MR-7047
Project 7120

THE EFFECTIVENESS OF SOIL AS SHIELDING FOR EXPEDIENT FALLOUT SHELTERS

Final Report
April 1976

Contract No. DCPA01-75-C-0331
Work Unit 3223H

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MATHEMATICAL APPLICATIONS GROUP, INC.
3 Westchester Plaza
Elmsford, New York 10523

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by

Mendel Beer

and

Martin O. Cohen

for

Defense Civil Preparedness Agency
Washington, D. C. 20301

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SUMMARY

A series of Monte Carlo calculations has been performed to evaluate the effectiveness of the use of soil in upgrading the fallout shielding effectiveness of typical light structures. In particular, exposure rates at several locations within one and two story thin-walled warehouse structures of different sizes were examined. In addition, we have obtained exposure rates at a number of locations within a small wood frame house.

Results were obtained for various countermeasures involving different amounts of soil loaded on the roof and bermed against the outer walls of the structures considered. As many combinations of buildings, detector locations and expedient countermeasures, as were possible under the scope of this work, were treated - although not all possibilities for all cases could be investigated. Our conclusions are summarized as follows:

1. It is possible to obtain protection factors greater than 1000 for warehouse structures by the use of 12' berms against the walls and 3' soil depths placed on shored up roofs of one story structures or on the second floor of multi-storied structures.

2. If such large berms cannot be attained but the use of sandbags is feasible, the next best alternative is the use of 7' berms truncated at 6' and the piling of sandbags on top to a 12' height, and use of 2' of soil depths on the roof. Better results are obtained by this method than by using 10' berms and 2' of roof soil. In the latter case, radiation incident upon the top 1' or 2' of the berm strongly increases the radiation dose at points within the building.

3. The 50' x 50' one story warehouse protection factors can be extrapolated to yield protection factors for any rectangular structure with dimensions that are not too small.

4. Addition of further soil (=1.5) to roof soil depths greater than 1' causes a further rate of drop in reduction factor by about a factor of 10 per foot.

5. Air conditioner units placed on the roof increase the dose substantially only for roof soil depths greater than 1'. However, almost no dose increase is found beyond interior points more than 15' from the vertical axis of the air conditioner shaft.

6. Adding one foot or more of soil to the second floor of a two-or multi-story building allows the reduction factor due to ground fallout to be computed in the same way as for a single story warehouse.

7. Houses with sloping roofs require soil berms or sandbags to be piled high enough so that attic walls are completely covered (together with roof soil depths of 2') if PFs of 200 are to be achieved. PFs greater than 1000 require berms reaching to the top of 3' of roof soil.

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1. INTRODUCTION

A scenario under current consideration by the Defense Civil Preparedness Agency (DCPA), as part of the Crisis Relocation Program (CRT), involves rising international tensions leading to the thinning of urban populations to rural areas. Those relocated would generally be housed in structures which do not afford appreciable protection against fallout radiation. However, given a few days notice, various expedient measures are available to them which could significantly enhance the protection factors of their buildings.

One of the measures involves the piling of earth on the roofs of the structures and against their sides. In addition, all apertures would be blocked and additional posts and braces added for structural integrity.

A series of Monte Carlo calculations has been performed to evaluate the effectiveness of such countermeasures in upgrading the fallout shielding effectiveness of typical light structures. In particular, we examined exposure rates at several locations within one and two story thin-walled warehouse structures of different sizes. In addition, we have obtained exposure rates at a number of locations within a small wood frame house*.

Results were obtained for various countermeasures involving different amounts of soil loaded on the roof and bermed against the outer walls of the structures considered. As many combinations of buildings, detector locations and expedient countermeasures, as were possible under the scope of this work, were treated - although not all possibilities for all cases could be investigated.

Section 2 describes the calculational technique used in this study. Descriptions of the structures considered, and results obtained are presented in Sections 3-5. Conclusions are summarized in Section 6.

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*These results complement the results previously obtained by us for a small wood frame house, a larger wood frame structure and a wing of a school building[1]. The two studies represent a sizeable body of data on expedient shelters for a number of different typical rural building types.

2. CALCULATIONAL TECHNIQUE

The Monte Carlo calculations described in the sections which follow were performed with the SAM-CE code[2], making use of its Combinatorial Geometry feature[3] to simulate realistically the buildings and expedient countermeasures which were under examination. In addition, a number of calculations were done for roof fallout sources utilizing the Standard Engineering Method[4].

Computations were, at all times, performed separately for fallout upon the roof and the ground. (Note that the "ground" included any soil which might be piled against the sides of the structures.)

The fallout was represented by an assumed deposition of cobalt-60; with the emitted radiation consisting of one 1.33 MeV and one 1.17 MeV photon per disintegration. A special *ad hoc* source generation routine allowed the fallout to be deposited uniformly (in the horizontal plane) upon both horizontal and sloping surfaces.

For both roof and ground sources, dose rates were calculated at selected point detector locations. These dose rates were then normalized to a standard dose rate of 490 R/hr per Ci/ft^2 *. The normalized data, known as reduction factors (RF), are presented and discussed. The inverse of the sum of the contributing reduction factors known as the protection factor (PF) - is also presented in many cases**.

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*At a point detector located 3' above a smooth infinite fallout field of ^{60}Co. This normalization constant was obtained by a separate calculation.

**The protection factor - being the ratio of the dose rate for an unshielded detector 3' above a smooth infinite source plane to the sheltered location dose rate - is usually the quantity used in the literature to describe the effectiveness of the shelter considered.

In the sections which follow we refer to various berm "heights" against the buildings. The berm height will always be the height of a 45° wedge of soil piled against all four sides of the building as seen in Figure 1a. At the corners of the buildings, the wedges were connected by quarter-sections of right cones, which had radii equal to the wedge bases (see Figure 1b).

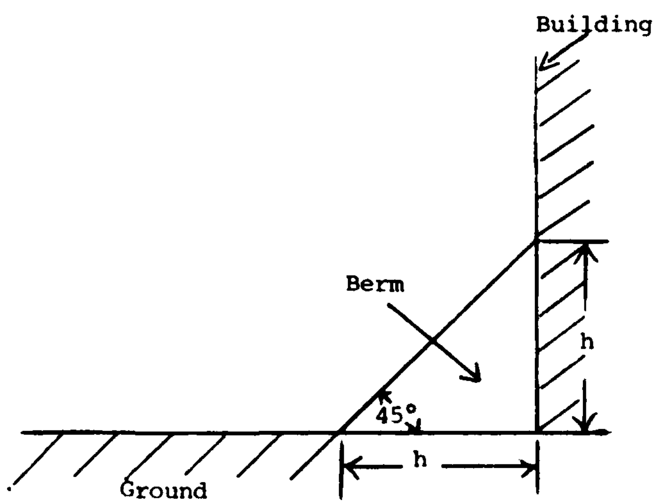

Figure 1a

Berming - Side View

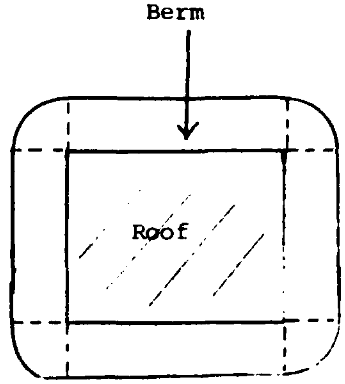

Figure 1b

Berming - Top View

For all structures, it was assumed that the walls were of constant thickness. Thus all windows and doorways were taken to be blocked up with materials equal in mass density to the containing walls.

Ground sources were handled in a way that allowed separation of the skyshine from direct and building scatter components. The technique utilized for this purpose is now described.

The building of interest and any surrounding soil berms are enclosed within a close-fitting right circular cylinder coaxial with the building center and with a height equal to the maximum building height (including roof soil). Gamma rays emanating from ground source points exterior to the cylinder are divided into two components; those "aimed" at the cylinder and all others ("unaimed").

The contribution of the unaimed component of the dose is almost entirely due to skyshine. Only a very small portion of the unaimed radiation which collides in the ground ultimately finds its way to (and enters) the building.

Most of the aimed radiation reaches the circumscribing cylinder without suffering any collisions. This component has a high probability of striking the enclosed building or its associated berms. The air scattered portion of the aimed radiation contributes a minute portion of the skyshine dose. This stems from the small solid angle subtended by the building at almost all ground source points.

Finally, it should be noted that gamma rays from source points within the aiming cylinder contribute very little to skyshine and can, therefore, be included with the aimed component.

We may conclude from the above, that dose due to unaimed gamma rays emanating from ground source points exterior to the aiming cylinder, represents the total skyshine component to a very good approximation. Our results have been obtained in such a way that the skyshine, the direct dose (from uncollided gamma rays) and the building scattered dose are tabulated separately, in close conformity to the definitions given in the Shelter Design and Analysis handbook[4].

3. SINGLE-STORY WAREHOUSE

3.1 Description of Building Geometry

The majority of calculations in this work were conducted for square steel (thin sheet) warehouse structures of dimensions which increased from 50' x 50' to 200' x 200'. The walls and 10' high ceiling were assumed to be 5 lb/ft^2 (psf).

Several series of calculations were performed for 3' high point detectors at three different locations; first, in the center of the building; second at a point three feet from an edge and equidistant from the walls perpendicular to the edge; and third, at a point near a corner and three feet from both walls meeting at the corner.

