43	37	32	50	34	9.9
		4	59	63	51	44	42	72	73	64
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	51	44	32	20	12	6.7	7.0	3.6
		2	55	55	44	41	35	50	37	11
		4	61	63	57	50	47	73	78	60
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	58	44	35	24	12	6.0	6.0	3.8
		2	61	54	42	41	36	45	44	9.9
		4	62	61	56	48	47	72	72	6.0
9	Rectangular shelter of 75-psf walls, 70-psf ceiling located at position C	1	51	45	35	17	9.9	6.5	7.2	5.2
		2	59	56	45	41	35	49	45	9.9
		4	65	61	56	49	47	78	77	60
10	Stairway shelter of 64 psf located at position N	1	62	53	21	12	9.0	7.4	6.7	5.7
		2	68	65	--	33	28	53	37	11
		4	71	71	59	41	43	77	73	62
11	Stairway shelter of 64-psf with north wall baffle of 76 psf located at position N	1	49	41	6.3	7.0	7.0	5.6	8.4	3.5
		2	50	42	--	12	11	36	27	11
		4	59	53	37	16	21	77	67	62
12	Same as 11 plus south wall baffle of 76 psf	1	49	36	9.9	5.1	5.6	6.9	6.0	4.1
		2	58	49	--	9.9	16	37	29	14
		4	61	58	37	16	23	67	74	78
13	Same as 12 plus east wall baffle of 76 psf	1	54	39	7.2	5.9	5.4	--	6.5	5.0
		2	61	48	--	9.9	12	--	28	14
		4	64	59	41	14	20	--	63	67

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TABLE 5

MODEL KITCHEN AND STAIRWAY TRAVERSE, 50-PSF EXTERNAL WALLS — DOSE RATE FROM OUTER CONTAMINATED RING OF 20-FT RADIUS

Data normalized to (r/hr)/(curie/ft)

Test Case	Structure	Detector Height (in.)	Detector Positions							
			K	L	M	N	O	P	Q	R
1	Surrounding houses removed	1	1.2	1.1	0.59	0.26	0.19	0.17	0.17	0.12
		2	1.5	1.4	1.1	0.73	0.49	0.49	0.37	0.13
		4	1.4	1.9	0.99	1.1	0.99	1.5	1.9	1.4
2	With surrounding houses	1	0.90	0.84	0.39	0.25	0.14	0.14	0.14	0.12
		2	1.2	1.1	0.89	0.65	0.50	0.56	0.45	0.18
		4	1.2	1.2	0.89	0.99	1.1	1.9	1.7	1.4
3	65-psf lean-to shelter at position E	1	0.76	0.87	0.35	0.20	0.14	0.13	0.14	0.090
		2	0.68	0.76	0.80	0.59	0.34	0.36	0.40	0.15
		4	0.99	1.1	0.99	0.86	0.72	1.4	1.6	1.4
4	65-psf "A" frame shelter at position C	1	0.85	0.65	0.38	0.24	0.20	0.16	0.15	0.090
		2	1.1	0.99	0.88	0.65	0.41	0.59	0.63	0.11
		4	1.1	1.1	0.99	1.1	0.85	1.9	2.0	1.5
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	0.80	0.71	0.35	0.23	0.15	0.13	0.13	0.090
		2	1.1	0.99	0.74	0.51	0.35	0.32	0.28	0.15
		4	0.99	1.1	0.80	0.74	0.74	1.4	1.4	1.3
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	0.090	0.99	0.48	0.35	0.19	0.19	0.17	0.20
		2	1.2	1.3	0.99	0.83	0.59	0.69	0.43	0.67
		4	1.2	1.4	1.1	1.1	0.99	1.8	1.7	1.4
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	0.80	0.77	0.40	0.26	0.16	0.15	0.14	0.14
		2	1.3	0.99	0.80	0.64	0.44	0.37	0.29	0.15
		4	1.1	1.1	0.90	0.90	0.80	1.8	1.6	1.4
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	0.74	0.61	0.30	0.23	0.16	0.16	0.15	0.14
		2	0.90	0.99	0.77	0.56	0.36	0.32	0.30	0.15
		4	0.90	1.1	0.99	0.73	--	1.5	1.5	1.3
9	Rectangular shelter of 75-psf walls, 70-psf ceiling located at position C	1	0.77	0.63	0.32	0.20	0.15	0.15	0.13	0.13
		2	0.99	0.90	0.77	0.59	0.35	0.29	0.28	0.13
		4	0.86	0.86	0.86	0.70	0.82	1.5	1.4	1.2
10	Stairway shelter of 64 psf located at position N	1	0.70	0.52	0.22	0.16	0.18	0.13	0.21	0.082
		2	0.81	0.67	--	0.32	0.19	0.27	0.27	0.19
		4	0.85	1.2	0.85	0.73	0.85	1.4	1.4	1.3
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	0.74	0.50	--	0.13	0.13	0.077	0.15	0.077
		2	0.90	0.71	--	0.20	0.13	0.29	0.33	0.13
		4	0.90	1.1	0.68	0.35	0.42	1.4	1.4	1.4
12	Same as 11 plus south wall baffle of 76 psf	1	0.71	0.48	0.099	0.086	0.025	0.23	0.14	0.090
		2	0.79	0.59	--	0.15	0.12	0.26	0.26	0.14
		4	0.85	0.85	0.59	0.36	0.48	1.5	1.4	1.2
13	Same as 12 plus east wall baffle of 76 psf	1	0.77	--	0.090	--	--	--	--	0.099
		2	--	--	--	0.14	0.12	--	--	0.16
		4	0.86	0.90	0.83	0.26	0.47	--	1.6	--

TABLE 6

MODEL SITTING AND DINING ROOM TRAVERSE, 100-PSF EXTERNAL WALLS — DOSE RATE FROM INNER CONTAMINATED AREA FROM 2- TO 10-FT RADIUS

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (in.)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
2	With surrounding houses	1	8.4	8.1	8.1	7.4	4.4	7.4	--	9.3	--	6.7
		2	8.8	9.3	9.3	9.8	9.8	10	--	11	--	13
		3	32	17	14	11	13	21	--	29	--	57
		4	41	29	22	17	16	22	--	27	--	57
3	65-psf lean-to shelter at position E	1	7.6	8.6	8.6	--	4.1	9.1	--	10	--	6.5
		2	10	11	10	--	6.3	13	--	12	--	12
		3	33	11	12	--	--	20	--	33	--	56
		4	37	26	20	14	--	22	--	35	--	59
4	65-psf "A" frame shelter at position C	1	7.3	--	4.6	--	--	8.3	--	9.5	--	7.5
		2	9.7	--	4.9	--	--	16	--	12	--	12
		3	38	--	--	--	13	20	--	34	--	49
		4	38	--	--	--	12	23	--	35	--	57
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	6.6	--	2.1	--	3.8	6.6	--	10	--	6.2
		2	8.2	--	2.7	--	7.2	12	--	13	--	13
		3	31	--	--	--	8.6	20	--	29	--	54
		4	36	--	--	--	12	24	--	36	--	56
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	--	--	0.95	--	--	7.9	--	11	--	6.6
		2	--	--	1.4	--	--	13	--	11	11	11
		3	--	--	--	--	--	20	23	32	38	55
		4	38	26	13	13	11	23	26	33	38	63
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	--	--	0.78	--	--	8.9	8.1	9.4	8.9	6.5
		2	--	--	1.1	--	--	11	12	11	11	12
		3	--	--	--	--	--	20	26	31	35	53
		4	--	--	--	--	--	22	26	33	39	57
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	--	--	1.9	--	--	7.5	--	10	--	7.5
		2	--	--	2.5	--	--	12	--	12	--	12
		3	--	--	--	--	--	21	--	32	--	53
		4	--	--	--	--	--	30	--	33	--	56
10	Stairway shelter of 64 psf located at position N	1	7.4	8.5	8.1	8.5	5.5	8.1	--	9.3	--	6.3
		2	8.9	10	10	9.7	8.9	12	--	10	--	12
		3	23	16	14	13	12	20	--	31	--	53
		4	29	24	21	16	14	22	--	33	--	55
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	7.6	7.6	8.4	7.4	5.2	7.2	--	10	--	6.3
		2	10	12	12	11	6.8	12	--	13	--	13
		3	25	15	14	12	6.8	20	--	31	--	54
		4	35	27	22	16	13	25	--	35	--	57
13	Same as 12 plus east wall baffle of 76 psf	1	8.1	8.1	8.8	7.7	5.0	6.6	--	8.1	--	6.3
		2	9.9	11	11	8.1	8.5	8.5	--	9.2	--	12
		3	29	16	13	11	11	18	--	31	--	55
		4	37	28	22	17	14	22	--	35	--	59

TABLE 7

MODEL SITTING AND DINING ROOM TRAVERSE, 100-PSF EXTERNAL WALLS — DOSE RATE FROM OUTER CONTAMINATED RING OF 10-FT RADIUS

Data normalized to (r/hr)/(curie/ft)

Test Case	Structure	Detector Height (in.)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
2	With surrounding houses	1	0.39	0.43	0.47	0.45	0.35	0.56	--	0.53	--	0.45
		2	0.51	0.47	0.58	0.58	0.58	0.95	--	0.83	--	0.67
		3	1.9	0.85	0.65	0.69	0.58	1.3	--	1.6	--	2.8
		4	1.4	1.1	0.75	0.66	0.67	1.4	--	1.6	--	2.8
3	65-psf lean-to shelter at position E	1	0.26	0.35	0.32	--	0.21	0.47	--	0.57	--	0.34
		2	0.34	0.38	0.37	--	0.35	0.86	--	0.52	--	0.72
		3	1.1	0.66	0.49	--	--	1.0	--	1.5	--	--
		4	1.1	0.72	0.60	0.41	--	1.2	--	1.5	--	--
4	65-psf "A" frame shelter at position C	1	0.38	--	0.22	--	0.30	0.46	--	0.60	--	0.46
		2	0.52	--	0.21	--	0.38	0.88	--	0.63	--	0.86
		3	1.0	--	--	--	0.49	1.2	--	1.6	--	2.8
		4	1.7	--	--	--	0.60	1.2	--	1.7	--	3.0
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	--	--	0.084	--	--	0.51	--	--	--	0.46
		2	--	--	0.120	--	--	0.90	--	0.56	--	0.55
		3	0.70	--	--	--	0.51	1.1	--	1.6	--	2.3
		4	0.85	--	--	--	0.62	1.1	--	1.6	--	2.6
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	--	--	0.050	--	--	0.48	0.50	0.52	0.54	0.41
		2	--	--	0.079	--	--	0.80	0.76	0.60	0.60	0.66
		3	--	--	--	--	--	1.1	1.3	1.3	1.6	2.8
		4	1.2	0.76	0.66	0.63	0.60	1.1	1.4	1.8	1.7	2.9
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	--	--	0.034	--	--	0.44	0.44	0.55	0.46	0.33
		2	--	--	0.051	--	--	0.84	0.90	0.70	0.68	0.59
		3	--	--	--	--	--	1.0	1.3	1.6	1.9	2.7
		4	--	--	--	--	--	1.1	1.4	1.7	1.9	2.8
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	--	--	0.11	--	--	0.46	--	0.61	--	0.42
		2	--	--	0.18	--	--	0.94	--	0.61	--	0.67
		3	--	--	--	--	--	1.2	--	1.6	--	2.9
		4	--	--	--	--	--	1.2	--	1.7	--	3.0
10	Stairway shelter of 64 psf located at position N	1	0.39	0.95	0.42	0.86	0.27	0.51	--	0.46	--	0.33
		2	0.45	0.52	0.42	0.91	0.46	0.84	--	0.58	--	0.63
		3	0.75	1.1	0.58	0.86	0.49	1.1	--	1.5	--	2.4
		4	0.69	1.1	1.3	0.58	0.52	1.0	--	1.5	--	2.5
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	0.33	0.37	0.40	0.38	0.25	0.46	--	0.54	--	0.35
		2	0.44	0.56	0.48	0.44	0.46	0.86	--	0.58	--	0.84
		3	0.66	0.61	0.52	0.44	0.46	1.04	--	1.52	--	2.7
		4	0.69	0.66	0.64	0.56	0.56	1.07	--	1.87	--	2.6
13	Same as 12 plus east wall baffle of 76 psf	1	0.29	0.31	0.39	0.32	0.21	0.42	--	0.54	--	0.27
		2	0.44	0.53	0.47	0.48	0.45	0.85	--	0.65	--	0.55
		3	0.98	0.66	0.58	0.50	0.50	1.0	--	1.5	--	2.7
		4	1.2	0.73	0.63	0.61	0.55	1.2	--	1.8	--	2.6

