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SHELTER DESIGN AND ANALYSIS

VOLUME 2 – EQUIVALENT BUILDING METHOD

DEPARTMENT OF DEFENSE • OFFICE OF CIVIL DEFENSE

SHELTER DESIGN AND ANALYSIS

Volume 2—Equivalent Building Method of Fallout Radiation Shielding Analysis and Design

Supersedes Shelter Design and Analysis, Volume 2,
dated September 1963, and change 1, dated April 15, 1964—which may be used

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FOREWORD

This publication is a simplified approach to fallout radiation shielding analysis and design. It has been distributed by the Architectural and Engineering Development Division, Technical Operations Directorate, Office of Civil Defense in the interest of providing to the engineering and architectural professions new technical data and methods which are more easily manipulated in the preliminary design stages.

This report is based on the Engineering Manual (OCD PM 100–1) and should provide results within a few percent of this approved method of analysis and design. The Equivalent Building Method presented here is designed to provide a rapid method of analysis of structures, a means of investigating the effect of the various shielding parameters and a procedure for the economic design of shelter shielding.

This report does not explain the basic physics of structure shielding against fallout radiation. Readers who are not familiar with the basic aspects of fallout radiation and fallout radiation shielding are advised to consult the OCD Engineering Manual,[1] NBS Monograph 42,[2] and the Effects of Nuclear Weapons.[3] This report will be of most value to those engineers and architects who have completed the OCD sponsored courses in Fallout Shelter Analysis or their equivalent.

NOTE: These superior figures refer to numbered references on page 13.

ABSTRACT

The Equivalent Building Method of Fallout Shielding Analysis and Design is a simplified approach to fallout shielding based on replacing a complicated actual situation by a simple, single-story, solid wall "equivalent" building of the same floor area. This is done by computing "equivalent" roof and wall mass thicknesses to replace the actual mass thicknesses and other shielding parameters. These equivalent mass thicknesses are used with a protection factor chart from which the proper protection factor is directly obtained. Two basic functional equations are used:

$Xo' = Xo(A,z,Xi)$ for Equivalent Roof

$Xw' = Xe'(Xe,Ap) + Xi \pm \Delta Xw$ for Equivalent Wall

Although the method is simple and quick, it is based on the OCD Engineering Manual and NBS Monograph 42 and solutions obtained with it will yield comparable results. In addition, the Equivalent Building Method offers a rapid means of obtaining the most economic shield for a required protection factor.

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SYMBOLS

Note: Wherever possible the Symbols used in the Equivalent Building Method are the same as those used in the Engineering Manual.

Mass Thickness Symbols, psf (pounds per square foot)

Xe —Exterior Wall
Xf —Floor
Xi —Interior Wall
Xo —Total Overhead
Xr —Roof
Xw —Total Wall
Xop—Equivalent Peripheral Roof
Xe′ —Equivalent Exterior Wall
Xo′ —Equivalent Total Roof
Xw′—Equivalent Total Wall

Mass Thickness Correction Factors, psf

ΔXo(Xi) —Interior Partition to Overhead
ΔXw —Total Wall
ΔXw(A,H)—Height
ΔXw(Ms) —Mutual Shield
ΔXw(Xf) —Floor Barrier
ΔXw(Ex) —Exposed Basement Wall
ΔXw(FC) —Floor Above and Below Detector Floor

Area Symbols

A —Total Area of Building
Ab —Equivalent Basement
Ac —Core
Ar —Roof
Aw—Wall
A′ —Adjusted Total Building
Ac′—Adjusted Core

Protection Factors

Pf —Protection Factor for Detector Location
Pfo—For Contribution From Detector Floor Only
Pfu—For Contribution From Floor Above Only
Pfb—For Contribution From Floor Below Only