The density of the soil bermed against the sides of the buildings and piled on the roof was assumed to be at a density of 1.5 g/cm^3. This soil density was used throughout the entire study.

3.2 One-Story Warehouse

3.2.1 Fallout on Roof

We first considered the expedient countermeasures that could be taken to reduce the dose at the three detectors from roof fallout. In the calculations we considered layers of soil covering the entire roof to depths of 0', 1' and 2'. Warehouse edge lengths of 50, 100 and 200 feet were used in order to cover a wide range of potential shelters. For extrapolation purposes, we also considered a very small (6 feet square), and an infinitely large, warehouse.

The simple geometry of the warehouse roof allows straightforward use of the Standard Engineering Method of reference 4. However, several Monte Carlo calculations were first performed to serve as checkpoints. (Both sets of results are shown in Figure 2, below). A further Monte Carlo calculation showed that the inclusion of a 10' high berm around the entire warehouse did not alter the roof dose (within 5% statistics) even for edge and corner detectors.

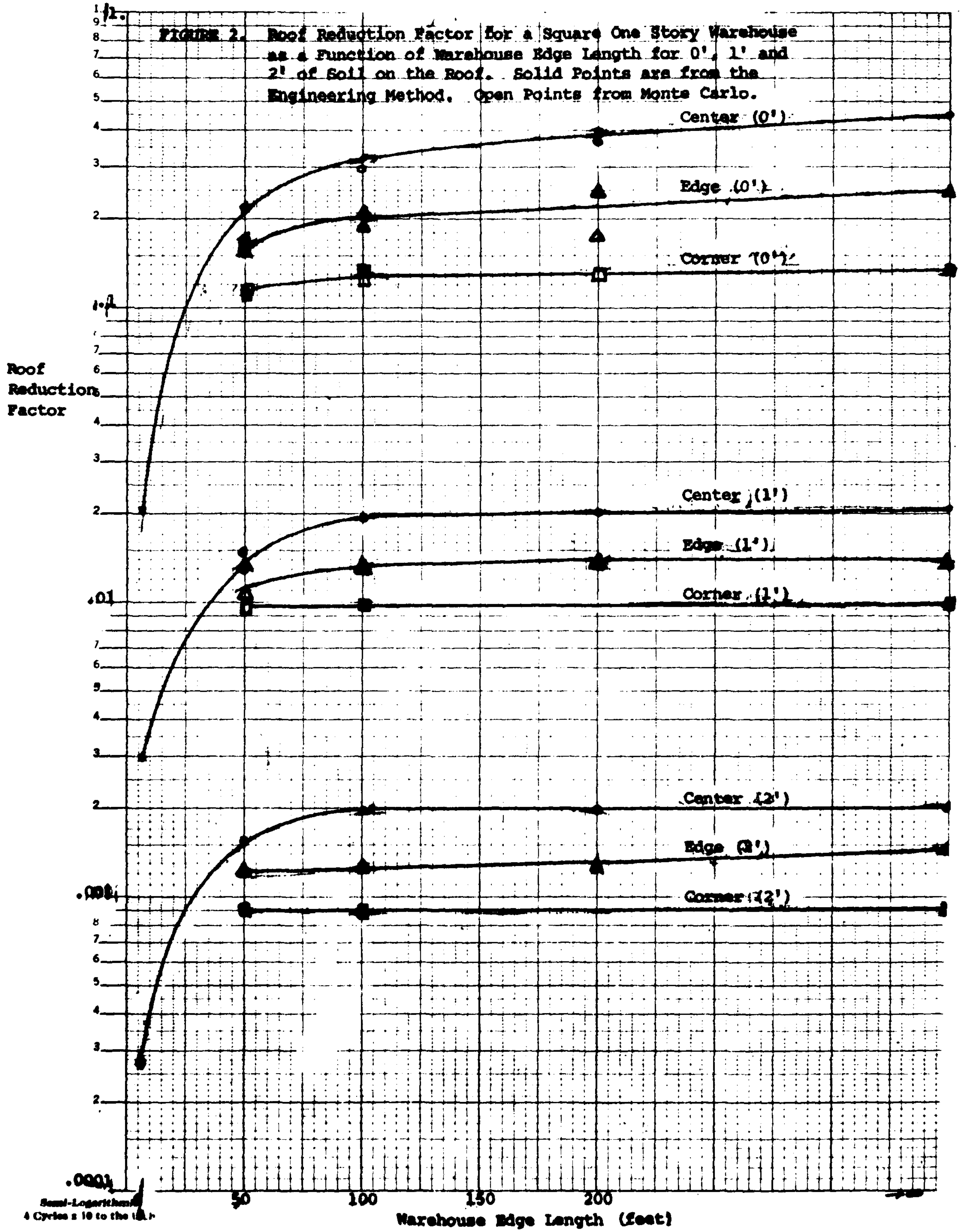

FIGURE 2. Roof Reduction Factor for a Square One Story Warehouse as a Function of Warehouse Edge Length for 0', 1' and 2' of Soil on the Roof. Solid Points are from the Engineering Method. Open Points from Monte Carlo.

A further preliminary note is that the curves shown by Spencer in NBS-42[5] indicate the dose due to fallout on small roofs or at edge and corner detectors to be somewhat different for ^{60}Co and early time (1.12 hours) fission product sources. For these reasons it was found necessary to use Figure B45 in reference 5 to obtain the dose reduction factors for a ^{60}Co source.

The single-story warehouse results are shown in Figure 2. Roof reduction factors are plotted versus roof dimension (square roof) with depth of soil as the parameter. For each value of depth, results are displayed for the center, edge and corner detectors.

From Figure 2 we can see that soil loading on the roof can be a very effective countermeasure. For example, for all detectors in all size warehouses, roof reduction factors of about .001 to .002 can be achieved by using 2 feet of soil on the roof.

The results of Figure 2 also show some interesting trends. Perhaps the most important of these is the fact that the first foot of soil added to the roof attenuates dose somewhat more than does the second foot. For example, for a 100' x 100' warehouse, center detector attenuation of the first foot is 16.3 and for the second foot it is 9.8. The relative decrease in attenuation is due to a drop in the relative contribution of distant* source components for soil depths greater than one foot.

The same explanation accounts for the rapid saturation of the roof reduction factor with respect to roof size for soil depths equal to or greater than one foot. Even for the 0' depth, the dose increases only slowly with roof size beyond a 50' edge length.

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*i.e., radiation which is not essentially overhead.

Figure 2 also shows that the 1' soil and 2' soil curves show about the same ratios of corner/edge/center detector reduction factors.

Finally, we have concluded from additional analyses that greater soil depths (if structurally feasible) will yield additional dose attenuation factors of approximately 10 for each added foot of soil.

3.2.2 <u>The Effects of a Roof Air Conditioner Unit</u>

It is a common situation for a warehouse roof to contain an air conditioning unit within which one cannot place soil for radiation protection. It is, therefore, of interest to determine the effects of such a unit on the dose at interior warehouse points.

We have considered the effects of a centrally located 6' x 6' x 4' (high) roof air conditioner unit. To be conservative, we treat the unit as a hollow shell only. Therefore the unit, in effect, generates a void within the soil loaded on the roof. The dose, due to fallout deposited on the unit (4' above the roof), was calculated at interior points by means of the SAM-CE Monte Carlo Code. The perturbations in the reduction factor, relative to the no-air conditioner case, were calculated at points 3 feet above the ground along an axis of a 100' x 100' warehouse starting at the center (see Figure 3). The points chosen were at 0, 6, 12, 18, 24 and 47 feet. Calculations were carried out for soil depths of 0, 1 and 2 feet of soil on the roof and 0 feet on the unit*. Two new components of the dose may be considered, vis-a-vis the no unit case; an additive dose due to fallout on the top of the unshielded unit and a subtractive dose due to removal of fallout on that part of the roof that is now occupied by the unit.

*Obviously, if it is feasible to place comparable soil loads on top of the unit, itself, the overall effect of the unit would be to further lower the reduction factors. This is so because the most important effect would then be the raising of the roof fallout (on the 6' x 6' unit), four additional feet away from the below-roof first story detectors. An illustrative example is given in Appendix A.