TABLE 8

MODEL KITCHEN AND STAIRWAY TRAVERSE, 100-PSF EXTERNAL WALLS–DOSE RATE FROM INNER CONTAMINATED AREA EXTENDING FROM 2- TO 10-FT RADIUS

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (in.)	Detector Positions							
			K	L	M	N	O	P	Q	R
2	With surrounding houses	1	20	19	19	15	16	35	37	36
		2	24	24	22	20	19	46	48	31
		3	28	27	26	23	19	45	46	36
		4	27	28	25	22	22	45	50	39
3	65-psf lean-to shelter at position E	1	19	19	18	14	16	46	34	22
		2	22	22	19	16	20	57	43	29
		3	25	23	20	19	22	60	45	31
		4	25	27	23	16	24	57	49	30
4	65-psf "A" frame shelter at position C	1	20	21	19	15	16	41	31	23
		2	24	25	20	18	19	50	41	29
		3	26	27	23	20	23	52	45	31
		4	26	27	25	23	25	53	49	33
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	20	17	16	15	15	57	32	19
		2	21	19	19	17	19	56	44	26
		3	24	23	19	19	19	62	43	28
		4	25	26	26	20	24	56	46	28
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	19	22	18	15	18	44	34	22
		2	26	26	22	21	21	49	45	29
		3	27	29	23	22	21	56	46	34
		4	26	28	24	23	23	53	49	38
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	20	24	18	19	20	43	32	23
		2	25	28	21	20	22	50	43	29
		3	27	29	25	22	23	52	44	34
		4	25	29	25	23	25	56	46	33
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	20	21	16	16	16	45	32	22
		2	26	29	21	20	21	49	42	31
		3	26	29	22	20	21	54	45	37
		4	25	30	24	23	24	55	49	36
10	Stairway shelter of 64 psf located at position N	1	17	16	–	8.9	14	43	26	19
		2	20	19	–	12	17	53	37	23
		3	21	21	–	14	18	57	42	28
		4	22	19	16	–	19	55	43	28
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	16	14	–	6.0	11	48	29	15
		2	20	18	–	7.6	14	57	38	25
		3	22	20	–	9.6	15	59	40	28
		4	21	21	15	–	16	59	45	25
13	Same as 12 plus east wall baffle of 76 psf	1	17	14	–	6.0	11	–	29	21
		2	19	19	–	8.1	12	–	38	29
		3	20	20	–	13	13	–	41	31
		4	22	20	16	–	14	–	42	33

TABLE 9

MODEL KITCHEN AND STAIRWAY TRAVERSE, 100-PSF EXTERNAL WALLS—DOSE RATE FROM OUTER CONTAMINATED RING OF 10-FT RADIUS

Data normalized to (r/hr)/(curie/ft)

Test Case	Structure	Detector Height (in.)	Detector Positions K	L	M	N	O	P	Q	R
2	With surrounding houses	1	0.72	0.81	0.64	0.58	0.64	1.9	1.7	1.3
		2	0.95	0.97	0.86	0.75	0.72	1.7	2.3	1.6
		3	1.1	1.1	0.92	0.86	0.75	2.0	2.1	1.7
		4	0.83	1.2	0.97	0.95	0.92	2.2	2.3	1.7
3	65-psf lean-to shelter at position E	1	0.72	0.72	0.66	0.54	0.60	1.6	1.5	0.92
		2	0.92	0.92	0.83	0.80	0.74	2.0	1.9	1.3
		3	1.1	0.94	0.86	0.94	0.92	2.0	1.9	1.4
		4	0.94	1.1	0.92	0.83	0.83	2.2	2.0	1.3
4	65-psf "A" frame shelter at position C	1	0.88	0.84	0.79	0.66	0.66	1.6	1.7	1.2
		2	1.1	1.2	0.96	0.84	0.66	2.1	2.3	1.6
		3	1.0	1.2	1.1	0.96	0.79	2.0	2.0	1.7
		4	1.0	1.3	1.4	1.1	0.96	2.3	2.3	1.8
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	0.66	0.70	0.66	0.58	0.66	1.7	1.2	.80
		2	1.0	1.0	0.66	0.61	0.78	1.9	2.0	1.1
		3	1.1	0.90	0.78	0.74	0.78	2.2	1.9	0.99
		4	0.55	0.98	0.82	0.82	0.98	2.4	2.0	0.90
6	Rectangular shelter of 120-psf walls, 25-psf ceiling located at position C	1	0.70	0.76	0.66	0.60	0.70	2.1	1.6	0.86
		2	0.96	0.96	0.83	0.73	0.83	2.3	2.1	1.2
		3	1.0	1.1	0.80	0.80	0.86	2.4	2.1	1.4
		4	1.0	1.2	0.83	0.80	0.90	2.5	2.2	1.4
7	Rectangular shelter of 120-psf walls, 50-psf ceiling located at position C	1	0.73	0.70	0.66	0.64	0.62	2.0	1.6	0.82
		2	0.97	1.0	0.81	0.77	0.81	2.2	2.1	1.1
		3	0.99	0.99	0.86	0.79	0.86	2.3	2.0	1.4
		4	0.99	1.1	0.88	0.90	0.92	2.5	2.2	1.4
8	Rectangular shelter of 75-psf walls, 35-psf ceiling located at position C	1	0.70	0.73	0.64	0.56	0.67	2.2	1.8	0.88
		2	0.97	1.0	0.85	0.67	0.79	2.5	2.2	1.1
		3	1.0	1.1	0.85	0.70	0.88	2.6	2.1	1.3
		4	1.0	1.2	0.88	0.82	0.94	2.6	2.2	1.5
10	Stairway shelter of 64 psf located at position N	1	0.60	0.53	–	0.39	0.63	2.0	1.5	0.69
		2	0.79	0.67	–	0.56	0.74	2.5	1.9	1.0
		3	0.84	0.87	–	0.56	0.81	2.6	2.0	1.2
		4	1.0	0.85	0.67	–	0.81	2.4	2.1	1.2
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	0.53	0.48	–	0.31	0.52	1.8	1.1	0.72
		2	0.84	0.53	–	0.44	0.69	2.2	1.7	0.89
		3	0.89	0.79	–	0.44	0.73	2.3	1.9	1.1
		4	0.69	0.74	0.58	–	0.86	2.3	2.0	1.2
13	Same as 12 plus east wall baffle of 76 psf	1	0.55	0.50	–	0.26	0.44	–	1.3	0.81
		2	0.68	0.55	–	0.40	0.50	–	1.9	1.1
		3	0.73	0.69	–	0.44	0.53	–	1.9	1.3
		4	0.79	0.77	0.58	–	0.63	–	2.1	1.3

TABLE 10

FULL-SCALE SITTING AND DINING ROOM TRAVERSE, 100-PSF EXTERNAL WALLS—DOSE RATE FROM INNER CONTAMINATED AREA FROM FOUNDATION WALLS TO 50-FT RADIUS

Data normalized to (r/hr)/(curie/ft²)

Test Case	Structure	Detector Height (ft)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
2	With surrounding houses	1	9.9	9.1	7.9	6.4	6.0	8.0	8.5	9.0	11	22
		2	13	10	10	7.8	7.7	9.9	12	11	13	16
		4	64*	18*	19	16	13	18	18	24	16*	34*
3	65 psf lean-to shelter at position E	1	–	–	6.8	3.9	4.5	8.8	9.0	–	–	–
		2	–	–	9.5	5.1	5.7	10	12	–	–	–
		4	–	–	20	14	8.4	18	21	–	–	–
4	65-psf "A" frame shelter at position C	1	9.1	3.0	4.1	3.8	3.8	7.8	8.7	9.1	8.9	23
		2	13	3.2	4.9	3.8	4.9	9.3	9.1	12	14	42
		4	0.5	33	4.7	7.2	8.2	17	20	25	36	–
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	9.1	1.9	2.3	2.1	3.6	7.9	9.1	9.6	12	24
		2	15	2.1	2.5	2.1	5.1	9.8	11	12	15	0.5
		4	0.5	36	3.8	7.6	8.7	18	18	27	38	0.5
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	10	9.3	7.7	6.7	6.3	8.4	8.8	9.5	12	25
		2	15	11	10	7.9	7.9	10	1.2	12	15	46*
		4	74*	36	22	16	14	20	20	27	38	81*
13	Stairway shelter of 64 psf located at position N with 76-psf north, south and east wall baffle	1	9.8	9.1	8.1	6.7	6.3	7.4	8.5	9.4	12	26
		2	15	11	9.8	7.4	8.3	9.3	11	12	15	39*
		4	74*	35	22	15	14	18	21	27	38	74*

*5-r dosimeters

TABLE 11

FULL-SCALE SITTING AND DINING ROOM TRAVERSE, 100-PSF EXTERNAL WALLS—DOSE RATE FROM INTERMEDIATE ANNULUS, 50-120-FT RADIUS

Data normalized to (r/hr)/(curie/ft²)

Test Case	Structure	Detector Height (ft)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
2	With surrounding houses	1	1.4	1.4	1.2	1.2	1.0	1.7	1.7	1.7	1.7	1.7
		2	1.3	1.7	1.7	1.6	1.6	1.9	2.5	2.5	2.4	1.7
		4	5.2*	0.86*	2.6	2.6	2.6	4.8	5.2	6.3	6.9*	6.0*
3	65-psf lean-to shelter at position E	1	1.2	1.1	0.79	0.79	0.79	1.8	1.4	1.7	1.8	1.7
		2	1.3	1.6	1.4	0.89	0.99	2.1	2.2	2.5	2.4	3.9
		4	5.4	3.5	2.1	1.7	2.1	4.4	5.4	6.0	7.4	12
4	65-psf "A" frame shelter at position C	1	0.96	0.54	0.40	0.54	0.86	0.86	1.6	1.5	1.5	1.3
		2	1.1	0.54	0.72	0.54	1.1	1.9	2.1	2.0	2.3	4.2
		4	5.0	3.0	0.75	2.0	2.4	4.4	4.8	5.8	7.3	11
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	0.61	0.20	0.41†	0.20	0.81	1.6	1.2	1.8	1.6	1.0
		2	1.0	0	0.51†	0.20	1.0	1.6	2.2	2.2	2.2	4.3
		4	4.9	2.8	0.41	2.2	2.2	4.5	4.7	5.9	7.5	13
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	1.0	1.2	1.0	1.2	1.0	1.4	1.4	1.4	1.6	1.4
		2	1.4	1.4	1.4	1.2	1.4	2.2	2.0	2.2	2.0	3.7
		4	5.1	3.7	2.4	2.0	2.4	4.3	4.7	5.7	7.3	11
13	Stairway shelter of 64 psf located at position N with 76-psf north, south, and east wall baffle	1	1.0	0.82	0.82	1.0	1.0	1.4	1.4	1.6	1.6	1.9
		2	1.2	1.6	1.4	1.2	1.6	2.1	2.1	2.3	2.3	3.9
		4	5.7	3.3	2.5	2.1	2.7	3.7	4.9	5.7	7.4	11