Miscellaneous

Ap —Percentage of Apertures in Wall
Co —Contribution from Overhead (Roof)
Cg —Contribution from Ground
Cr —Cost of Roof ($/pound)
Cw —Cost of Wall ($/pound)
Bo —Barrier Factor for Roof Barrier
Bo′ —Barrier Factor for Floor Barrier
Bw —Barrier Factor for Wall
EM —Engineering Manual
EBM—Equivalent Building Method
Ex —Exposed Basement Wall Fraction
FC —Floor Above and Below Contribution Factor
H —Height of Detector Above Ground
psf —Pounds per square foot
Rf —Reduction Factor (Reciprocal of Pf)
z —Distance of Detector from Roof Contamination

VOLUME 2—EQUIVALENT BUILDING METHOD OF FALLOUT RADIATION SHIELDING ANALYSIS AND DESIGN

I. Introduction and Background

During the late summer and fall of 1961, a number of fallout shielding courses were given throughout the United States to architects and engineers in support of the National Shelter Survey Program. The main text used and method taught at all the participating schools was the "Engineering Manual," and its method.[1] This publication was issued in draft form and the final edition is scheduled for printing in 1963. The Engineering Manual is based on the work of Dr. L. V. Spencer, NBS Monograph 42[2] which was issued in June 1962.

The Engineering Manual offers a complete method of analyzing fallout shielding problems, even for the most complex situations. The method is based on a series of functional equations which can be used for almost any conceivable shielding problem. It is a significant contribution to the engineering literature.

Solving for the protection factor at one detector location by the Engineering Manual method may take a number of pages of tedious calculations. The method requires numerous numerical calculations and the probability of a calculational error is therefore quite high. Furthermore, the solution of the protection factor for one building or for one location within a building, does not readily lend itself to a change of parameters for comparison purposes.

For these reasons, the author (CDR J. C. LeDoux), and a colleague (LCDR R. C. Vance, CEC, USN) began to investigate various other approaches to the fallout shielding problem. The objective was to provide a means of analyzing shielding problems which would give engineers and architects a better "feel" for the interplay of the various parameters involved and still provide answers comparable to those provided by the Engineering Manual. At first only a few simple protection factor charts were developed and used. These were inspired by the Canadian A&E Guide.[4]

The protection factor chart provided a quick means of analyzing the interaction of wall and roof thicknesses for a simple, single-story, solid wall structure, for a given floor area. These simple charts are the cornerstone of the Equivalent Building Method. The relative simplicity of the Equivalent Building Method rests on the fact that large changes in magnitude of building area produce only small changes in the protection factor. The difference in protection factor for a building with an area of 100 sq ft and one with an area of 100,000 sq ft is, in most cases, less than a factor or two. For the simple, solid wall single-story structure, then, only a few protection factor charts are needed to obtain the same answer as the Engineering Manual for the same type of simple structure.

Without further refinements, these protection factor charts are useful and instructive. With a little engineering judgment, they can be used to provide quickly maximum and minimum values of protection factors for structures with complicated geometry. Further investigation revealed that the other parameters, such as height, windows, mutual shielding, etc., also produced regular and slow variations to the protection factor. Instead of modifying the barrier factor or geometry factor directly, it is possible to substitute an "equivalent" wall or roof mass thickness which will yield the same answer.

II. Basis of the Equivalent Building Method

The Equivalent Building Method is based on the assumption that any complex shielding situation can be reduced to an equivalent simple, solid-wall, single-story structure problem. An analogy for engineers is the beam curves from the AISC Steel Handbook, where moment and span are used to find the correct beam to carry the load.

NOTE: Superior figures refer to numbered references on page 13.

No computation of section modulus, moment of inertia, etc., is needed since the beam curves are based on these parameters. Similarly, the Equivalent Building Method is based on thousands of shielding problems worked by the Engineering Manual or Spencer Monograph. The solutions of these problems have been translated into various charts and tables from which equivalent wall and roof mass thicknesses can be selected.