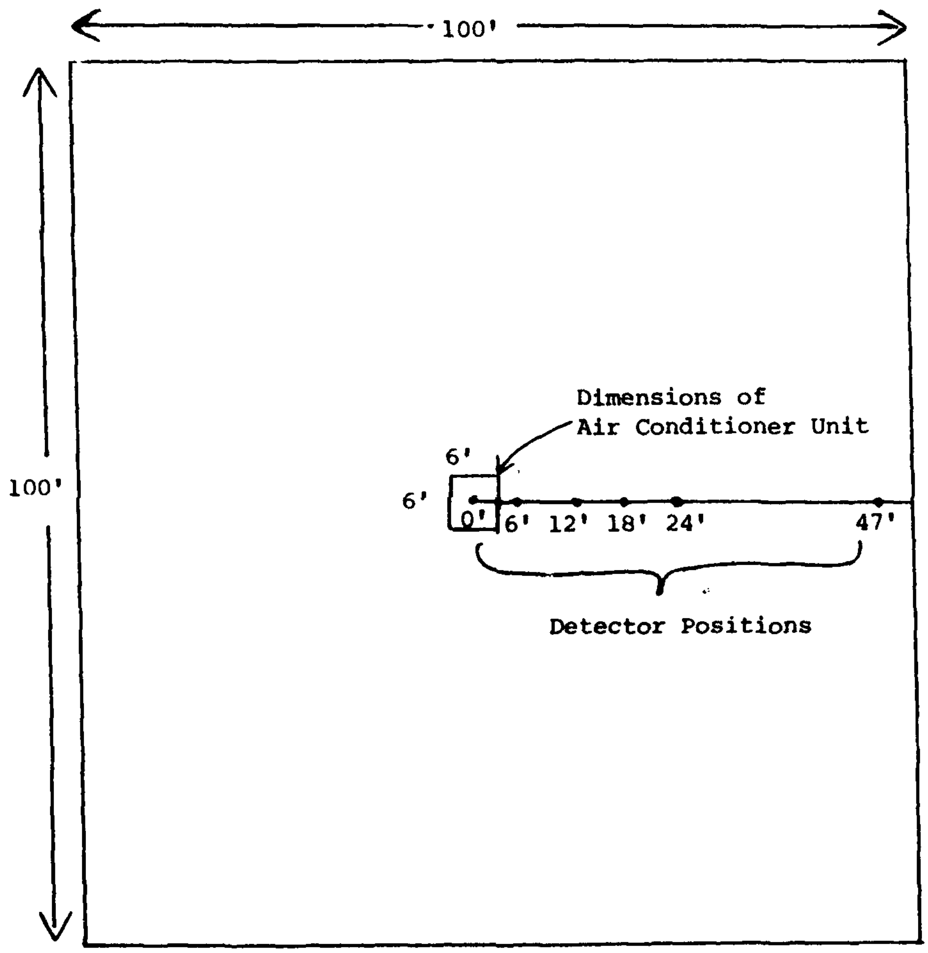

FIGURE 3. Location of First Story 3' High Detectors for the Air Conditioner Calculations.

Figure 4 shows the total perturbation in reduction factor due to the unit. For the case of no soil on the roof an overall negative perturbation occurs due to the removal of fallout at a lower height and addition of fallout at a greater height. The solid angle of the source subtended at the detector is thereby reduced. For the cases of 1' and 2' of soil on the roof, the removal of the protection afforded by the 6' x 6' area of roof soil outweighs the solid angle decrease obtained by raising the source. Thus, an increase in the reduction factor occurs. It is greater for 2' of soil than for 1' of soil primarily because of the removal of a larger amount of protection in the former case and because directly overhead radiation becomes increasingly important with increasing soil depth.

The shape of the curves is also rather interesting. The first 10.5' along the axis represents the range over which at least some radiation may pass directly from source to detector without striking the roof soil. The sharp decrease in dose over this range, with increasing axial positions is mainly due to the change in the area of unshielded source which can be seen by the detector. Beyond this range the dose drops off relatively slowly. The closeness of the 1' and 2' curves beyond 10.5' along the axis shows that this dose is mainly due to radiation which passes through the central duct, collides one or more times and finally scatters towards the detector.

The largest increase in reduction factor (∿.008) is seen to occur for a detector at the building center. This increase is important only in the case where large protection factors are desired; as when 2' of soil are placed on the roof. This point is more clearly established in Figure 5 in which we plot, for a 50' x 50' warehouse, the ratio of dose for fallout on top of a roof containing an air conditioner unit to the dose (for fallout on the same roof) without the unit. An increase in dose by more than a factor of five is found for the center detector with 2' of soil on the roof. In contrast, there is only a 30% increase in dose for 1' of soil and a 5% *decrease* for no soil on the roof. Note that

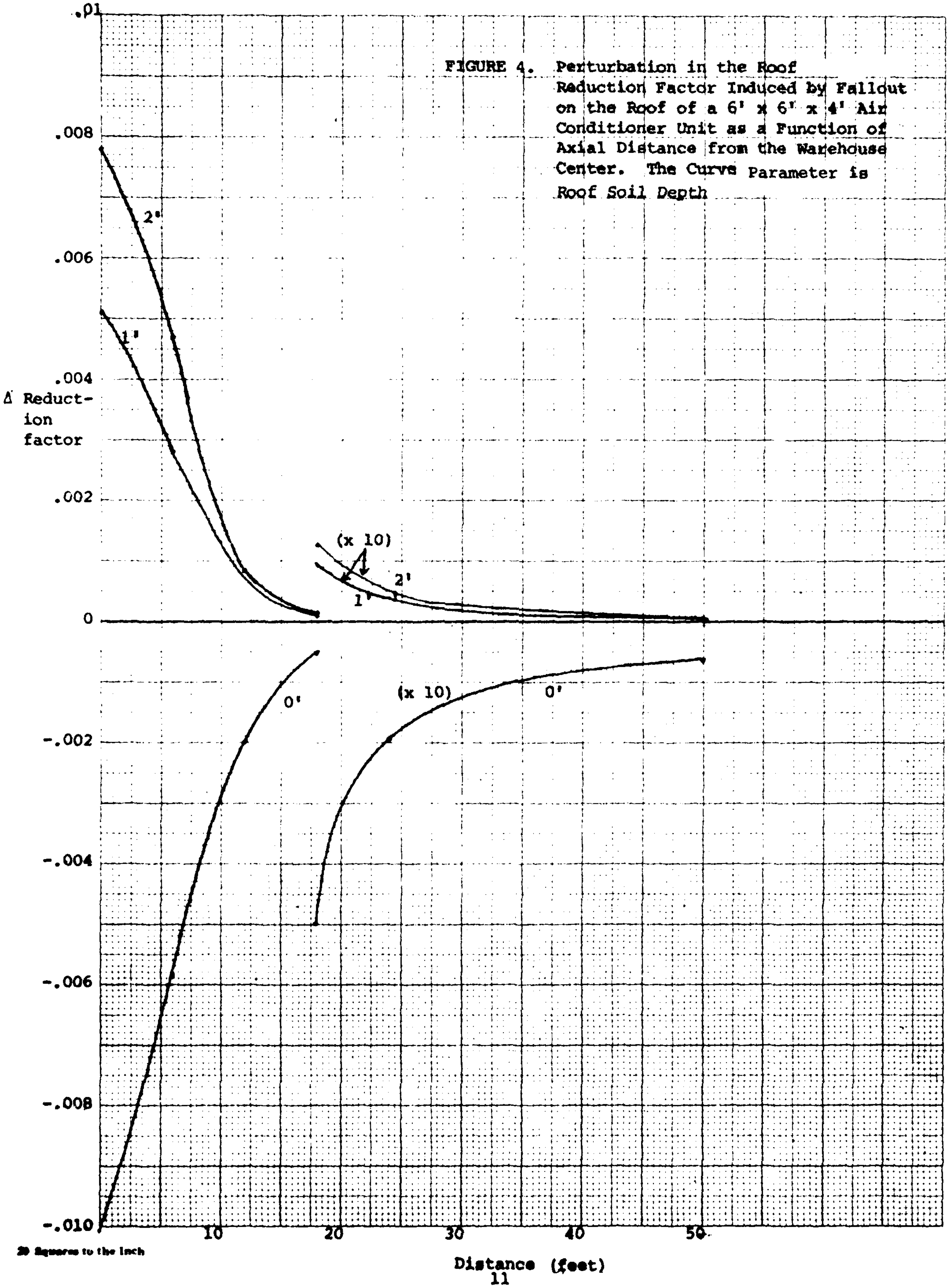

FIGURE 4. Perturbation in the Roof Reduction Factor Induced by Fallout on the Roof of a 6' x 6' x 4' Air Conditioner Unit as a Function of Axial Distance from the Warehouse Center. The Curve Parameter is Roof Soil Depth