*5-r dosimeters

†20-mr dosimeters

tech/ops

TABLE 12

FULL-SCALE SITTING AND DINING ROOM TRAVERSE, 100-PSF EXTERNAL WALLS
OUTER RING OF CONTAMINATION, 120-FT RADIUS

Data normalized and converted to far-field dose rate in (r/hr)/(curie/ft)

Test Case	Structure	Detector Height (ft)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
2	With surrounding houses	1	4.9	3.7	3.7	4.9	3.7	7.4	6.8	6.2	6.8	9.9
		2	4.9	5.5	6.2	5.5	5.6	8.6	8.0	9.2	6.8	13
		4	16	12	11	9.9	9.2	17	19	20	27	40
3	65-psf lean-to shelter at position E	1	3.2	3.7	3.2	3.7	2.8	6.4	8.7	6.9	6.9	6.0
		2	4.1	4.6	4.6	3.7	3.7	7.4	10	8.3	8.7	15
		4	16	9.7	8.7	6.0	6.9	18	18	23	29	41
4	65-psf "A" frame shelter at position C	1	2.9	1.9	2.1	0.95	2.9	6.7	5.7	6.7	6.7	5.7
		2	1.9	2.9	3.0	2.9	2.9	6.7	7.6	8.6	8.6	13
		4	17	7.6	2.8	8.9	7.6	16	18	22	28	44
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	0	1.4	1.1*	1.4	3.3	6.5	7.5	6.1	5.6	6.1
		2	3.3	1.9	1.8*	1.4	4.2	7.0	7.5	7.9	8.4	15
		4	16	7.9	3.3	7.9	8.9	16	18	22	29	44
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	2.8	3.8	2.8	3.8	3.8	6.6	6.6	6.6	6.6	5.7
		2	5.7	4.7	5.7	3.8	4.7	7.6	6.6	7.6	8.5	14
		4	16	9.5	9.5	7.6	8.5	16	16	21	26	42
13	Stairway shelter of 64 psf with north, south, and east wall baffle of 76 psf at position N	1	0.29	0.48	0.48	0.38	0.38	0.48	0.57	0.67	0.67	0.67
		2	0.57	0.48	0.48	0.38	0.38	0.48	0.76	0.76	0.86	1.3
		4	1.6	0.86	0.96	0.86	0.76	1.6	1.7	2.1	2.6	4.2

*20-mr dosimeters

TABLE 13

FULL-SCALE KITCHEN AND STAIRWAY TRAVERSE, 100-PSF EXTERNAL WALLS—DOSE RATE
FROM INNER CONTAMINATED AREA FROM FOUNDATION WALLS TO 80-FT RADIUS

Data normalized to $(r/hr)/(curie/ft^2)$

Test Case	Structure	Detector Height (ft)	Detector Positions							
			K	L	M	N	O	P	Q	R
2	With surrounding houses	1	23	23	18	13	15	20	24	21
		2	14	13	19	18	18	27	26	16
		4	15	14	23	18	21	29	30	16
4	65-psf "A" frame shelter at position C	1	23	23	19	14	16	0.5	57*	24
		2	28	28	20	20	19	0.5	0.5	34
		4	27	30	25	22	23	0.5	68*	38*
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	28	25	21	16	17	0.5	57*	25
		2	32	31	22	21	20	0.5	0.5*	37
		4	31	33	27	25	24	0.5	78*	38*
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	24	22	7.0	7.5	11	49*	53*	23
		2	28	29	6.8	9.6	12	51*	70*	33
		4	28	32	16	11	15	60*	75*	40*
13	Stairway shelter of 64 psf located at position N with 76 psf north, south, and east wall baffle	1	24	22	4.6	3.5	4.4	54*	48*	23*
		2	28	29	4.4	4.4	4.8	70*	74*	33
		4	28	31	15	7.0	7.4	70*	74*	35*

*5-r dosimeters

TABLE 14

FULL-SCALE KITCHEN AND STAIRWAY TRAVERSE, 100-PSF EXTERNAL WALLS – DOSE RATE FROM INTERMEDIATE ANNULUS, 80-120-FT RADIUS

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (ft)	Detector Positions							
			K	L	M	N	O	P	Q	R
2	With surrounding houses	1	2.0	2.6	2.3	1.9	2.4	3.5*	0.86	1.6
		2	0.86	3.1	2.6	2.5	2.6	4.3*	2.6*	0.86*
		4	2.76	4.2	3.6	3.4	3.7	7.8*	6.0*	4.3*
3	65-psf lean-to shelter at position E	1	2.2	2.5	2.2	1.7	2.1	4.9	7.9*	1.6
		2	2.8	3.8	2.6	2.4	2.4	8.1	7.7	3.2
		4	3.7	4.3	3.6	3.7	3.7	10	9.9*	7.9*
4	65-psf "A" frame shelter at position C	1	1.7	2.4	2.1	1.9	2.0	4.4	5.4*	1.3
		2	2.6	3.2	2.3	1.3	2.1	7.5	7.2	2.9
		4	3.5	4.1	3.6	3.4	3.5	9.7	9.6*	5.4*
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	2.0	2.6	2.4	2.0	2.4	4.9	6.1*	1.2
		2	2.6	3.3	2.6	2.6	2.4	7.9	8.3	2.6
		4	3.9	5.1	3.5	3.9	4.1	10	9.1*	4.1*
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	1.4	1.4	0.81	1.2†	1.4	4.1	5.1	1.0
		2	2.4	2.2	1.0	1.6†	1.4	7.1	6.9	2.6
		4	3.5	3.7	1.6	1.8	2.6	9.5	10*	4.1*
13	Stairway shelter of 64 psf located at position N with 76 psf north, south, and east wall baffle	1	1.4	1.6	1.0	0.68†	1.0	5.5	0*	1.9
		2	2.3	2.7	0.82	0.88†	0.82	8.6	7.2	3.1
		4	3.3	3.5	2.1	2.46	1.9	11	10*	4.1*

*5-r dosimeters

†20-mr dosimeters

TABLE 15

FULL-SCALE KITCHEN AND STAIRWAY TRAVERSE, 100-PSF EXTERNAL WALLS FROM OUTER RING OF CONTAMINATION, 120-FT RADIUS

Data normalized and converted to far-field dose rate in (r/hr)/(curie/ft)

Test Case	Structure	Detector Height (ft)	Detector Positions							
			K	L	M	N	O	P	Q	R
2	With surrounding houses	1	6.2	8.0	9.2	6.2	8.6	18	15*	4.3
		2	9.9	11	8.0	9.8	6.8	27	24	9.2
		4	12	15	12	15	12	35	37*	31*
3	65-psf lean-to shelter at position E	1	6.9	8.7	7.8	6.0	6.9	17	9.2*	10
		2	9.2	10	8.7	8.3	7.8	25	25	10
		4	14	15	13	12	13	37	41*	18*
4	65-psf "A" frame shelter at position C	1	6.7	9.5	7.6	4.8	5.7	16	9.5*	7.6
		2	9.5	9.5	8.6	17	7.6	23	26	11
		4	13	14	13	12	13	36	29*	4.8*
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	6.5	8.4	7.5	6.1	7.0	16	23*	5.1
		2	8.9	10	8.4	7.9	7.5	25	24	9.8
		4	13	15	13	13	13	36	44*	28*
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	5.7	5.7	2.8	4.1†	4.7	13	24*	4.7
		2	7.6	8.5	2.8	5.3†	3.8	23	22	7.6
		4	11	12	6.6	7.6	8.5	33	47*	38*
13	Stairway shelter of 64 psf with north, south, and east wall baffle of 76 psf located at position N	1	0.57	0.57	0.19	1.9	0.29	1.8	1.9*	0.38
		2	0.76	0.76	0.19	3.5†	0.29	2.9	2.3	0.86
		4	1.1	1.3	0.76	5.7	0.57	3.7	3.8*	1.9*

*5-r dosimeters

†20-mr dosimeters

TABLE 16

FULL-SCALE SITTING AND DINING ROOM TRAVERSE, 100-PSF EXTERNAL WALLS–DOSE RATE FROM CONTAMINATION ON THE ROOF

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (ft)	Detector Positions									
			A	B	C	D	E	F	G	H	I	J
2	With surrounding houses	1	7.0	8.3	7.8	7.8	7.2	7.8	8.6	8.8	8.9	3.8
		2	8.7	9.5	9.6	8.3	8.3	8.8	9.7	9.6	9.6	5.2
		4	9.7	12	12	12	10	12	12	13	18*	9.7
3	65-psf lean-to shelter at position E	1	–	–	–	1.7	1.8	6.9	7.7	–	–	–
		2	–	–	–	1.7	2.4	7.7	9.1	–	–	–
		4	–	–	–	0.5	3.0	11*	13*	–	–	–
4	65-psf "A" frame shelter at position C	1	6.4	1.7	2.3	1.8	6.6	7.7	8.4	8.4	8.4	4.1
		2	7.2	1.4	3.1	1.6	8.6	8.3	7.1	9.5	9.5	5.3
		4	6.2	11	5.2	0.5	10	10*	12.6	0.5	0.5	10
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	6.8	1.5	2.1	1.4	6.8	6.8	7.0	6.8	7.8	4.5
		2	8.0	1.7	2.9	1.6	8.2	6.9	7.7	7.8	8.5	5.5
		4	9.7	0.5	5.1	0.5	9.1	9.9	9.3	0.5	0.5	10
11	Stairway shelter of 64 psf with north wall baffle at 76 psf located at position N	1	7.0	8.4	7.4	7.4	6.4	6.3	6.7	7.3	7.4	4.2
		2	8.4	9.9	8.9	7.7	7.9	6.8	7.4	7.8	8.0	5.3
		4	9.7*	9.7*	12*	10*	9.0	8.4*	9.3	0.5	8.8*	8.4*
13	Stairway shelter of 64 psf with north, south, and east wall baffles of 76 psf	1	6.5	7.6	6.9	7.2	6.3	6.6	6.7	7.2	7.7	4.3
		2	7.8	8.8	8.3	7.6	7.6	7.2	8.1	8.0	8.4	5.4
		4	9.0	117*	0.5	8.6	8.4	9.0*	9.5	11*	10*	9.5*

*5-r dosimeters

TABLE 17

FULL-SCALE KITCHEN AND STAIRWAY TRAVERSE, 100-PSF EXTERNAL WALLS–DOSE RATE FROM CONTAMINATION ON THE ROOF

Data normalized to (r/hr)/(curie/ft^2)