The Equivalent Building Method is based on the Protection Factor (Pf) chart. The wall mass thickness is plotted along the abscissa; the protection factor along the ordinate; there are a series of overhead mass thickness curves from 0 psf to 300 psf (every 4″ of concrete). The overhead curves are bounded by an envelope based on an infinite roof mass thickness curve. This infinite roof curve is actually the ground contribution line since only ground contribution is included.

There are four aboveground charts for areas of 100, 1,000, 10,000, and 100,000, sq ft (figs. 1–4). There are five basement charts for areas of 100, 1,000, 4,000, 10,000, and 100,000 sq ft (figs. 5–9). The 4,000 sq ft chart is needed for the basement case since this area is a maximum point for ground contribution.

For aboveground, the basic structure assumed for these charts is a single-story, solid wall, square building. The wall height is 13 ft with the detector 3 ft above the floor. The sill height of any windows is assumed to be at detector height, 3 ft. Figure II–1 is a sketch of this equivalent building.

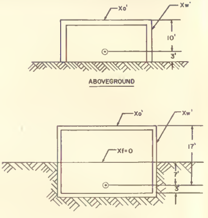
For the basement case, the basic structure is a 2-story, solid wall, square building with the lower story completely below grade. The story height assumed here was 10 feet with the detector 7 feet below grade. The floor above the detector was assumed to have zero mass thickness. A correction must be made for this added barrier. This was done so that the correction would always be positive. Section IV–7 describes this correction. Figure II–1 is a sketch of the belowground equivalent building.

The assumption of a square building will not cause much error since an eccentricity ratio of 5 to 1 will cause only a reduction in shape factor of about 20%. The shape factor applies only to wall-scattered radiation, and thus the total error will be less than 20%. Furthermore, using a square building is conservative when applied to an eccentric building.

Figure II - 1.

EQUIVALENT BUILDINGS

ABOVEGROUND AND BASEMENT



BASEMENT

If the actual structure happens to be of the simple type assumed in the construction of the protection factor charts, the solution is immediately available. Most buildings are not very simple. There may be windows; the detector may not be at the standard height of 3 ft; the distance to the roof may be other than the standard distance; adjacent buildings may provide mutual shielding, and so forth. Each of these variations from the simple geometry can be handled by modifying either the roof mass thickness, the wall mass thickness, or both so that a "substitute" building can be derived that will have the same protection factor as the actual building. The two structures are thus "equivalent" in the degree of protection provided.

In addition to the basic protection factor charts (four above-ground, five basement), there are eight auxiliary charts and three tables which are used to determine the equivalent mass thicknesses of roof and wall. Each of these charts and tables have been derived empirically since they were developed by solving shielding problems using the Engineering Manual. Once the true protection factor was known, the previously developed protection factor charts were used to determine the equivalent roof or wall mass thickness which would yield the same value. Thus, points on the auxiliary charts or tables were determined.

III. Equivalent Building Method Functional Equations

A functional equation describes in symbols what parameters are involved in determining a particular quantity. Thus, when we write $y=f(x)$, we mean that y depends on some function of x. It is often possible to write an explicit equation for x. In some cases, only the curve representing x may be available. In The Equivalent Building Method and in the Engineering Manual, the functional equation is used to indicate the dependent parameters and tables or curves are provided to determine the desired value of the function.

There are two basic functional equations for the Equivalent Building Method, one for the roof and one for the wall.

1. Equivalent Overhead Mass Thickness

The equivalent overhead mass thickness, Xo′, depends on the actual overhead mass thickness, Xo, the area of the contributing roof, A, and the distance from the detector to the roof, z. In certain problems, Xo′ also depends on the additional barrier effect of interior partitions.

In functional equation form, this relationship is written:

Xo′=Xo(A, z, Xi) ....(1)

Figures 16 and 17 are used to determine Xo′ as explained in Section V.