20 Squares to the Inch

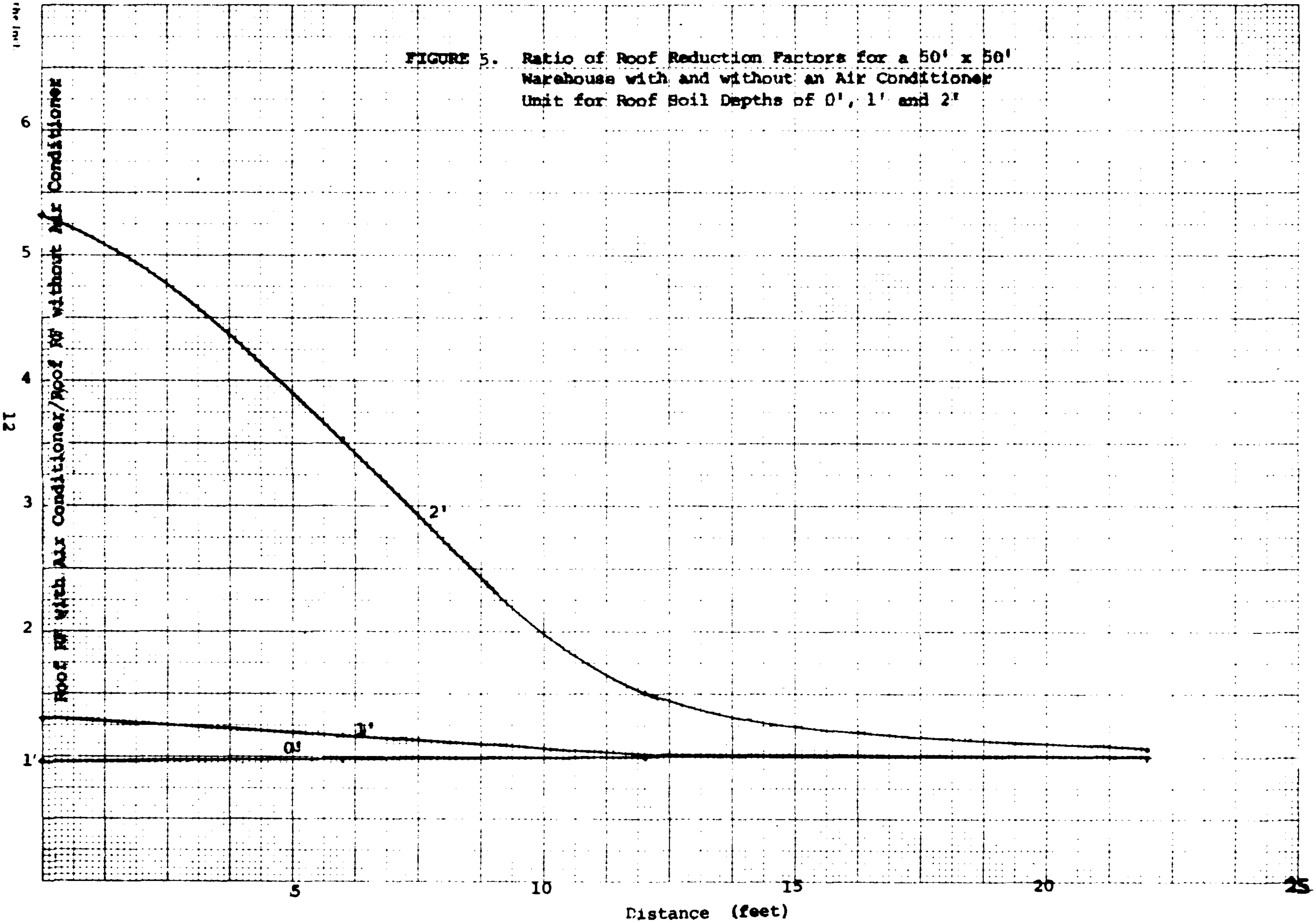

FIGURE 5. Ratio of Roof Reduction Factors for a 50' x 50' Warehouse with and without an Air Conditioner Unit for Roof Soil Depths of 0', 1' and 2'

since the air conditioner effect essentially disappears at a distance of ~15' from the center, the conclusions reached here are valid for all warehouses which exhibit dimensions greater than 30' x 30'.

If possible, soil should be placed on the air conditioner unit to obtain shielding against fallout on the unit. For example, it is shown in Appendix A that if 2' of soil are placed on the unit as well as on the roof, the net effect produced by the presence of the air conditioner unit is approximately an additional 6 to 7% decrease in the unperturbed roof reduction factor at the center detector.

Finally, it should be noted that very small additional contributions to dose may occur at internal warehouse points due to skyshine entering the air conditioner duct or to roof fallout radiation backscattering (from soil on top of the air conditioner) down into the warehouse. If protection against these components is desired a soil berm placed against the air conditioner duct wall will certainly suffice.

3.2.3 Fallout on a Building Overhang

There are situations in which a building may have an attached overhanging ledge. Many shopping centers have such protective ledges. Another example is that of house porches. Fallout on the ledge will contribute to the dose at interior points, particularly near edges and corners. Protection against the radiation can be obtained by placing soil berms against the building or by shoring up the ledges (if necessary) and placing soil on the ledge. When berms are used, the amount of soil can be minimized by placing sandbags on top of berms (see below).

We have carried out a set of calculations to determine the protection against roof overhang radiation afforded by the above means. A ledge 8' wide and 10' above ground was placed along one edge of the 50' x 50' one-story warehouse. The reduction factor was obtained at center, edge and corner positions for fallout uniformly distributed on the ledge. In Figure 6, we plot the results of Monte Carlo calculations for 45° berms of 0', 7' and 10' heights. For a 0' berm, edge and corner detectors show much higher doses than does the center detector because they are nearer to the fallout on the overhanging ledge. As one increases the berm height no noticeable change in the reduction factor occurs until the berm is of sufficient height (the critical berm height) to cut out some of the uncollided radiation. A simple geometric construction by the reader will show that for edge and corner detectors the critical berm height is 4.9' while for the center detector, the critical berm height is 8.25'. For a berm height of 10', center and edge detector reduction factors of ∿.0020 can be obtained. For the corner detector a reduction factor of ∿.0013 can be achieved.

Next consider two alternative choices (shown in Table 1). A 7' base berm is covered with sandbags from a 6' to a 10' height. A thickness of 93.8 psf was used for the sandbags. Reduction factors of .0019, .0028 and .0018 are found for center, edge and corner detectors, respectively. Another possibility is placing a one foot thick layer of soil on top of the ledge instead of using berms or sandbags placed against the building. The corresponding reduction factors in this case are .0011, .0034 and .0023.

We may conclude that with respect to protection against roof overhang fallout radiation, no clearcut advantage is obtained by using any of the three methods. The choice becomes a matter of convenience.

3.2.4 Fallout on the Ground

In addition to the roof reduction factors reported in the previous sections, reduction factors were also calculated (for the center, edge and corner detectors) in a 50' x 50' warehouse due to a uniform surrounding smooth fallout field. The percent contribution of each of the three components (direct, scattered and skyshine) and the overall ground reduction factors are tabulated in Table 2 for various combinations of roof soil depths, berms, and sandbags placed at a height of 6'-10' on a 7' base berm.

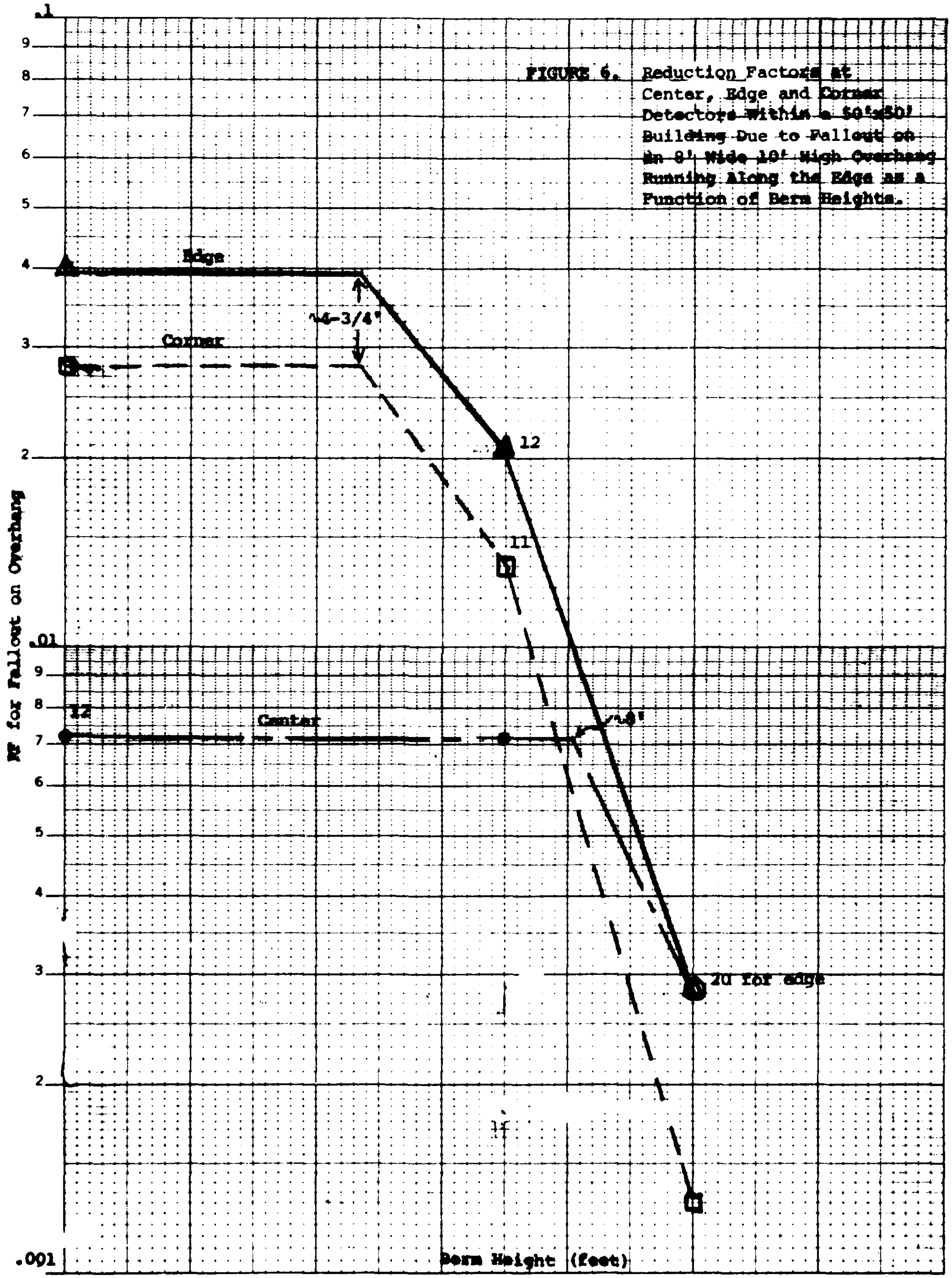

FIGURE 6. Reduction Factors at Center, Edge and Corner Detectors Within a 50'x50' Building Due to Fallout on an 8' Wide 10' High Overhang Running Along the Edge as a Function of Berm Heights.