Test Case	Structure	Detector Height (ft)	Detector Positions							
			K	L	M	N	O	P	Q	R
2	With surrounding houses	1	6.0	8.9	7.8	8.7	7.3	7.8*	1.3*	3.8
		2	6.7	8.6	7.8	9.2	7.8	5.8*	1.9*	7.8*
		4	8.3	10	13	12	9.7	8.8*	4.8*	8.8*
4	65-psf "A" frame shelter at position C	1	5.3	7.6	7.8	8.4	7.1	4.5	5.8*	4.2
		2	6.3	7.9	8.2	9.2	7.6	5.4	7.0	4.5
		4	7.9	9.6	12	11	9.2	7.6	7.9*	5.8*
5	65-psf "A" frame shelter and 65-psf north wall baffle at position C	1	1.6	6.9	6.7	7.8	6.1	3.8	6.2*	4.1
		2	7.2	7.0	7.3	8.6	6.8	4.9	3.8*	4.9
		4	8.7	8.9	10	0.5	8.3	6.0	8.1*	6.7*
11	Stairway shelter of 64 psf with north wall baffle of 76 psf located at position N	1	6.0	6.7	2.6	4.5	4.1	2.9	4.4*	3.9
		2	6.8	7.5	1.9	4.5	4.2	3.4	5.1	4.4
		4	9.1	9.7	0.5	4.2	4.1	3.9	5.7*	8.4*
13	Stairway shelter of 64 psf with N, S, and E wall baffle of 76 psf	1	6.2	6.9	1.2	1.9	3.4	2.7	5.4*	3.7
		2	6.6	7.8	1.4	1.8	3.6	3.3	5.2	4.3
		4	8.6	9.5	9.0*	3.1	4.0	4.9	7.2*	6.8*

*5-r dosimeters

CHAPTER 4

DATA ANALYSIS

COMPUTATION OF SHELTER FACTORS

The shielding calculations in the OCD Engineering Manual[8] are based upon 1-hr fallout spectra, while model results were obtained by using cobalt-60 as a fallout simulant. Spencer,[9] however, presents curves for both cobalt-60 and fallout for contamination—adjacent to a vertical barrier, adjacent to a horizontal barrier, and on a horizontal barrier. Here the methods of Ref. 8 together with the functions evaluated in Ref. 9 were used.

In the OCD Engineering Manual method of shielding analysis, the dose contribution from each mode of radiation penetration is determined by multiplying the effects of barrier shielding by the effects due to geometric shielding. The sum of all contributions, through various contributing surfaces of a structure, such as the exterior walls and roof, is the total contribution or "reduction factor." This reduction factor is a decimal fraction of the standard that is transmitted to the detector. The standard used for the analysis of structures is the amount of radiation that is received by a point 3 ft above an infinite, smooth, uniformly contaminated plane.

The OCD Engineering Manual method of computing the dose expected from ground sources of radiation in the experimental building requires: (1) the calculation of the dose received by a detector, assuming no interior partitions, and (2) the calculation of the effects of interior partitions.

The "position variation" method described in Refs. 8 and 10 was used to calculate the off-center detector positions. The basic idea of this procedure is to divide the building into four quadrants and to calculate the ground contribution for each quadrant by assuming that the detector is at the center of a fictitious structure four times the size of each quadrant. The total contribution for all four fictitious structures is then added and the sum divided by four.

The functional equations that describe this calculation using the notation of Ref. 8 are given below (see Figure 15)

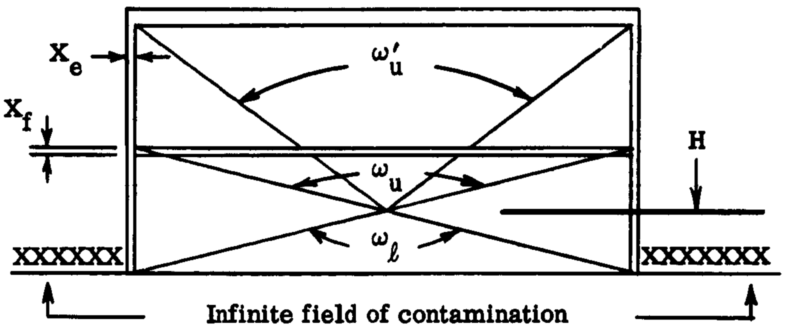


Figure 15. Schematic Diagram of Structure

Ground contribution first floor, neglecting interior partitions, assuming that apertures do not extend below the detector:

$$C_{g_1} = \left\{ \left[G_d(\omega_\ell, H) + G_a(\omega_u)(1 - P_r) \right] (1 - S_w) + \left[G_s(\omega_\ell) + G_s(\omega_u)(1 - P_r) \right] S_w E \right\} B_w(X_e, H) + \left[G_a(\omega_u) \right] P_r B_w(0, H); \tag{1}$$

Ground contribution through the second floor to a detector in the center of the first floor, neglecting interior partitions:

Solid Wall Contribution:

$$C'_{g_2} = \left\{ \left[G_a(\omega'_u) - G_a(\omega_u) \right] (1 - S_w) + \left[G_s(\omega'_u) - G_s(\omega_u) \right] S_w E \right\} B_w(X_e, H)\, B'_o(X_f)(1 - A_p); \tag{2}$$

Aperture Contribution:

$$C''_{g_2} = \left[G_a(\omega'_u) - G_a(\omega_u)\right] A_p B_w(0, H)\, B'_o(X_f); \qquad (3)$$

Total ground contribution to a detector in the center of the first floor, neglecting interior partitions:

$$C_g = C_{g_1} + C'_{g_2} + C''_{g_2} \qquad (4)$$

where

$G_a(\omega)$	=	the directional response of atmospheric-scattered radiation
$G_s(\omega)$	=	the directional response of wall-scattered radiation
$G_d(\omega, H)$	=	the directional response of direct radiation
ω	=	a solid angle fraction (solid angle/2π)(see Figure 15)
H	=	detector height above ground
S_w	=	the fraction of radiation scattered by the wall
E	=	an eccentricity factor depending upon length-to-width ratio
$B_w(X_e, H)$	=	the barrier shielding introduced by a vertical wall of thickness X_e at height H above the ground
$B'_o(X_f)$	=	the barrier shielding introduced by an overhead mass of thickness X_f to atmospheric or wall-scattered radiation
P_r	=	perimeter ratio of apertures = fraction of open area
A_p	=	percentage of apertures = area of apertures/area of wall

It should be noted that Eqs. (1) through (4) apply equally well whether the house is located on flat horizontal ground or on flat ground that slopes with respect to the structure, providing that the dimensions H and ω and the barrier thickness X_e are measured along paths parallel and perpendicular to the ground. As previously described, the 50 psf external wall model was inclined approximately 8° from the vertical, causing the rear wall to be buried to a depth of 3 ft equivalent. Similarly the 100 psf model and the full-scale structures were inclined approximately 4° from vertical, causing the rear wall to be buried approximately 1-1/2 ft.

Burial of the rear wall has the chief effect of lowering the sill height with respect to the detector. A detector located above the sill will receive both direct and skyshine radiation through the aperture while a detector at or below sill level will receive only skyshine radiation through the aperture. Then Eq. (1) becomes (see Figure 16):

$$C'_{g_1} = \Bigg[\Bigg[\Big\{G_d\left(\omega_\ell, H\right) - G_d\left(\omega_\ell^*, H\right) + \left[G_d\left(\omega_\ell^*\right) + G_a\left(\omega_u\right)\right]\left(1 - P_r\right)\Big\}\left(1 - S_w\right)$$
$$+ \Big\{G_s\left(\omega_\ell\right) - G_s\left(\omega_\ell^*\right) + \left[G_s\left(\omega_\ell^*\right) + G_s\left(\omega_u\right)\right]\left(1 - P_r\right)\Big\} S_w E\Bigg] B_w\left(X_e, H\right)$$
$$+ \left[G_a\left(\omega_u\right) + G_d\left(\omega_\ell^*\right)\right] P_r B_w(0, H). \qquad (5)$$

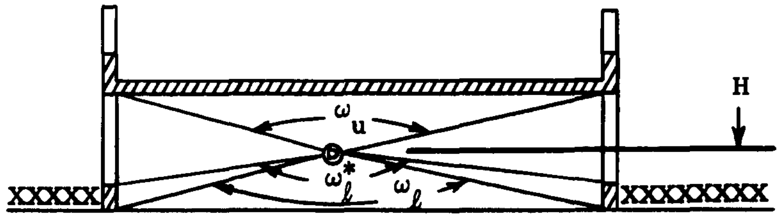


Figure 16. Schematic Diagram of Detector Above Sill Level

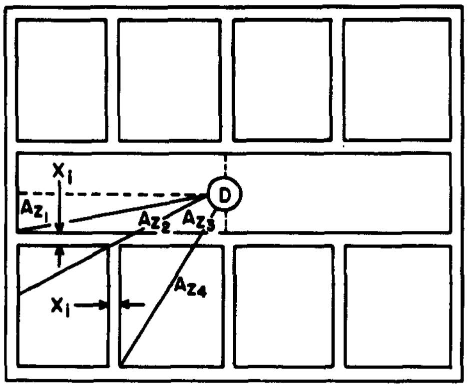


Figure 17. Schematic Diagram of Interior Partitions

The effects of interior partitions and shelters upon the dose rate within the structure can be estimated with the azimuthal sector approach analyzed sector by sector (see Figure 17) and assuming that each wall attenuates radiation as a barrier only. Thus the dose rate at the detector is that tor the structure with no partitions, multiplied by the weighted average barrier factor for the partition walls surrounding the detector. The weight of each sector is its azimuth fraction; the barrier in each sector is taken to be the sum of the masses per unit area of each wall crossing the sector. Thus the dose reaching the detector in Figure 17 is:

$$D_1 = C_{g_1} \left[A_{z_1} + A_{z_2} B_w(X_i) + A_{z_3} B(X_i + X_i') \right] \ldots \qquad (6)$$

where A_{z_n} is the angle in degrees of the nth azimuthal sector divided by 90^o.

A similar relationship may be written for radiation penetrating the second floor wall and contributing to the dose rate on the first floor.