2. Equivalent Wall Mass Thickness

The equivalent wall mass thickness depends on the exterior wall mass thickness, the window area, the interior wall mass thickness, the height of the detector, any mutual shielding, contributions from the floor above and below the detector floor, and the percentage of wall exposed for semiburied cases. The functional equation is:

Xw′=Xe′(Xe, Ap)+Xi±ΔXw .....(2)

The Δ symbol stands for an additional quantity of mass thickness added or subtracted to the wall mass thickness. For the floor of the detector, ΔXw has the following components:

a. *Floor of detector*

ΔXw(A, H)—Correction for height of detector above contaminated plane (fig. 12).

ΔXw(Ms) —Correction for mutual shielding (fig. 13).

ΔXw(Ex) —Correction for exposed basement walls (fig. 15).

b. *Floor above or below detector floor*

ΔXw(A, H)—Correction for height (fig. 12).

ΔXw(Ms) Correction for mutual shield (fig. 13).

ΔXw(FC) —Correction for floor above or floor below detector floor (tables II and III).

ΔXw(Xf) —Correction for barrier effect of floors (fig. 14).

IV. Explanation of Wall Factors

1. Effect of Apertures—Xe′(Xe, Ap)

The first term of equation 2 adjusts the exterior wall mass thickness, Xe, for the effect of windows. Figures 10a–10d are used to obtain the equivalent exterior wall mass thickness, Xe′, for aboveground locations. Figures 11a–11e are used to obtain the equivalent exterior wall mass thickness for the basement case. The wall considered for the basement case is the exposed first story wall and not the buried wall. These charts plot Xe along the abscissa and Xe′ along the ordinate. There are a series of aperture percentage (Ap) curves on each chart. Enter with Xe, go vertically to the proper Ap curve and read out Xe′. The aperture percentage is the ratio of window area to total wall area×100. The detector is assumed to be at sill height.

The aperture curves give a pictorial view of the effect of windows on wall mass thickness. The curves flatten out when the amount of radiation streaming in the windows is the predominant effect. Adding more weight to exterior walls at this point will not produce any added shielding. These curves can be used in design problems to determine the best exterior wall weight (from a shielding viewpoint). If the slope of the curves is at or near 45°, every pound of wall produces an effective pound for shielding. As the slope decreases, adding weight to the walls does not produce the same weight in shielding.

For detectors above sill height, an approximate solution is to assume Xe 0 for the entire wall where windows are present. Protection factors from the window area and from solid wall are weighted in accordance with the fraction of each.

2. Interior Partitions—Xi

In this method the interior wall mass thickness, Xi, is added to Xo′. This is equivalent to using a barrier factor which is a function of the sum of the exterior and interior wall mass thicknesses, or Bw (Xe′+Xi). The Engineering Manual uses Bw (Xe)Bw(Xi); i.e., the product of barrier factors. Recent experimental work [5] indicates that the product method predicts too low. The sum method will always yield a higher contribution than the product and thus brings theory closer to experiment.

3. Detector height—ΔXw(A,H)

Figure 12 is used to obtain a correction to equivalent wall mass thickness when the detector is elevated above the standard height of 3 feet. The curves include two effects: the change in wall barrier effectiveness with height; and the screening effect of the floor below the detector. This second effect is dependent on the area of the building. Calculations show that for exterior walls equal to or greater than 50 psf, the combined correction remains constant for a particular height. For weights below 50 psf, there is a noticeable change in the positive direction. Two supplementary tables for Xw=0 and Xw=25 have been placed above the curves. These tables provide additive corrections to the basic curves for walls less than 50 psf.

The fact that lighter walls require heavier equivalent weights requires further explanation. For heavy walls, radiation absorption is greater than radiation scatter. For very thin walls (Xw=0), the radiation is neither absorbed nor scattered but is transmitted. For detectors in upper floors, the detector is screened from much of the direct radiation by the floor below. Since radiation is not scattered by the thin walls into the detector, very little except skyshine and ceiling shine reaches the detector and thus walls appear to be relatively thick which requires an added equivalent wall weight. For medium thick walls (Xw=25) a considerable portion of the incident radiation is scattered by the walls into the detector. The 25 psf corrections are thus lower than the 0 psf correction.