TABLE 1 Reduction Factors at Center, Edge and Corner Detectors Within a 50' x 50' Building Due to Fallout on an 8' Wide 10' High Overhang Running Along the Edge for the No Shielding and the Following Three Shielding Configurations: 1) 10' Berm, No Soil on Overhang; 2) 7' Berm + Sandbags Along Wall at Heights of 6-10 Feet, No Soil on Overhang; 3) No Berm or Sandbags, 1' Soil on Overhang.

SHIELDING DESCRIPTION			DETECTORS		
Berm Height (feet)	Overhang Soil Depth (feet)	Sandbags	Center	Edge	Corner
0	0	No	0.0074	0.040	0.028
10	0	No	0.0028	0.0028	0.0013
7	0	Yes	0.0019	0.0028	0.0019
0	1	No	0.0011	0.0035	0.0023

TABLE 2. The Ground Fallout Reduction Factor and its Direct, Scattered and Skyshine Components for a 50' x 50' x 10' Single Story Warehouse

1) Reduction Factor ± % Statistical Error
2) % Direct, % Scattered, % Skyshine

Berm Height (feet)	Roof Soil Thickness (feet)	Sandbags*	Center	Edge	Corner
0	0	No	0.41±6.2 80.8,6.5,12.7	0.44±7.5 80.8,8.2,11.0	0.58±12 78.2,5.2,16.0
0	1	No	0.42±6.2 79.8,9.5,10.7	0.49±7.7 81.6,9.7,8.7	0.60±12 74.9,10.4,14.7
7	0	No	0.025±13 8.2,43.2,48.6	0.027±16 13.8,47.7,38.5	0.026±16 14.7,64.1,21.2
7**	0	No	.024±19 0,47.3,52.7	.020±19 0,53.4,46.6	.013±26 0,57.9,42.1
7	1	No	.021±14 11.6,66,22.4	.022±13 18.9,59.5,21.6	.025±20 18.5,74.8,6.7
7	2***	No	.021±14 11.6,66,22.4	.022±13 18.9,59.5,21.6	.025±20 18.5,74.8,6.7
7	2	Yes	.004±20 2.1,92.6,5.3	.0033±22 3.2,93.2,3.6	.0034±29 7.2,90.9,1.9
10	0	No	.020±17 9.7,31.6,58.7	--	.015±21 5.6,16.3,78.1
10	1	No	.013±33 13.4,84.6,2.0	.0069±21 21.6,76.9,1.5	.0069±16 21.6,78.1,0.3
12	2	No	.00033±12 <6.1 skyshine	.00077±40 <1.6 skyshine	.00051±20 <1.3 skyshine

*The sandbags column indicates whether a 93.76 psf thick sandbag is placed from a height of 6' to 10' above a 7' base berm.

**In this case fallout was removed from the innermost 3.5 feet of the berm to check the effect of close in fallout.

***A run for the skyshine component alone showed that there were no sigificant changes from the case of a 7' berm and of 1' soil on the roof.

First note that for the case of no protection at all the ground fallout dose is higher than the roof fallout dose*. The addition of one foot of soil on the roof (while it substantially decreases the roof fallout dose), actually serves to increase the ground fallout dose due to some radiation which enters the house through the walls and is then backscattered by the roof soil towards the detectors.

A 7' berm is seen to decrease the ground dose by about a factor of two. For this case the addition of one foot of soil on the roof now slightly decreases the ground dose. This occurs because the radiation entering the house through the sides for the 7' berm case is not as important as it is for the 0' berm case. In the former case, skyshine entering through the roof is a significant component of the dose. The effect of 1' of soil on the roof serves to decrease the skyshine more than to enhance the backscattered direct component. However, adding a second foot of soil to the roof results in no apparent effect on the dose. This leads to the conclusion that one foot of soil effectively screens out the soft skyshine radiation impinging upon the roof.

If we place sandbags from six to ten feet above a 7' base berm and place two feet of soil on the roof we obtain a sharp decrease in the reduction factor. The skyshine component, in particular, is reduced by factors of 20-40 with respect to the case of a 7' berm with no sandbags but with the same two feet of soil on the roof.

We note that a 10' berm with one foot roof soil depth provides less protection than does the corresponding 7' berm with sandbags. This is due to the combination of ground radiation which is scattered by the top of the 10' berm towards the detector, and fallout on top of the 10' berm which emits radiation which can directly or indirectly reach the detector.

*Compare Table 2 with Figure 2, above, for the 50' warehouse.

Finally, we note that the maximum protection is obtained by using a twelve foot berm and two feet of soil on the roof. For the center, edge, and corner detectors, ground reduction factors of .00033, .00077, and .00051, respectively can be achieved.*

The results found for the 50' x 50' warehouse can be used to estimate results for the 100' x 100' and 200' x 200' cases or indeed any fairly large rectangularly shaped warehouse. We first note that edge and corner results should be very much the same for the different warehouse sizes. This stems from the fact that radiation entering the warehouse close to the detector is much more important than radiation entering further away. (A comparison of the 50' x 50' case (Table 1) with that of the 29' x 39' KSU case (see Section 5.2 and Table 3) bears out this conclusion.) Since the edge and corner detectors remain 3' from the nearest walls the results do not vary widely with warehouse dimension.

The situation for the center detector is obviously quite different. Consider first radiation which collides within the walls and berms**. The walls and berms for this scattered radiation can be considered as radiation sources for direct radiation to the center detector. (It is assumed that radiation from this wall and berm source, which collides with building structure, is not of great significance.) It can be readily shown that for a building of length ℓ and width w the dose at the center, D_c, is given to good approximation by the following proportionality:

$$D_c \propto w^{-1} \text{Arctan}(\ell/w) + \ell^{-1} \text{Arctan}(w/\ell). \qquad (1)$$

For a square building, therefore, $D_c \propto \ell^{-1}$, that is, the scattered dose at the center is inversely proportional to the building side.

For direct radiation in the case of 7'-10' berms, the radiation source comes primarily from fallout resting on the top of the berms. Once again, then, the berms serve as radiation sources and therefore, equation 1 is again valid

*Analysis of the geometry in this case shows that the skyshine radiation dose is at least a factor of 10 lower than other components of the dose.

**This analysis is for the situations of warehouses with 7'-12' berms.

Skyshine, on the other hand, behaves differently. For skyshine coming through the roof, the situation is not much different than described previously for fallout on the roof. Recall that with sufficient material on the roof, saturation of the roof dose with warehouse size occurs. Since skyshine radiation is much softer than roof fallout radiation, lesser thickness are required for the saturation. Skyshine streaming through walls should also show a constant behavior with building size since increasing the building size just decreases the solid angle of wall subtended at the center detector proportionately. This is exactly cancelled by the larger area for skyshine radiation offered by the increased length of wall.

Further justification of the models presented here will be considered in Section 5.2.

We have, therefore, developed methods for obtaining dose for different size buildings. They will be utilized below.

3.3 Overall Protection Factors for the One-Story Warehouse

The protection factors for various combinations of roof soil, berms and sandbags were obtained by taking the reciprocal of the sum of roof fallout reduction factors obtained from Section 3.2.1 and ground fallout reduction factors of Section 3.2.4. These were obtained directly for the 50' x 50' warehouse. For the 100' x 100' and 200' x 200' warehouses they were obtained as described in Section 3.2.4. The results are given in Table 3.

From Table 3, it is seen that very small PFs are afforded for no countermeasures at all. Adding 1' of roof soil does not do much good since the ground radiation is dominating the problem. Using a 7' berm but no roof soil is noticeably better but now the roof contribution is important enough to keep the PFs well below 10. That is why even the 10' berm - 0' on roof also has PFs well below 10. In the next category are the 7' berm - 1' roof, 7' berm - 2' roof, 10' berm - 1' roof, 10' berm - 2' roof cases for which PFs in the 30-150 range are obtainable.*

*In the remainder of this paragraph numerical results are given for the 50' x 50' warehouse. The trends for the other warehouses are similar.