The test building in both model and full scale was surrounded by other structures that interrupted the essentially infinite field of ground contamination. Since the surrounding structures were of substantial construction, contamination beyond them could not contribute significantly to the dose rate within the test structure. The effects of the fields of contamination between the test building and its neighbors may be allowed for by applying an over-all reduction factor to the calculated infinite-field dose rate from ground-based sources of contamination. For the geometry in Figure 18 this reduction factor, F, is:

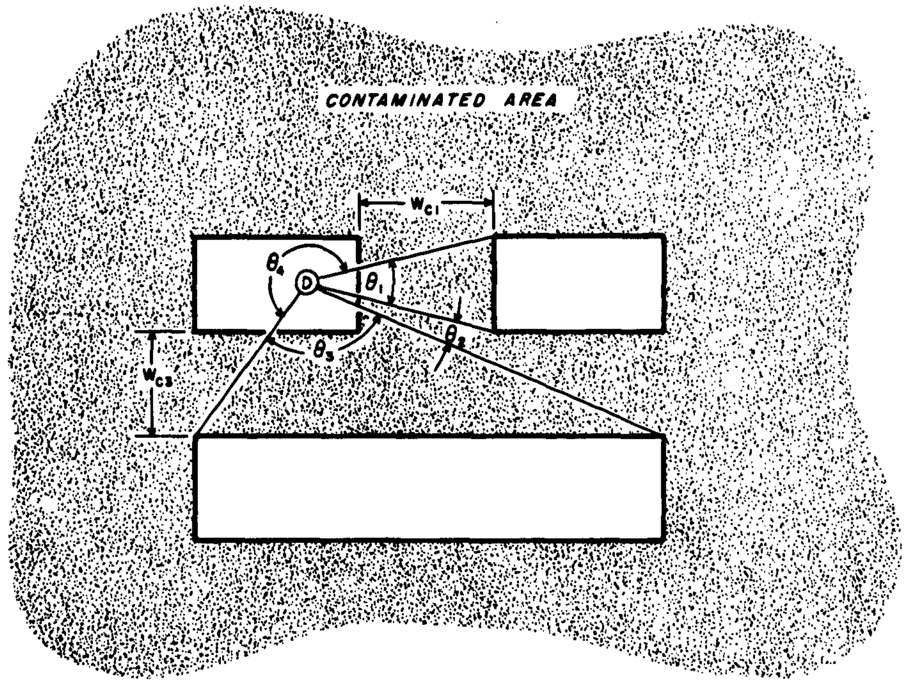


Figure 18. Schematic Diagram of a Structure Surrounded by Fields of Contamination Limited by Other Structures

$$F = \frac{\theta_1}{360} M_L \left(\frac{W_c^1}{H}, X_e \right) + \frac{\theta_2}{360} + \frac{\theta_3}{360} M_L \left(\frac{W_c^3}{H}, X_e \right) + \frac{\theta_4}{360} \qquad (7)$$

where

W_c^n = width of the nth rectangular strip of contamination

H = the detector height

X_e = exterior wall thickness of structure under consideration

M_L = fraction of infinite field dose rate produced by a rectangular strip of width W_c surrounding the structure (see Table 18).

TABLE 18

M_L, MULTIPLICATIVE CORRECTION FACTORS[11]
FOR RECTANGULAR STRIPS OF CONTAMINATION
($W_c/h \leq 10$, $W_c \leq 300$ ft)

W_c/h	Thin Floors ($X_f \leq 40$ psf)		Thick Floors ($X_f \geq 40$ psf)			
	0 psf walls	20 psf walls	20 psf walls		80 psf walls	
	All Floors	All Floors	First Floor	Upper Floors	First Floor	Upper Floors
0	0.000	0.0000	0.0000	0.0000	0.0000	0.0000
0.32	0.011	0.0021	—	0.0004	—	0.0003
0.44	0.018	0.0050	—	0.0011	—	0.0010
0.58	0.026	0.021	—	0.0024	—	0.0023
0.75	0.035	0.034	—	0.0046	0.014	0.0046
0.98	0.050	0.051	—	0.0086	0.022	0.0094
1.33	0.069	0.069	—	0.015	0.032	0.017
2.06	0.110	0.10	0.043	0.028	0.056	0.037
2.5	0.13	0.12	0.052	0.036	0.070	0.049
5	0.18	0.18	0.12	0.070	0.15	0.11
10	0.32	0.30	0.25	0.20	0.28	0.22

RATIONALIZATION OF DATA

To permit comparisons of predictions with the various measurements, it was necessary to correct the data in several ways. Although all measurements have been reported in terms of (r/hr)/(curie/ft^2) for area sources and (r/hr)/(curie/ft) for ring sources, the values needed adjustment to bring them to a common basis. Three distinct areas were treated: (1) conversion from model into equivalent full-scale results; (2) correction for incomplete coverage of the ground immediately adjacent to the model building; and (3) conversion of ring data into far-field dose rates.

Appendix A describes the rationale and method used to convert data obtained from model tests into equivalent full-scale results. Briefly, however, it can be said that the model constitutes an exact replica of the full-scale situation if all materials remain identical and their density is increased by the same scale factor that their dimensions are reduced. Practical modeling requires some relaxation from this ideal situation.

In this experiment, slightly different areas of ground contamination were simulated in the model and full-scale experiments. The plan dimensions of the full-scale structure were 37-1/2 ft x 20-1/4 ft, an equal-area circle yielding an equivalent inner radius of 15.6 ft; however, because of the minimum radius to which tubing may be bent, ground contamination in the model was simulated from an equivalent full-scale inner radius of 24 ft. Thus, the model was surrounded by a field extending from 2 to 10 ft radius (24 to 120 ft full-scale equivalent), while the full-scale structure was surrounded by a field extending from 16.1 to 120 ft radius. If these dimensions are substituted into Eq. (A-4) of Appendix A, one obtains a ratio of 1.19 between model and full-scale dose rates

The dose rate from an annular field of simulated ground contamination extending from 2 to 10 ft radius surrounding the model, multiplied by 1.19, is thus equivalent to the dose rate that would be received in a similar full-scale structure surrounded by a field of simulated ground contamination of the same density extending from the foundation walls to a radius of 120 ft from the center of the structure.

The experimental ring representing far-field radiation was constructed differently for each of the test series. The first test series, that on a model with 50 psf external walls, used a ring source of 20 ft radius (240 ft full-scale equivalent) to represent area sources at distances greater than 10 ft from the model structure (120 ft full-scale equivalent). However, when setting up the full-scale test it was found that tubing could not be laid at distances greater than about 120 ft on one side of the test structure. The dose contribution from far-field contamination was therefore represented by a ring of 120 ft radius. When the model with 100 psf external walls was tested, this same radius, scaled to 10 ft, was maintained.

The ratio of expected full-scale far-field dose to that obtained from the outermost ring of simulated contamination may be calculated using Eqs. (A-6) and (A-7) of Appendix A. The resultant ratios required for the analysis of the data described in this report are presented in Table 19.

TABLE 19

RATIOS OF FAR-FIELD DOSE CONTRIBUTION

Ratio	Inner Radius ρ_i (ft)*	Ring Radius ρ' (ft)*	Value
$D_{FS}(\rho_i \rightarrow \infty)/D_M(\rho')$	10	20	28.7
$D_{FS}(\rho_i \rightarrow \infty)/D_M(\rho')$	10	10	14.1
$D_{FS}(\rho_i \rightarrow \infty)/D_{FS}(\rho')$	10	10	193

*Note that dimensions are in terms of the model; thus to obtain actual full-scale dimensions multiply by 12.

RESULTS OF 50-PSF WALL MODEL TESTS

The data obtained from the model experiments have been converted to infinite-field full-scale results and then to reduction factors by normalizing to the source density (2.01 millicuries/ft^2) that would produce a dose rate of 1.0 r/hr 3 ft above an infinite smooth plane in the absence of a structure. These reduction factors for the positions within the shelters are presented in Table 20 together with calculated values for the various shelter configurations investigated. It should be noted here that the experimental values are for detector heights of 1, 2, and 4 ft, while the calculated values are for detector heights of 3 ft. It is evident from this table that the agreement between experimental and calculated values is good, though the British Home Office method tends to underestimate the dose rates slightly.

TABLE 20

CALCULATED AND EXPERIMENTAL REDUCTION FACTORS

Model house with 50 psf exterior walls; infinite plane source on ground

Test Case*	Structure	Position†	Model Experimental Data	Calculated Data at 3 ft: OCD Engr. Manual	Calculated Data at 3 ft: British Home Office‡
1	Empty house alone	C-1	.11		
		2	.13	.14	.098
		4	.20		
		E-1	.061		
		2	.098	.11	.098
		4	.13		
		N-1	.067		
		2	.15	.15	.13
		4	.20		
2	Empty house with surrounding houses	C-1	.079		
		2	.092	.103	.098
		4	.13		
		E-1	.046		
		2	.085	.087	.098
		4	.096		
		N-1	.081		
		2	.13	.12	.13
		4	.19		
3	Lean-to shelter	E-1	.027		
		2	.053	.052	.05
4	A-frame shelter	C-1	.029		
		2	.033	.036	.033
5	A-frame shelter with end baffle	C-1	.017		
		2	.020	.027	.019
6	Rectangular shelter 120 psf walls; 25 psf roof	C-1	.0074		
		2	.012	.014	.013
7	Rectangular shelter 120 psf walls; 50 psf roof	C-1	.0062		
		2	.010	.011	.013
8	Rectangular shelter 75 psf walls; 35 psf roof	C-1	.017		
		2	.021	.025	.019
9	Rectangular shelter 75 psf walls; 70 psf roof	C-1	.014		
		2	.019	.023	.019
10	Stairway shelter	N-1	.041		
		2	.11	.10	.099
		4	.16		
11	Stairway shelter, N wall baffle	N-1	.027		
		2	.044	.045	.048
		4	.066		
12	Stairway shelter, N wall and corridor baffle	N-1	.019		
		2	.036	.035	.037
		4	.066		
13	Stairway shelter, N wall, E wall and corridor baffle	N-1	.020		
		2	.035	.025	.025
		4	.055		

*See Figures 8 to 12 for details of test cases.

†Position-height code. Thus C-2 is Position C, 2 ft (full scale) height.

‡U.K. method ignores rear-wall burial and presence of surrounding houses.

Results from a horizontal traverse of the infinite-field dose rate through the sitting room and dining room for the test structure with and without the adjacent houses are shown in Figure 19. Here it can be seen that the surrounding houses, as expected, have a large effect on the dose rate within the sitting room and practically no effect on the dose rate within the dining room. This is because the neighboring houses are located adjacent to the sitting room. Calculated OCD Engineering Manual and British Home Office values* are plotted in Figure 19 for detector positions at the center and rear of the living room (Positions C and E). Shielding by adjacent buildings was allowed for.

The OCD Engineering Manual calculations include a single multiplicative factor to account for the effects of neighboring houses (see previous section). It is of interest here to compare this multiplicative factor with experimental results illustrated in Figure 19. The infinite-field dose rate in the center of the sitting room (Position C) with surrounding houses is 76% of the dose rate without surrounding houses; while the multiplicative factor for the same position is 79%.

Agreement between model experimental and calculated values for all shelter configurations is remarkably good considering the degree of complexity in the calculation introduced by off-center detector positions, heavy interior walls, sloping ground, and adjacent structures. The A-frame shelter with the 65 psf baffle wall on the north side provided about 35% more protection from ground-based sources of contamination than the unbaffled A-frame shelter. The rectangular shelters located in the center of the sitting room provided the most protection. Changing the rectangular shelter roof from 25 to 50 psf resulted in a 15% increase in protection, while decreasing the shelter wall mass thickness from 120 psf to 75 psf resulted in a decrease in protection of 40%. Agreement between calculated and experimental values for all rectangular shelter mass thicknesses was excellent. Both experimental and OCD Engineering Manual values show a definite effect of varying shelter roof mass thickness while the British Home Office values remain the same for varying roof mass thickness. Agreement between calculated and experimental values for the stairway shelters was again good. Table 20 shows that the addition of the north wall baffle increased the protection factor under the stairway

*Private communication, A. D. Perryman. Details of these calculations will be reported in Ref. 1.