4. Mutual Shield—ΔXw(Ms)

A mutual shield improves the protection factor of a building. This effect can be simulated by changing the actual wall mass thickness by the proper amount to obtain the same effect. Figure 13, ΔXw(Ms), is an incremental increase to Xw due to the effect of a limited strip of contamination. For a strip 100 ft wide, the wall is increased by 40 psf. (See example problem No. 10.)

5. Exposed Basement Walls—ΔXw(Ex)

When basement walls are partially exposed, the protection factor of the basement location decreases. Such a problem could be handled in two ways; the basement protection factor curves could be used by providing a negative correction to the belowground charts or an additive correction could be used with the aboveground charts. The latter proved to be more feasible, since exposing even a small portion of a basement wall drastically reduces the protection factor and more nearly approaches the aboveground case.

Figure 15, ΔXw(Ex), is used with the *aboveground charts*, though a correction for a semibasement case. We simply consider all such cases as partially buried instead of partially exposed. The belowground curves do not provide low enough protection factor values and thus the aboveground curves were easier to use. The exposed wall fraction (EX) is the ratio of wall exposed to total walls.

6. Contributions from Floor Above and Below the Detector Floor—ΔXw(FC)

In addition to the ground contribution through the walls of the detector floor, significant amounts of radiation may reach the detector from the floors above and below the detector floor. For nominal floor and wall thicknesses, this usually amounts to approximately 10%. Table I has been provided as an approximate correction for this additional contribution. The values in table I are subtracted from Xw.

Tables II and III and figure 14 are provided so that a more accurate computation of this effect can be made. The method used is to obtain the protection factor for the floor of the detector (Pfo), the protection factor for the floor above (Pfu), and the protection factor for the floor below (Pfb). These three protection factors are then directly combined to obtain the Pf of the detector, as follows:

$$Pf = Pfo \times \frac{Pfu}{(Pfo+Pfu)} \times \frac{Pfb}{(Pfo+Pfb)}$$

(See Example, p. 5.)

a. *For Floor Above Detector.* Since the protection factor for the floor of the detector included the roof contribution, the protection factor for the floor above should be determined by excluding any roof contribution. This is easily

EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

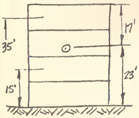
W= 100 L= 100 A= 10,000
Wc= – Lc= – Ac= –
Z= 17 A′= 3460
H= 23 Ac′=
Ap= Xo= 700
Ms= Xe= 100
Xi=
X_f = 50

EQUATIONS

$$Xw' = Xe'(Ap) + Xi + \sum \Delta Xw$$

$$Xo' = Xo(A,Z) + \Delta Xo(Xi)$$

SKETCH



ACCURATE METHOD USING TABLES II + III (SECTORS #1, 2, 3)

$$P_f = 31 \times \frac{3300}{3331} \times \frac{740}{771}$$

P_f = 29.5 ANS.

APPROXIMATE METHOD USING TABLE I (SECTOR #4)

P_f = 28 ANS

EQUIVALENT WALL MASS THICKNESS Xw′

		Pfo	Pfu	Pfb	Pf (TAB I)
Factor	Fig.	Sector #1	Sector #2	Sector #3	Sector #4
Xe′(Ap)	10 11	100	100	100	100
Xi	--	0	0	0	0
ΔXw(A,H)	12	32	41	24	32
ΔXw(Ms)	13	0	0	0	0
ΔXw(FC)	I	0	45	-3	-7.5
* ΔXw(Xf)	14	0	125	117	0
* ΔXw(Ex)	15	0	0	0	0
Xw′		132	311	238	124.5

EQUIVALENT ROOF MASS THICKNESS Xw′

Co(A′, Xo+ΔXo)				
-Co(Ac′,Xo+ΔXo)				
Co(Periphery)				
+Co(Ac′,Xo)(Core)				
Co(Total Roof)				
Area=				
Xo′=	100	∞	∞	100
P_f =	31	3300	740	28

* For Basement Case

accomplished by assuming a roof with infinite mass thickness. The upper curve of the protection factor charts is the infinite roof case or simply the ground contribution curve. Table II provides the $\Delta Xw(FC)$ correction of the floor above. In addition, figure 14 (upper curves) must be used to correct for the barrier effect of the floor above the detector. All other corrections which apply must be made.