TABLE 3. Protection Factors for Square Single Story Warehouses 50, 100 and 200 Feet on a Side

DESCRIPTION				DETECTOR LOCATION		
Warehouse Side (feet)	Berm Height (feet)	Roof Soil Thickness (feet)	Sandbags	Center	Edge	Corner
50	0	0	No	1.6	1.7	1.4
50	0	1	No	2.3	2.0	1.6
50	7	0	No	4.1	5.5	7.1
50	7	1	No	28	28	29
50	7	2	No	45	43	39
50	7	2	Yes	180	220	230
50	10	0	No	4.2	5.4	7.7
50	10	1	No	36	50	61
50	10	2	No	69	120	130
50	12	2	No	520	500	710
50	12	3	No	2000	1100	1700
100	0	0	No	1.8	1.5	1.4
100	0	1	No	--	2.0	1.6
100	7	0	No	2.9	4.1	6.2
100	7	1	No	31	28	29
100	7	2	No	68	43	39
100	7	2	Yes	240	220	230
100	10	0	No	3.0	4.0	6.7
100	10	1	No	39	49	60
100	10	2	No	120	120	130
100	12	2	No	460	480	710
100	12	3	No	2600	1100	1700
200	0	0	No	1.9	1.4	1.4
200	0	1	No	--	2.0	1.6
200	7	0	No	2.4	3.6	7.0
200	7	1	No	37	28	29
200	7	2	No	110	43	39
200	7	2	Yes	307	210	230
200	10	0	No	2.4	3.6	6.6
200	10	1	No	42	48	60
200	10	2	No	190	120	130
200	12	2	No	470	470	700
200	12	3	No	3200	1100	1700

For the 10' berm - 2' roof case, most radiation is reaching the detectors through the top of the berm. Therefore, when the 10' berm is replaced by a 7' berm with sandbags, the PFs rise to ∿200. When a 12' berm is used PFs of 500-700 are obtainable with 2' of soil on the roof. At this point roof and ground contributions are of the same order of magnitude. The placing of another foot of soil on the roof (if feasible) would effectively screen out the roof contribution entirely and more than doubles the overall PFs to the 1000-2000 range.

Increasing warehouse size is seen to increase the protection obtainable at center detector points in some cases (such as a 12' berm and 3' of roof soil). In other center detector cases, and for edge and corner detectors, building size has little effect on the dose.

4. THE TWO STORY WAREHOUSE

4.1 Description of Building Geometry

The two-story warehouse consisted of a 50' x 50' x 20' steel shell. The walls were again assumed to be 5 psf. A concrete floor 15 psf thick was placed 10' above the ground. Once again, detectors 3' above the ground floor were placed at the center, edge, and corner positions.

4.2 Fallout on the Roof

Monte Carlo calculations were carried out for three cases: no soil on second floor or roof; one foot of soil on the roof; one foot of soil on the second floor and one foot of soil on the roof. The results are plotted in Figure 7. Also shown for comparison are roof results as a function of soil depth for an "equivalent" one story warehouse with a 20 psf thick roof*.

We note that the two story house offers somewhat more protection than the equivalent one-story house. There are two reasons for this. First, the roof radiation source in the former case is further removed from the detector. Second, some of the radiation striking the soil on the roof of the two story house is scattered out of the building without ever hitting the second floor.

4.3 Fallout on the Ground

Several Monte Carlo calculations were performed to determine differences in dose, between the one and two story warehouses, due to fallout on the ground. The results are summarized in Table 4. The case of no protective berms or soil on the roof shows no appreciable difference in the reduction factors for the two buildings. The reason for this is that $\sim$80% of the dose is due to direct uncollided radiation which is unaffected by the presence of a second story. In addition, most of the remaining dose comes from radiation impinging upon the walls of the first story.

*That is, the 5 psf roof and the 15 psf second floor are combined into a 20 psf roof.

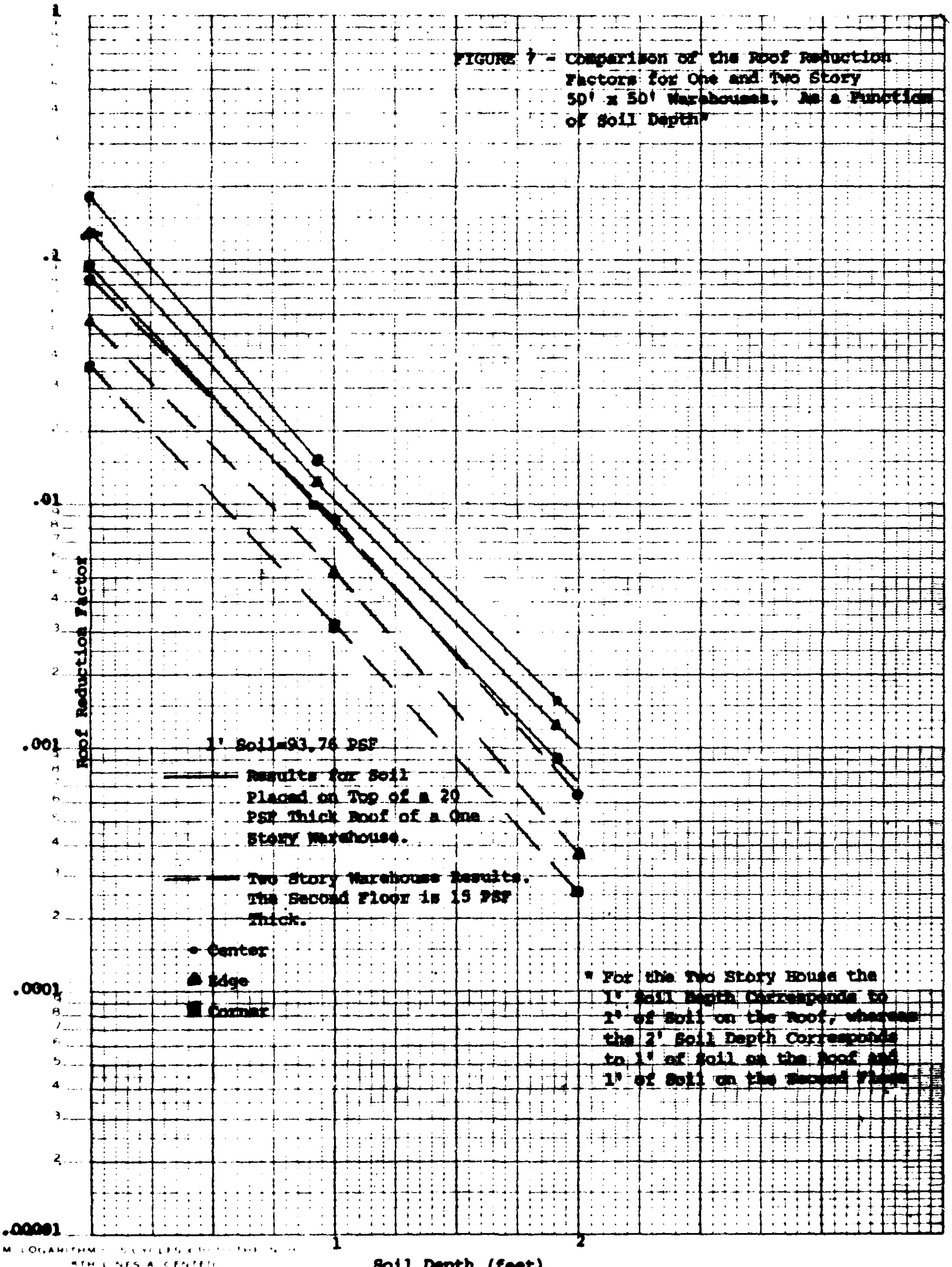

FIGURE 7 - Comparison of the Roof Reduction Factors for One and Two Story 50' x 50' Warehouses, As a Function of Soil Depth*

TABLE 4. The Ground Fallout Reduction Factor and its Direct, Scattered and Skyshine Components for a 50' x 50' x 20' Two Story Warehouse

(1) Reduction Factor ± Statistical Error
(2) % Direct, % Scattered, % Skyshine
(3) (Reduction Factor Single Story Warehouse ± % Statistical Error)

Berm Height (feet)	Roof Soil Thickness (feet)	Second Floor Soil Thickness (feet)	Center	Edge	Corner
0	0	0	0.40±5.6 80.3,13.4,6.3 (0.41±6.2)	0.47±5.9 79.0,14.8,6.2 (0.44±7.5)	0.50±13 74.6,9.1,16.3 (0.58±12)
7	0	0	0.042±20 5.1,79,15.9 (0.025±13)	.040±18 9.2,78.2,12.6 (0.027±16)	.028±8.5 16.5,74.0,9.5 (0.026±16)
7	1	0	.0507 --- (.021±14)	.043 --- (.022±13)	.030 --- (.025±20)
7	1	1	.0217±12 10.4,68.2,21.4 (.021±14)*	.025±13 16.9,63.8,19.3 (.022±13)*	.029±18 14.1,80.1,5.8 (.025±20)*

*These results are for two feet of soil on the roof.

The situation is qualitatively different for the case of a 7' berm with 0' soil on the roof and on the second floor. Under these conditions, uncollided dose, except for that arising from fallout on the berm, is effectively eliminated. Also, the 15 psf second floor eliminates much of the soft skyshine radiation. On the other hand, scattered radiation is strongly increased over the one story warehouse due to the presence of the second story walls. This results in a 70% increase in the reduction factor for a center detector. For a corner detector there is almost no effect due to the large scattering angle required for close-in radiation striking the second story walls to reach the detector. The edge detector is intermediate between the two other cases.

If we add a foot of soil above the second floor we once again find results consistent with the one story house. The large amount of soil sharply cuts down any radiation scattered from second story walls. We may conclude that for one foot (or more) of soil on the second floor, the reduction factor at first floor detectors is essentially the same as for a one story warehouse with the corresponding amount of soil on the roof.

Our data also allows conclusions to be made for the case of one foot or more of soil on the roof but none on the second floor. Obviously, the direct component of the ground dose must be the same as for the no roof soil case. One may estimate the effect of the roof soil on the scattered component by noting the effect of roof soil on this component for a one story warehouse. From Table 2, above, we find that for the 7' berm case, one foot of roof soil increases the scattered dose by about 25% for the center detector and about 10% for the corner detector. (The edge detector increase may also be regarded as 10% even though no increase seems to occur due to statistics). These increases may be regarded as conservative upper limits due to the larger scattering angle (and subsequently lower dose) required for scattering of radiation from soil located on a 20' high roof over that required for soil on a 10' roof. For the skyshine component, we can obtain the effect of a second story roof by observing the difference of these components between the no soil case and the case of 1' on roof and 1' on second floor for a 7' berm. Less than 5% effect is found. Skyshine entering above the first story is effectively shielded out.