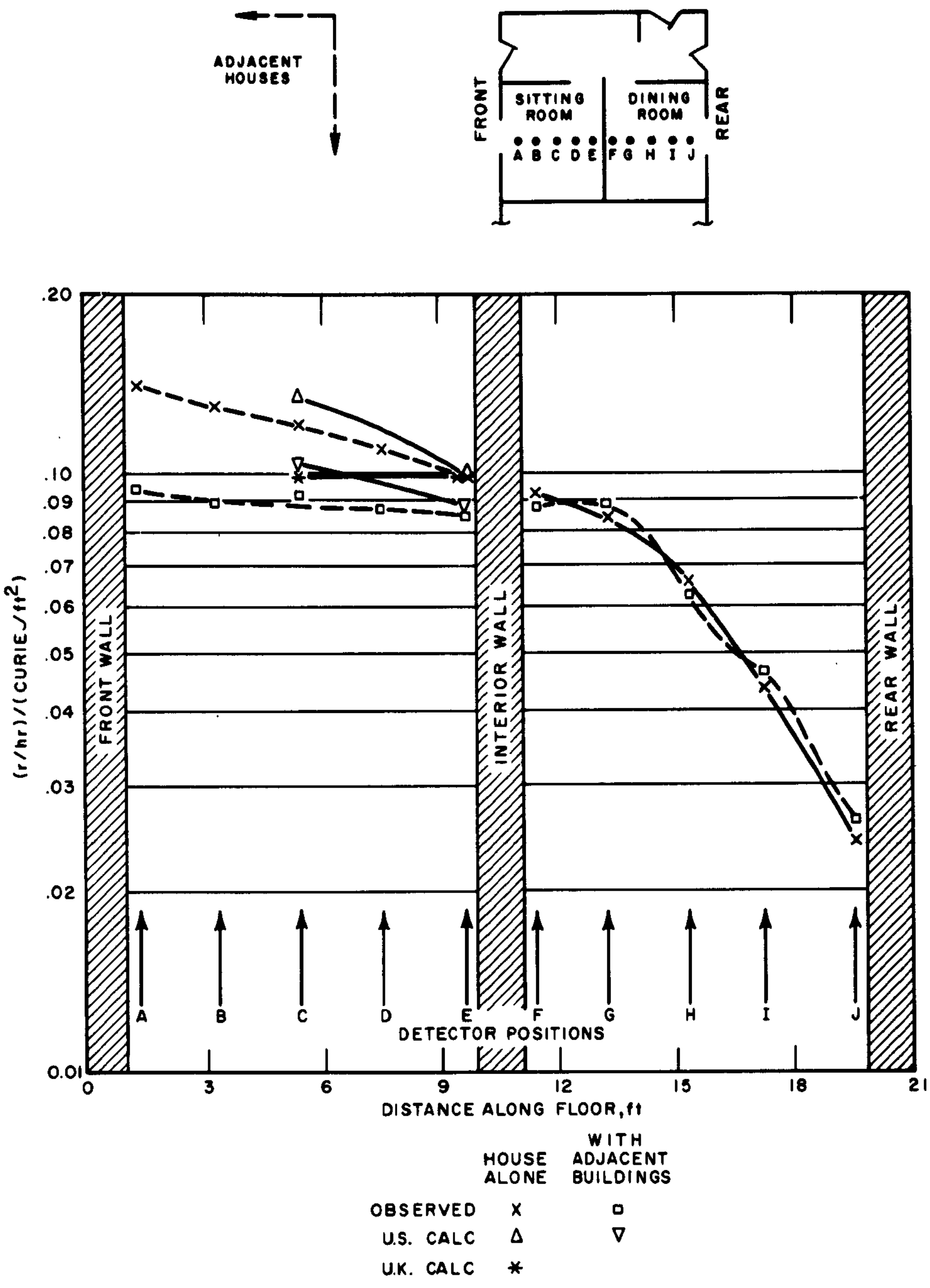


Figure 19. Horizontal Traverse Two Feet Above the Floor of Model House (50-psf external walls) Sitting Room and Living Room. Infinite Field Ground Dose

by 60%. The addition of the corridor baffle increased the protection by another 16%, while the addition of the east wall baffle had little or no effect upon the dose rate from ground-based sources of contamination.

RESULTS OF 100-PSF WALL MODEL AND FULL-SCALE TESTS

The data in Chapter 3 for the 100 psf model and for the 100 psf full-scale structure experiments have been converted to infinite-field full-scale results and reduced to reduction factors by normalizing to the uniform source density (2.01 millicuries/ft^2) that would produce a dose rate of 1.0 r/hr 3 ft above an infinite smooth plane in the absence of a structure. These normalized data for the model and full-scale structures without shelters are presented in Table 21 for both sitting room-dining room traverses and kitchen-stairway traverses at detector heights of 1, 2, and 4 ft. Comparable values with the various shelter arrangements installed are presented in Table 22.

The horizontal traverses through the bare structure (without shelters) are illustrated in Figure 20 for the sitting room and dining room, and in Figure 21 for the kitchen and stairway.

Here it can be seen that the agreement between model and full-scale results at locations away from windows and apertures is good. It should be noted that when this structure is scaled by a factor of 12, the wall thicknesses are approximately 25% of the average room plan dimension and hence the model should not be expected to provide better than about 25% accuracy near walls and apertures. From Figure 20 it is obvious that agreement between model and full-scale is excellent for the 4-ft detector position. At the 2-ft and 1-ft heights agreement is not as good, the largest discrepancy occurring at Position J near the rear aperture and wall. As previously described the 100 psf wall model was inclined approximately 4^o from the vertical, causing the rear wall to be buried to a depth of 1-1/2 ft, thereby allowing direct radiation to penetrate the aperture of the structure directly to the detector. While the 4-ft detector in the model was in direct line with the source, the 1- and 2-ft detectors were well below the sill level. The high readings observed in the full-scale experiment for the 1- and 2-ft detectors indicate that either the detectors were placed at or above sill level or the slope was greater than the 4^o estimated for the full-scale structure.

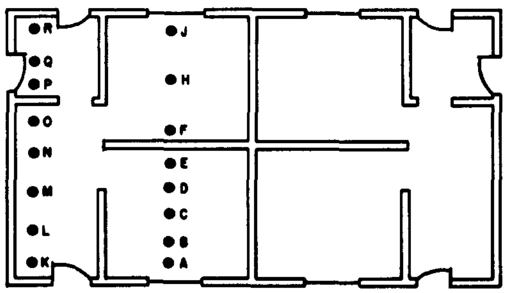
TABLE 21

MODEL AND FULL SCALE REDUCTION FACTORS

Bare house with 100 psf walls;
infinite plane source on ground

Position	Model	Full Scale	Position	Model	Full Scale
A-1	.031	.033	K-1	.068	.070
2	.036	.049	2	.085	.082
4	.14	.17	4	.087	.088
B-1	.032	.029	L-1	.069	.068
2	.036	.036	2	.086	.084
4	.097	.11	4	.10	.10
C-1	.033	.026	M-1	.072	.059
2	.039	.036	2	.078	.064
4	.075	.074	4	.078	.085
D-1	.031	.025	N-1	.053	.043
2	.040	.030	2	.070	.062
4	.060	.058	4	.081	.080
E-1	.021	.022	O-1	.056	.053
2	.039	.030	2	.067	.060
4	.056	.058	4	.078	.080
F-1	.034	.034	P-1	.14	.12
2	.052	.041	2	.16	.16
4	.091	.091	4	.17	.20
H-1	.037	.039	Q-1	.14	.15
2	.051	.052	2	.18	.20
4	.11	.12	4	.19	.24
J-1	.029	.068	R-1	.098	.068
2	.049	.13	2	.13	.11
4	.22	.27	4	.14	.14

REAR



FRONT

Detector Positions

TABLE 22

CALCULATED AND EXPERIMENTAL REDUCTION FACTORS

Model and full scale house (100 psf walls); infinite plane source on ground

Test Case	Structure	Position	Model	Full Scale	Engr. Manual*
1	Empty house and blockhouses	C-1	.033	.026	
		2	.039	.036	
		3	.053	–	.059
		4	.075	.074	
		E-1	.021	.022	
		2	.039	.030	
		3	.048	–	.043
		4	.056	.058	
		N-1	.053	.043	
		2	.070	.063	
		3	.080	–	.070
		4	.081	.080	
2	Lean-to shelter	E-1	.016	.016	
		2	.025	.021	
		3	–	–	.026
3	A-frame shelter	C-1	.015	.013	
		2	.016	.017	
		3	–	–	.018
4	A-frame with baffle	C-1	.0074	.0080	
		2	.010	.011	
		3	–	–	.012
5	Rectangular shelter 75 psf walls; 35 psf roof	C-1	.0084	.011	
		2	.012	.013	
		3	–	–	.014
6	Rectangular shelter 120 psf walls; 25 psf roof	C-1	.0038	.011	
		2	.0056	.012	
		3	–	–	.0052
7	Rectangular shelter 120 psf walls; 50 psf roof	C-1	.0028	.011	
		2	.0042	.012	
		3	–	–	.0045
8	Stairway	N-1	.033	.048	
		2	.045	.059	
		3	.050	–	.054
		4	–	–	
9	Stairway and N wall baffle	N-1	.024	.025	
		2	.031	.033	
		3	.036	–	.026
		4	–	–	
10	Stairway and NSE wall baffles	N-1	.022	.012	
		2	.031	.018	
		3	.044	–	.016
		4	–	–	

*OCD Engineering Manual values are for 3-ft detector height.

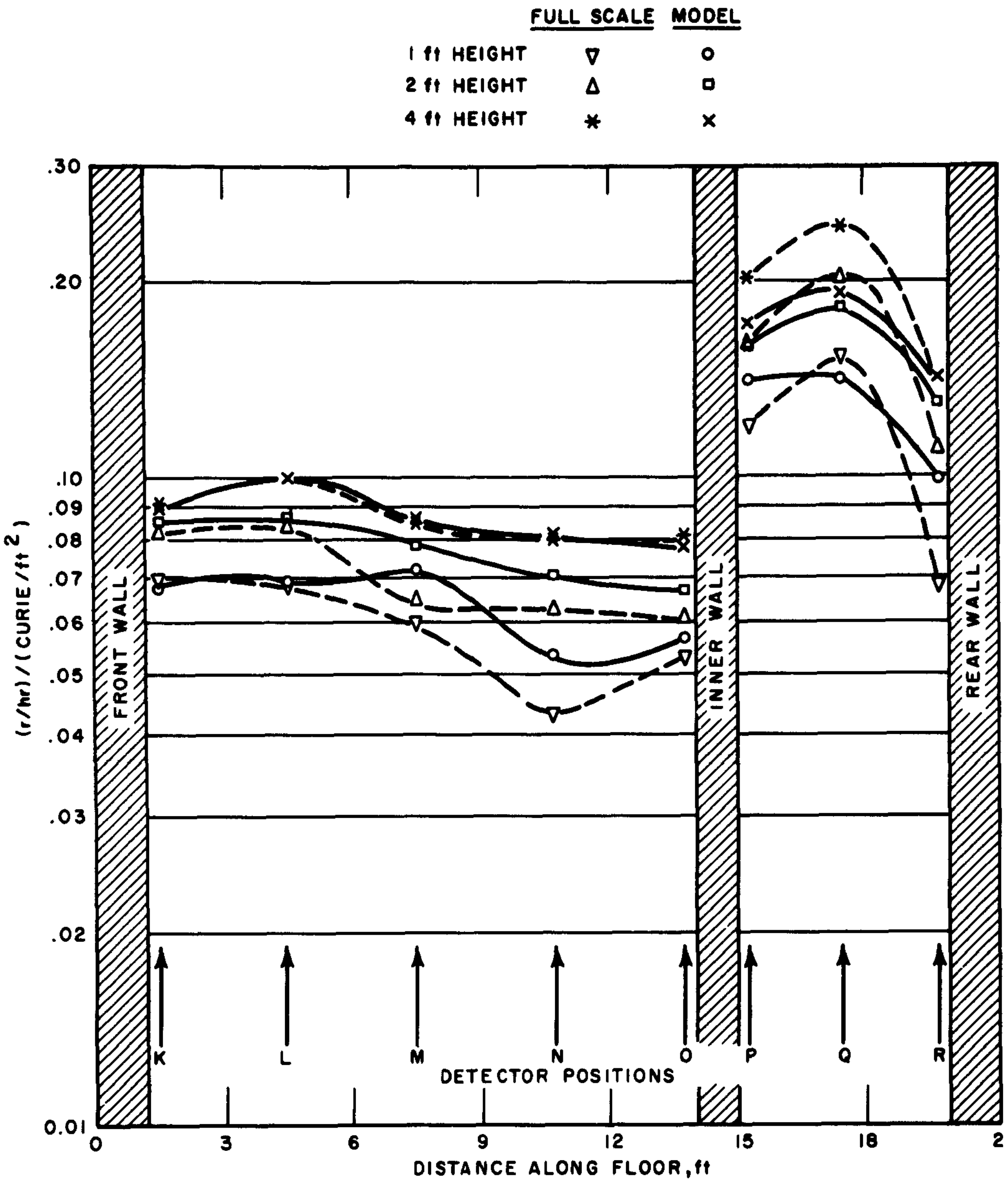


Figure 20. Dose Rates in Sitting Room and Living Room of Model and Full-Scale Structures Without Shelters

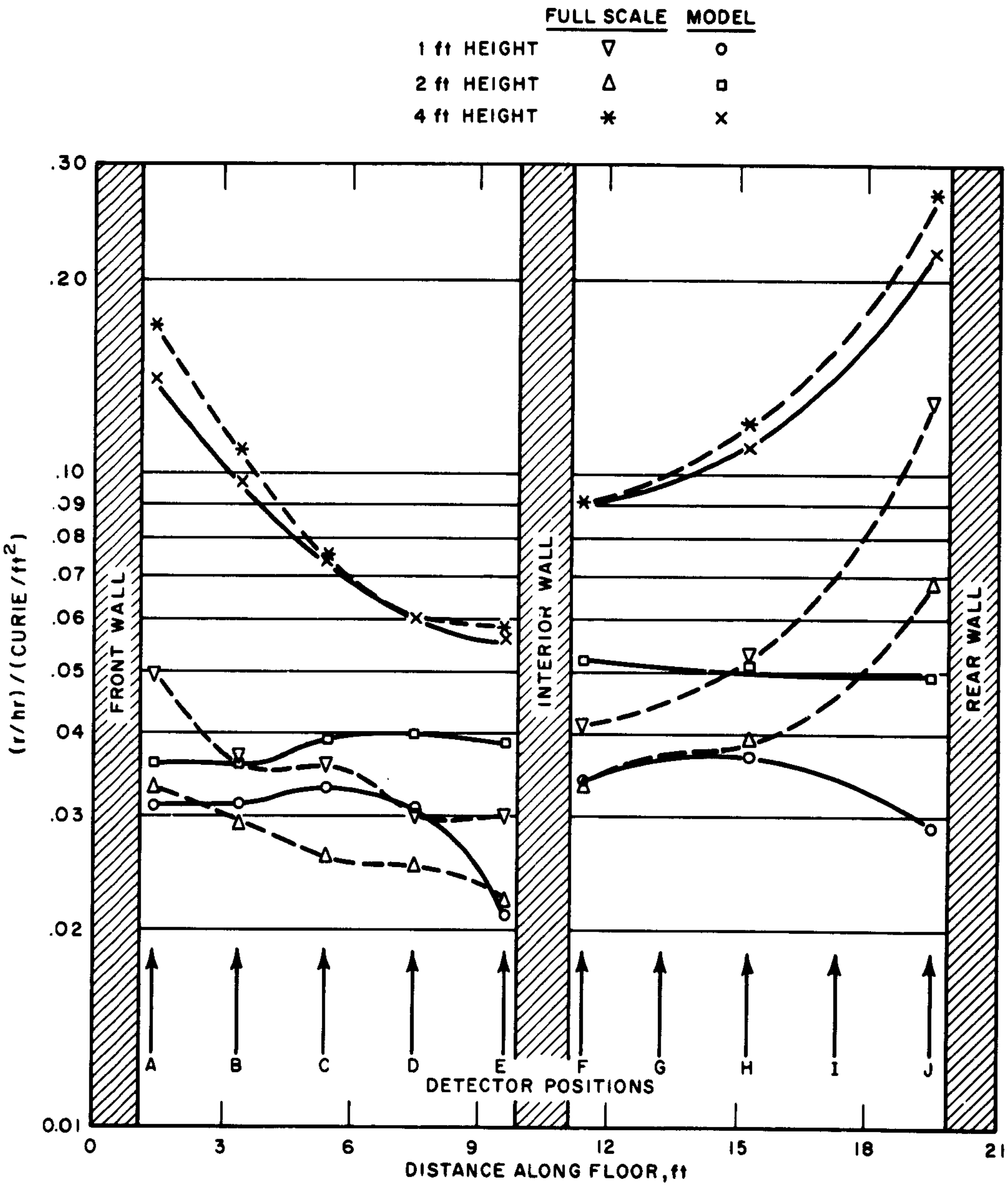


Figure 21. Dose Rates on Kitchen and Stairway of Model and Full-Scale Structures Without Shelters

The relative agreement between model and full-scale results in the kitchen and stairway area is good. The 4-ft values within the stairway are in excellent agreement (see Figure 21), while the 1-ft and 2-ft model values are somewhat higher than the full-scale values. The small kitchen with its two exterior doorways also is in good general agreement.

Model and full-scale experimental values for the various shelter configurations (Table 22) agreed except for the heavier-walled rectangular shelter. In Test Cases 6 and 7 where the wall mass thickness was increased to 120 psf, the full-scale results remain the same as for Test Case 5, while the model results show a definite decrease in dose rate by as much as a factor of 2. This discrepancy could possibly be accounted for by (1) a shelter constructed too loosely thereby allowing radiation to penetrate where bags abutted end to end or (2) underestimating the mean thickness of the sandbags.

The OCD Engineering Manual calculated values agreed quite well with the experimental values except for the baffled stairway shelters.

Experiments to determine the roof contribution were conducted on the full-scale structure and are shown in Table 23 for several locations. Modeling does not lend itself to this type of experimentation because the roof is too small to permit the source tubing to be laid out on it. Agreement between calculations and experiment is good except for the lean-to shelter and the baffled stairway. In both these configurations the calculation appears unable to account properly for the vertical barriers that intercept radiation coming down from above.

Table 23 also shows ground source reduction factors at selected locations, obtained from model and full-scale measurements as well as from U.S. and U.K. calculations. These ground source and roof source reduction factors have been summed and inverted to obtain the protection factors shown in Table 24. The U.S. methods predict shelter factors close to the experimental results except for the full-scale rectangular shelter. Both methods show that this shelter should offer the most protection; the discrepancy is probably due to inadequate construction of the full-scale sandbag shelter, as noted above.

TABLE .3

OBSERVED AND CALCULATED REDUCTION FACTORS

Structure	Position	Ground Source Radiation				Radiation From Roof		
		Calculated		Experimental		Calculated		Experimental
		HO	OCD[3]	Model	Full Scale	HO	OCD	Full Scale
Empty House	E-2	.044	.043	.039	.030	.019	.016	.017
Lean-To Shelter	E-2	.024	.026	.025	.021	.0088	.0078	.0048
A-Frame Shelter	C-2	.016	.018	.016	.017	.0048	.0056	.0054
A-Frame Shelter with End Baffle	C-2	.010	.012	.010	.011	.0048	.0052	.0058
Rectangular Shelter 120 psf wall; 50 psf roof	C-2	.0037	.0045	.0042	.012	.0084	.0061	.0066
Stairway Shelter with N Wall Baffle	N-2	.024	.026	.031	.033	.010	.012	.0092
Stairway Shelter with NSE Wall Baffles	N-2	.012	.016	.031	.018	.0066	.0059	.0036

Notes: 1. Outside wall thickness of bare house is 100 psf; partitions 50 psf; floor and roof total 14 psf.
2. Emergency shelters constructed of sandbags averaging 65 psf thick.
3. Experimental data based on 2-ft height; calculated on 3-ft height.

TABLE 24

OBSERVED AND CALCULATED PROTECTION FACTORS

Structure	Position	Protection Factors			
		Calculated		Experimental	
		OCD	HO	Model*	Full Scale
Empty House	E-2	17	16	18	21
Lean-To Shelter	E-2	29	32	34	39
A-Frame Shelter	C-2	43	49	47	44
A-Frame Shelter with End Baffle	C-2	58	68	63	61
Rectangular Shelter 120 psf wall; 50 psf roof	C-2	94	83	93	53
Stairway Shelter with N Wall Baffle	N-2	26	29	25	24
Stairway Shelter with NSE Wall Baffles	N-2	46	54	29	47

*Computed using model ground results and full-scale roof results.

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APPENDIX A

RADIATION SCALE MODELING

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RADIATION SCALE MODELING

SCALING LAWS AND TECHNIQUES

Shielding results obtained from experimentation on model structures may be considered to be exact replicas of full-scale experiments if three basic laws of scaling are obeyed:

1. All dimensions must be scaled geometrically by the same factor.
2. Each absorbing surface must attenuate radiation to the same degree as the original surface independent of scaling factor.
3. The specific scattering and absorption factors must remain unchanged.

These basic rules lead to the conclusion that the densities of all materials, including the building materials, the ground, and surrounding atmosphere, should be increased by the same scaling factor that governs the geometry. These considerations produce perfect scaling; in practice, however, the problem of increasing densities by a factor large enough to be useful makes it difficult to achieve this ideal.

Compromise procedures must be adopted to obtain useful scale factors. These include substitution of higher density materials for the ones actually used in the full-scale version, and thickening the walls relative to the rest of the dimensions of the structure so as to increase the mass per unit area. Substitution of iron for concrete is acceptable, but it raises the question of the proper basis on which to arrive at the correct amount of iron for a given thickness of concrete.

Three points of comparison with full-scale walls can be made:

1. Mass thickness may be matched.
2. Electron density may be maintained.
3. Broad-beam absorption data for flat slabs can be applied.

Mathematically, mass thickness is proportional to ρx, where x is the physical thickness and ρ is the material density; electron thickness is proportional to mass thickness times electrons per unit mass, or $(\rho x)(ZN_0/A)$, where N_0 is the number of molecules per gram molecular weight. Scaling relationships for two different materials, designated by subscripts, are therefore

$$\left(\frac{x_1}{x_2}\right)_m = \frac{\rho_2}{\rho_1} \qquad \text{(constant mass thickness)}$$

$$\left(\frac{x_1}{x_2}\right)_e = \frac{(Z/A)_2}{(Z/A)_1}\left(\frac{\rho_2}{\rho_1}\right) \qquad \text{(constant electron thickness).}$$

Values of 2 Z/A for concrete and for iron are 1.005 and 0.931, respectively; densities are 147 and 480 psf. With these the relative thicknesses of concrete and iron in Table A-1 can be calculated.