Using these considerations, we estimate the reduction factor for the case of a 7' berm with 1' of soil on the roof. This is shown in Table 4 to be 0.051, 0.043 and 0.030 for center, edge and corner detectors, respectively.

4.4 Protection Factors for the Two Story Warehouse

The two story protection factors are given in Table 5. Notice that for no shielding one obtains somewhat better protection than for the one story warehouse. The reason for this is the reduction in the roof dose due to the presence of the 15 psf second floor and the removal of the roof fallout by an additional 10'. For a 7' berm and no roof or second story soil, the roof component becomes very important and twice as much protection is gained by the two story warehouse as compared to the one story warehouse. If, however, one foot of soil is placed on the roof with a 7' berm around the warehouse, the dose is higher for the two story case than for the one story warehouse. Adding soil to the second story does not do quite as much good as would adding an extra foot of soil to the roof of the one story warehouse

The 10' berm case for 1' of soil on roof and second floor gives slightly better protection for the two story case as compared with two feet of soil on the roof of a corresponding one story warehouse.

TABLE 5. Protection Factors for One and Two Story 50' x 50' Warehouses. The One Story Results are Given in Parentheses

DESCRIPTION			DETECTOR LOCATION		
Berm Height (feet)	Roof Soil Thickness (feet)	Second Floor Soil Thickness (feet)	Center	Edge	Corner
0	0	0	2.1 (1.6)	1.9 (1.7)	1.9 (1.4)
7	0	0	8 (4.1)	10 (5.5)	16 (7.1)
7	1	0	17 (28)	21 (28)	31 (29)
7	1	1	45 (45)*	40 (43)*	34 (39)*
10	1	1	75 (69)*	130 (120)*	140 (130)*

*These results are for two feet of soil on the roof.

5 SMALL WOOD-FRAME BUILDING

5.1 Description of the Building

The final structure considered in this study was the Kansas State University (KSU) House[6]. This smaller house is a one-story wood frame structure. (See Figure 8.) The floor area is 29' x 39'. Above the ceiling of the first story (at a height of 10') is an attic formed by a pitched roof which rises to a maximum height of 6'. The roof overhang extends past the building walls and covers a 36' x 43' horizontal area. The wall thicknesses are 5.30 psf. Thicknesses of ceiling, roof and roof side sheathing are 3.92, 4.2 and 2.085 psf, respectively. No internal wall structure is assumed.

In earlier work, described in the literature[1], a large number of calculations were performed for the KSU house with no basement (main floor at grade level) and with a basement (main floor 3' above grade level). Since this work is largely concerned with the grade level warehouses, the no basement KSU house was the one considered for additional investigations. For the new studies, we treated center, edge (along the longer edge) and corner detectors for purposes of comparison with the warehouse calculations. In the present set of KSU house calculations, tightly packed earth (ρ=1.5) was used instead of the loosely packed earth used previously (ρ=1.05).

The main goal of the present work was a more detailed consideration of dose components than in the previous work. This was particularly true for the ground dose reduction factor which was, for this study, separated into direct, scattered and skyshine components. Furthermore, one can obtain more general modeling results by intercomparing the 50' x 50' one story warehouse and the KSU house results.

KSU-House

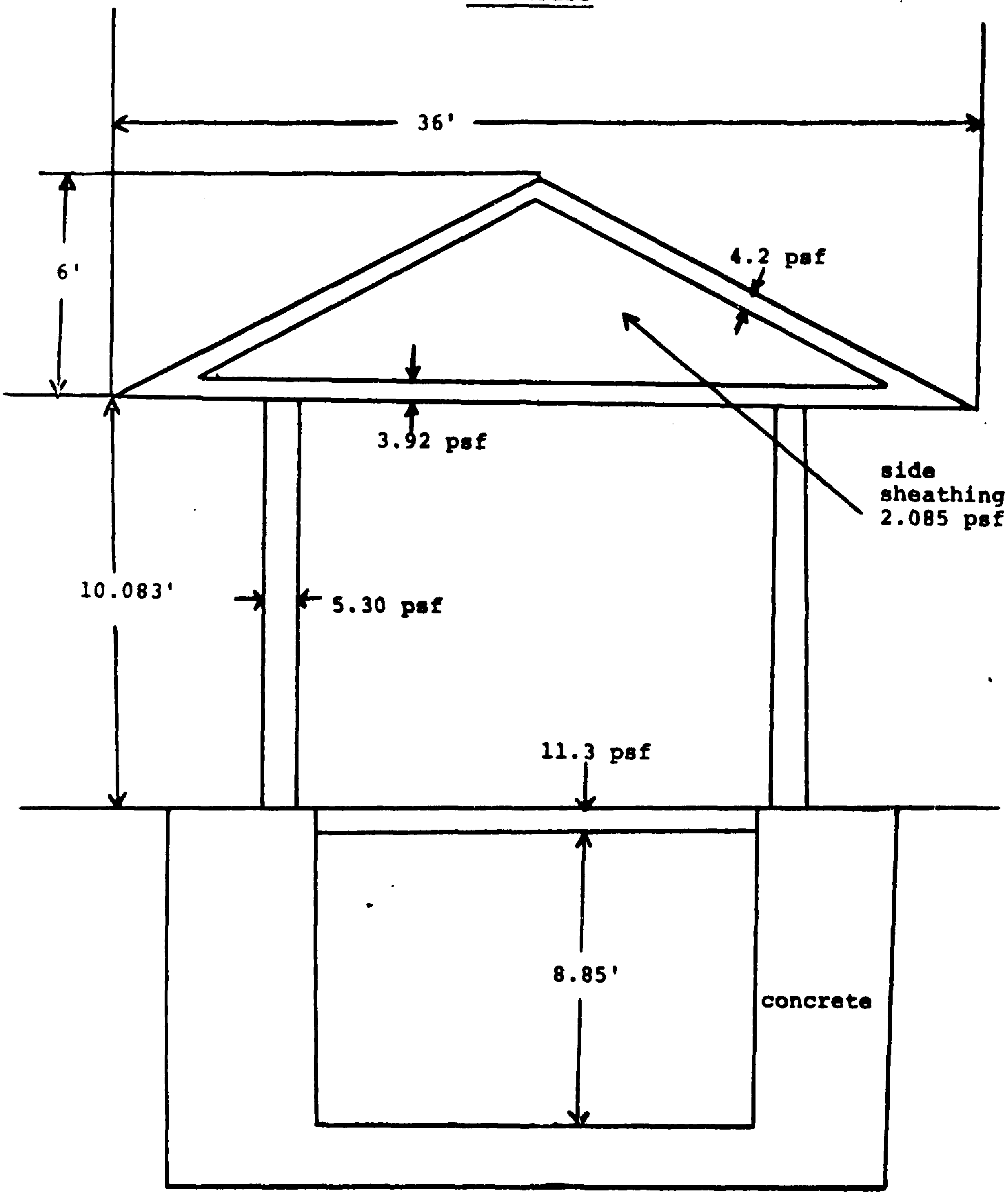

Figure 8 (not to scale)

5.2 KSU House Ground Fallout Results

Reduction factors are given in Table 6. First note that for a 7' berm with 0' of soil on the roof, the dose for a center detector is sigificantly higher than the similar 50' x 50' warehouse case (Table 2) in which fallout within 3.5* feet of the walls has been removed from the berm (both buildings have about 5 psf walls). For the scattered radiation component, the ratio of reduction factors of the KSU house to the 50' x 50' warehouse is 1.7. Using the model presented in section 3.2.4 (Equation 1) we obtain a ratio of 1.5. The results are clearly consistent within statistics. For the skyshine component, the dose ratio is 1.0. Our model claims equality for the two results.

For edge and corner detectors, ratios of total ground reduction factors are 1.05 and 1.26. Both values are statistically consistent with the expected value of 1.0.

Comparisons between houses for other configurations for the scattered component are difficult due to either poor statistics or different fallout patterns. The 50' x 50' warehouse has fallout on the full berm while the roof overhang cuts off fallout from the top ~2½ feet of the KSU berm. The one other case where results for both houses are comparable is that for sandbags atop six feet of a 7' berm. Here one foot of fallout is cut off by the sandbags. For this case, the scattered reduction factor ratio is 1.34. This is statistically consistent with the predicted value of 1.54.

The comparison of KSU results with the 50' x 50' warehouse results with fallout on the full berm, in general, show a slight increase in dose of the former over the latter for a center detector.

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*The KSU house has roof overhangs averaging ~2.5 feet.

TABLE 6. The Ground Fallout Reduction Factor and its Direct, Scattered and Skyshine Components for the KSU House. One Story 50' x 50' warehouse Results are Given in Parenthesis for Comparison

(1) Reduction Factor ± % Statistical Error
(2) % Direct, % Scattered, % Skyshine
(3) (Reduction Factor Single Story Warehouse ± % Statistical Error)

Berm Height (feet)	Roof Soil Thickness (feet)	Sandbags	Center	Edge	Corner
0	0	No	0.45±4.5 80.1,11.1,8.8 (0.41±6.2)	0.49±5.2 78.8,13.1,8.1 (0.44±7.5)	0.49±6 79.1,13.3,7.6 (0.58±12)
7	0	No	0.033±14 0,60,40 (.025±13)	0.021±12 0,56.2,43.8 (.027±16)	0.017±12 0,64.4,35.6 (.026±16)
7	1	No	0.037±23 0,83.6,16.4 (.021±14)	0.024±22 0,86.1,13.9 (.022±13)	0.016±22 0,93.0,7.0 (.025±20)
7	0	Yes	0.022±19 0,65.0,35.0 --	0.012±16 0,50.1,49.9 --	0.0095±15 0,50.2,49.8 --
7	1	Yes	0.0063±22 0,81.8,18.2 (.0041±20)	0.0035±22 0,97.6,2.4 (.0033±22)	0.0035 -- (.0034)
10	1	No	0.013±24 0,92.2,7.8 (0.013±33)	0.0082±30 0,98.6,1.4 (0.0069±21)	0.0063±21 0,98.8,1.2 (0.0069±16)
7*	1	No	0.014 0,60.1,39.9 --	0.013 0,51.9,48.0 --	0.0074 0,62.9,37.1 --

*A buried source was used in this case.

Corner and edge detector results indicate a somewhat higher dose for the warehouse than for the KSU house.

The division of dose between scattered and skyshine components shows some interesting features. Both components are relatively small for the case of no berms or roof soil with the scattered component somewhat larger than the skyshine component. Adding berms cuts out the direct dose. Adding 1' of roof soil and a 7' berm cuts down the skyshine dose at center, edge and corner detectors by factors of about 2, 3, and 5, respectively.

Adding 4' of sandbags atop six feet of the 7' berm sharply decreases the dose if one also adds 1' of soil to the roof. It should be noted that the skyshine component for this case is not negligible for a center detector. This is due to skyshine entering the attic wall above the sandbags.

The skyshine component also has the same value for the case of a 10' berm and 1' of soil on the roof as for the sandbag case for obvious reasons. The scattered radiation, however, seems to be about twice as high as in the sandbag case. An explanation for this phenomenon may come from the fact that for the 10' berm, fallout on the berm along the building width lies close to the region between berm top and roof. On the other hand, for the sandbag case, fallout on the 7' berm lies further away from the region between the top of the sandbag and the roof. More radiation is, therefore, scattered from the side of the building towards the detector, in the former case than in the latter.

The last row in the Table is the reduction factor for a 7' berm and 1' of soil on the roof for fallout on rough rather than smooth ground. The fallout on the ground is covered by 0.5 inches of soil to simulate roughness (the berm is assumed pressed down and smooth). The soil density is 1.5 g/cm^3 rather than the 1.05 g/cm^3 used in reference 1, i.e., our soil is rougher than the reference 1 soil. The ratio of rough to smooth ground doses for center, edge and corner detectors is .38, .52, and .45, respectively. The ratio for the scattered component is about .30 for all the detectors. By comparison, reference 1 results showed that for a lesser amount of rough ground, a 6' berm showed a ratio of .55 for a corner detector and .40 for a 4' berm. If we assume a linear extrapolation of the ratio with berm height and apply the rate of rise to our case, we find a ratio of .70 for a 10' berm. This is a conservative value because reference 1 indicates a fall in the rate of rise of the ratio above 6' berms.

5.3 KSU House Protection Factors

The protection factors for the KSU house are given in Table 7. The results clearly show that radiation protection at a corner detector is greater than or equal to that at a center detector. A second point to note is that large berms or sandbags piled to a height of 10' in conjunction with 2' of roof soil give lower protection at center locations for the KSU house than for the 50' x 50' warehouse. Piling of soil or sandbags to the top of attic walls is clearly required for the KSU house if larger PFs are to be achieved. To obtain PFs 1000 it also seems to be necessary to pile soil so that berms reach to the top of 3' of roof soil.

TABLE 7. Protection Factors for the KSU House and a 50' x 50' One Story Warehouse. Warehouse Results are given in Parenthesis

DESCRIPTION			DETECTOR LOCATION	
Berm Height (feet)	Roof Soil Thickness (feet)	Sandbags	Center	Corner
0	0	No	1.7 (1.6)	1.7 (1.4)
7	0	No	6.5 (4.1)	8.1 (7.1)
7	1	No	20 (28)	36 (29)
7	2	No	26 (45)	57 (39)
7	0	Yes	7.0 (2.9)	8.7 (6.2)
7	1	Yes	53 (52)	63 (76)
7	2	Yes	130 (180)	220 (230)
10	1	No	39 (36)	58 (61)
10	2	No	68 (120)	130 (130)
7*	1	No	38 --	54 --

*A buried source was used in this case.

6. CONCLUSIONS

Due to the many variations of warehouse and other light frame structures which exist in rural areas, any study, such as this one, can serve only as an indication of the typical kinds of results which may be achieved by the use of soil as a countermeasure against fallout radiation. Nevertheless, certain conclusions of a general nature can be reached and these are summarized below:

1. It is possible to obtain protection factors greater than 1000 for warehouse structures by the use of 12' berms against the walls and 3' soil depths placed on shored up roofs of one story structures or on the second floor of multi-storied structures.

2. If such large berms cannot be attained but the use of sandbags is feasible, the next best alternative is the use of 7' berms truncated at 6' and the piling of sandbags on top to a 12' height, and use of 2' of soil depths on the roof. Better results are obtained by this method than by using 10' berms and 2' of roof soil. In the latter case, radiation incident upon the top 1' or 2' of the berm strongly increases the radiation dose at points within the building.

3. The 50' x 50' one story warehouse protection factors can be extrapolated to yield protection factors for any rectangular structure with dimensions that are not too small.

4. Addition of further soil (ρ=1.5) to roof soil depths greater than 1' causes a further rate of drop in reduction factor by about a factor of 10 per foot.

5. Air conditioner units placed on the roof increase the dose substantially only for roof soil depths greater than 1'. However, almost no dose increase is found beyond interior points more than 15' from the vertical axis of the air conditioner shaft.

6. Adding one foot or more of soil to the second floor of a two-or multi-story building allows the reduction factor due to ground fallout to be computed in the same way as for a single story warehouse.

7. Houses with sloping roofs require soil berms or sandbags to be piled high enough so that attic walls are completely covered (together with roof soil depths of 2') if PFs of 200 are to be achieved. PFs greater than 1000 require berms reaching to the top of 3' of roof soil.

7. REFERENCES

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5. Spencer, L. V., "Structure Shielding Against Fallout Radiation From Nuclear Weapons", NBS-42 (June 1962).

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APPENDIX A

AIR CONDITIONER UNIT LOADED WITH SOIL

The results presented in Section 3.2.1 and 3.2.2 can be used to assess the effects of loading the same amount of soil on the air conditioner unit (if feasible) as is loaded on the rest of the roof.

Let us examine the center detector for the 100' x 100' warehouse, with 2' of soil on the roof and 2' on the 6' x 6' x 4' (high) air conditioner unit. Then the perturbation in the reduction factor is almost entirely the perturbation due to raising a 6' x 6' x 2' soil mass (no air conditioner unit) four feet higher in the air:

$$\Delta RF \simeq RF(6' \times 6' \times 2' \text{ on roof}) - RF(6' \times 6' \times 2' \text{ on } 4' \text{ unit}) \quad (1)$$

Expression (1) can be rewritten as:

$$RF = \left[\frac{RF(6x6x2 \text{ on roof})}{RF(6x6x0 \text{ on roof})}\right] \times RF(6x6x0 \text{ on roof}) - \left[\frac{RF(6x6x2 \text{ on } 4' \text{ unit})}{RF(6x6x0 \text{ on } 4' \text{ unit})}\right] \times RF(6x6x0 \text{ on } 4' \text{ unit})$$

From Figure 2 of the main text (6x6 warehouse-center detector), the term in the first set of brackets is found to be .00026/.02=.013. Furthermore, we assume that the attenuating effect of a 2' thick 6' x 6' area is essentially independent (at the 3' high indoor detector) of whether the mass is at roof level or 4' higher than that. Therefore, the term in the second set of brackets is also .013. Thus,

$$\Delta RF \simeq .013 \left[RF(6x6x0 \text{ on roof}) - RF(6x6x0 \text{ on unit})\right]$$

Adding the rest of the roof (outside the 6x6 area) to both terms:

$$\Delta RF \simeq .013 \left[RF(100x100x0) - RF(100x100x0 \text{ with 6x6 unit on mid-roof})\right]$$

From Figure 4, it is seen that the term in brackets is $\sim -.01$.

Hence:

$\Delta RF \approx .013\ (-.01)$

or $\Delta RF \approx -.00013.$

Returning to Figure 2, it is seen that the RF for a 100 x 100 warehouse with 2' of soil on the entire roof, center detector is ∿.002. Therefore, the overall perturbation in reduction factor due having present a 4' high air conditioner unit with 2' of soil on the unit as well as on the rest of the roof, is a further lowering of the reduction factor by

$$.00013/.002 = .065$$

or by about 6½%.

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Results were obtained for various countermeasures involving different amounts of soil loaded on the roof and bermed against the outer walls of the structures considered.

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