TABLE A-1

EQUIVALENT THICKNESS OF CONCRETE AND IRON

Material	Thickness (in.)	
Concrete	4	12
Iron (mass thickness)	1.22	3.68
Iron (electron thickness)	1.32	4.00
Iron (broad-beam, Co-60)	1.20	3.60
Iron (broad-beam, Cs-137)	1.24	3.70
Iron (broad-beam, Ir-192)	1.05	3.30

The thicknesses for broad-beam absorption shown in Table A-1 are taken from AECU-2967[A1] (Co-60 and Cs-137) and from Ritz[A2] (Ir-192). Experience with models indicates that scaling is most accurately done on the basis of mass thickness; Table A-1 shows that this agrees with broad-beam slab absorption except at low energies.

It has been found[A3,A4] that scaling will still be realistic if the wall thicknesses are not permitted to be more than 10% of the average dimensions of any room. This criterion permits the wall masses to be increased by a further factor of 3 or 4. As a result, it is possible to achieve a factor of 12:1 on scaling dimensions.

CONVERSION OF MODEL TO FULL-SCALE DATA

It is difficult, if not impossible, to increase the density of the atmosphere in a practical way to the extent required for perfect scaling. Results obtained from model tests must therefore be treated analytically to correct for this density difference. Perhaps the most straightforward method of computing the effect of unscaled atmospheric density is as follows. The attenuation of radiation reaching a detector is a function of the geometry and mass thickness of the structure and the attenuation and scattering properties of the atmosphere. Since the model is assumed to represent accurately the full-scale structure in geometry and mass thickness, the difference between model and full-scale results is a function only of the ratio of the scattering and attenuation properties of the real and "model" atmospheres.

The scattering and attenuation properties of the atmosphere for cobalt radiation have been experimentally measured in many investigations.[A5-A7] These data, in general, may be expressed by an analytical expression of the form:

$$I = I_o \frac{e^{-\mu r}}{r^2} \left[1 + a_1(\mu r) + a_2(\mu r)^2 + \ldots\right] \qquad \text{(A-1)}$$

where

I_o = dose rate at a unit distance for a source

r = distance from the source

μ = total cross section

$\left[1 + a_1(\mu r) + a_2(\mu r)^2 + \ldots\right]$ = dose buildup factor

$a_1, a_2, a_3 \ldots$ = experimentally measured constants.

Various investigators have evaluated the constant a_1 as varying from about 0.55 several feet above the ground-air interface to about 1.0 at altitudes of 50 ft or more for values of $\mu r \geq 0.1$. A more exact analytical fit of the data may be obtained by adding terms of the form $a_n(\mu r)^n$. However, since in general these buildup factors have been measured over paths essentially parallel to the ground and, in radiation penetrating a structure, the radiation predominantly traverses angular paths, the increase in accuracy obtained in computing the ratio of model to full-scale results using additional terms is unwarranted in view of the lack of accuracy of angular buildup data and the increased complexity of computation required.

This representation of dose-buildup factor is admittedly crude; however, it is probably adequate as a ratio to compare model with full-scale experiments. The major problems that have arisen from use of this approximation are attributable to its poor representation of the scattered portions of the dose at small distances ($\mu r \leq 0.1$). As shown below, however, the actual ratio that must be computed to compare data obtained from a model with those obtained from a full-scale structure is that of total dose from a full-scale annular contaminated field to that from the corresponding model field. Thus, for close-in field locations, while the dose due to scattered radiation may be seriously in error, it is but a few per cent of the total dose for both model and full-scale conditions. Hence, the ratio may be accepted as valid.

The total dose arriving at a position located in a structure at the center of a contaminated annular area with radii r_i, r_o (see Figure A-1) may be written as:

$$D(h, r_i \rightarrow r_o) = I_o G(X_e, h, a, b \ldots) \int_{r=r_i}^{r=r_o} \frac{2\pi\sigma B(\mu\rho) e^{-\mu\rho} r dr}{\rho^2} \qquad \text{(A-2)}$$

where

$D(h, r_i \rightarrow r_o)$	=	dose rate at detector position of interest
h	=	detector height
r_i	=	inner radius of contaminated annulus

r_o = outer radius of contaminated annulus

ρ = $\sqrt{r^2 + h^2}$ = slant distance

I_o = dose rate at a unit distance from a 1-curie source

$G(X_e, h, a, b \ldots)$ = geometric and barrier shielding introduced by the structure at detector height h

X_e, a, b = barrier thickness and geometric factors describing the structure

σ = source density in curies per unit area

$B(\mu\rho)$ = air-ground buildup factor $\cong 1 + 0.55\,\mu\rho$

μ = total linear coefficient for air = $(1/445)\text{ft}^{-1}$ for Co-60

which upon integration reduces to:

$$D(h, r_i \rightarrow r_o) = 2\pi\sigma I_o G(X_e, h, a, b \ldots) \left[E_1(\mu\rho_i) + 0.55\,e^{-\mu\rho_i} - E_1(\mu\rho_o) - 0.55\,e^{-\mu\rho_o}\right] \quad \text{(A-3)}$$

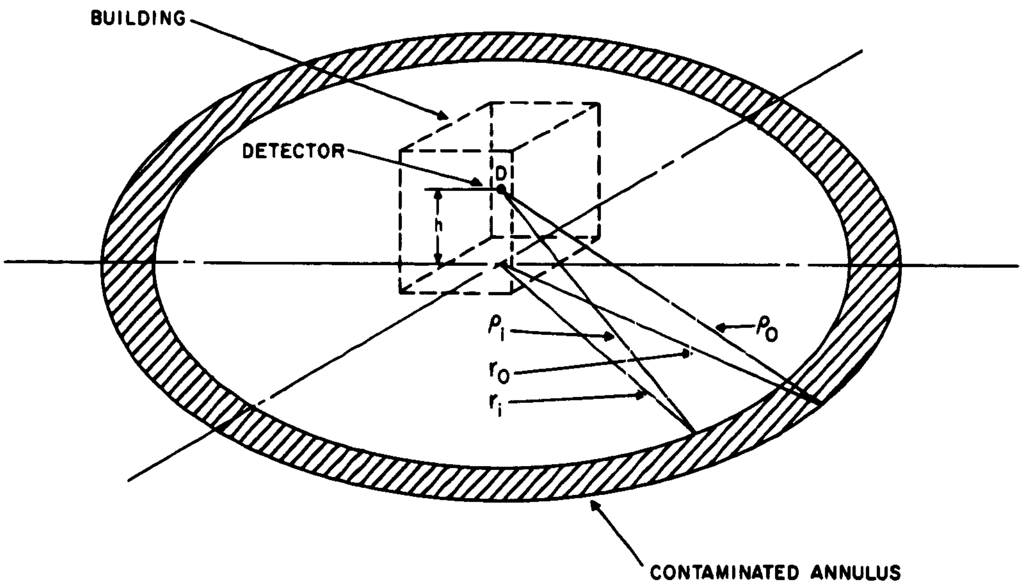

Figure A-1. Schematic Diagram of Building Irradiated by an Annular Contaminated Field where

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

The dose rates for the model and full-scale structure are both represented by the equation given above. Thus, if we take as the dimensions of interest the actual dimensions for the model, the corresponding equation for the full-scale structure would simply have each linear dimension multiplied by the scale factor S. If it is assumed that the shielding factor G is scale-invariant, the ratio of the dose that would be obtained from a full-scale test to that of the model test may be written as:

$$R = \frac{D_{FS}\left(Sh, Sr_i \rightarrow Sr_o\right)}{D_M\left(h, r_i \rightarrow r_o\right)} = \frac{E_1\left(S\mu\rho_i\right) - E_1\left(S\mu\rho_o\right) + 0.55\left[e^{-S\mu\rho_i} - e^{-S\mu\rho_o}\right]}{E_1\left(\mu\rho_i\right) - E_1\left(\mu\rho_o\right) + 0.55\left[e^{-\mu\rho_i} - e^{-\mu\rho_o}\right]} \qquad \text{(A-4)}$$

where

$D_{FS}(Sh, Sr_i \rightarrow Sr_o)$ = dose that would be measured by a detector at height Sh in a full-scale building from an annulus of dimensions Sr_i, Sr_o

$D_M(h, r_i \rightarrow r_o)$ = dose as measured in the model structure from a scaled-down area containing the same source density

ρ_i, ρ_o = slant radii from detector to contaminated area.

The data obtained from model experiments may then be multiplied by this ratio to obtain values that would have been obtained from a full-scale experiment.

Further, if it is desired to simulate in the model a slightly different area of contamination than that which might exist about the full-scale structure and yet predict from the model experiments the actual full-scale situation, the correct ratio may be calculated by replacing the terms $S\mu\rho_o$ and $S\mu\rho_i$ in the numerator of the above expression by the actual desired full-scale dimensions.

ESTIMATE OF FAR-FIELD RADIATION

One of the principal limitations to the experiments, both model and full scale, is the absence of far-field radiation. Since it is uneconomical and impractical to extend the simulated contaminated area to the distances required to obtain the full far-field effect, an analytical-experimental procedure has been developed to evaluate its effects.

This procedure is based upon the fact that the angular distribution of radiation striking a vertical wall from sources at extremely large distances from the wall is not much different from that obtained from a ring contamination of radius greater than about ten times the wall height. Thus the attenuation afforded by the structure to radiation from either far-field contamination or a large radius ring of contamination is virtually identical. The dose rate within a structure due to a ring source of contamination may then be written as:

$$D_{ring} = I_o G(X_e, h, a, b \ldots) \frac{2\pi\sigma' e^{-\mu\rho'} B(\mu\rho')}{\rho'} \quad \text{(A-5)}$$

where

D = the dose rate from a ring source of radius ρ'

σ' = the source density (curies/ft)

ρ' = the ring slant radius (ft)

and the other quantities are as defined previously.

Now returning to Eq. (A-3) for the dose rate from an annular area, we may express the ratio of the dose expected from a full-scale far-field annulus extending from ρ_i to infinity to that which would be obtained from either a full-scale ring of slant radius ($12\rho'$) or a model ring of slant radius ρ' :

$$\frac{D_{FS}\left(Sr_i \rightarrow \infty\right)}{D_{FS}\left(S\rho'\right)} = \frac{\left[E_1\left(S\mu\rho_i\right) + 0.55\, e^{-S\mu\rho_i}\right]\sigma}{\left[\frac{e^{-S\mu\rho'}\,(1 + 0.55\, S\mu\rho')}{S\rho'}\right]\sigma'} \quad \text{(A-6)}$$

$$\frac{D_{FS}\left(Sr_i \rightarrow \infty\right)}{D_M\left(\rho'\right)} = \frac{\left[E_1\left(S\mu\rho_i\right) + 0.55\ e^{-S\mu\rho_i}\right]\sigma}{\left[\frac{e^{-\mu\rho'}\left(1 + 0.55\ \mu\rho'\right)}{\rho'}\right]\sigma'} \qquad \text{(A-7)}$$

where

$D_{FS}(Sr_i \rightarrow \infty)$ = the dose rate in the full-scale structure from contamination lying beyond radius Sr_i

$D_{FS}(S\rho')$ = the dose rate in a full-scale structure from a ring of contamination of slant radius $S\rho'$

$D_M(\rho')$ = the dose rate in a model building from a ring of contamination of slant radius ρ'.

It is thus possible with the use of Eqs. (A-6) and (A-7) to estimate the dose rate contribution arising from far-field contamination in both model and full-scale structures from the dose rate obtained from a ring source of contamination about either a model or full-scale structure. A rigorous treatment of the estimate of far-field contribution for detectors at positions other than the center of the ring source is given in References (A3) and (A8).

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