For the height correction $\Delta Xw(A,H)$, the mid-height of the floor above the detector is used for H. If there is no floor below the detector, the final Pf is:

$$Pf = (Pfo \times Pfu)/(Pfo + Pfu)$$

b. *Basement Problems*. In addition to charts 5–9, the above procedure can be used to solve basement problems since the only ground contribution in a basement is from the floor above the detector. For basement problems, however, the equivalent roof mass thickness, Xo′, must be used so that roof contribution will be included.

c. *For Floor Below Detector*. The same procedure is used for this case as for the floor above the detector. Table III is used to provide the $\Delta Xw(FC)$ correction. Figure 14 (lower curves) provides the correction for the floor barrier effect, in this case, the floor below the detector. The height used for the $\Delta Xw(A,H)$ correction is the mid-floor height of the floor below the detector. Again an infinite roof mass thickness is used to insure that only ground contribution is added. If there is no floor above the detector, the final Pf is:

$$Pf = (Pfo \times Pfb)/(Pfo + Pfb)$$

7. Floor Barrier Factor Correction—$\Delta Xw(Xf)$

In the Engineering Manual method, floor barrier factors Bo and Bo′ are included as multipliers in the ground contribution equations. The previous section explained how figure 14 was used to include this factor in the contribution from the floors above and below the detector floor. Figure II–1 indicates that the basement Pf charts (fig. 5–9) are based on a floor barrier factor of 1.0 or a mass thickness of zero for the floor above the detector. This was done so that any correction made would be additive. When using figures 5–9 to compute a Pf for a basement location, figure 14 (upper curves) must be used to correct for the barrier effect of the floor above the detector. The curves of figure 14 were derived by simply converting the Bo and Bo′ curves from chart 1 of the Engineering Manual to equivalent weights of wall barrier factor, Bw, from the same chart.

V. Computing Equivalent Overhead Mass Thickness

The equivalent overhead mass thickness, Xo′, depends on the contributing roof area, the distance of the detector from this roof area, and for certain problems, the interior screening partitions. The functional equation for Xo′ is:

$$Xo' = Xo(A, z, Xi)$$

The basic value of roof mass thickness, Xo, is the total mass overhead between the detector and the contributing roof area. The protection factor charts have curves for each 50 psf of equivalent roof mass thickness up to 300 psf. The final upper curve is for an infinite roof mass thickness for those cases when Xo′ exceeds 300 psf. This infinite roof curve is also the plot of Cg since only ground contribution is included.

Figure 16 with subsections a, b, c, and d is used to determine Xo′. Figure 16 is a plot of roof contribution, Co, vs the adjusted roof area, A′. Figure 16 is based on a Z distance of 10 ft. The adjusted area depends on the actual Z distance which may be different than 10 ft. The roof mass thickness is plotted for each 10 psf from 0 to 300 psf. Every point on Figure 16 is the intersection of three parameters; roof weight, Xo, roof contribution, Co, and the adjusted roof area, A′.

1. Detector to Roof Distance Variation

Part a) of Figure 16 is a nomogram for computing A′. Since the solid angle fraction varies inversely with the square of the distance, the adjusted area can be found by the following equation:

$$A' = A(10/Z)^2$$

To find A′ using the nomogram, draw a line from the total roof area A (left hand line) through the Z distance (middle line) to the left hand ordinate of part b) of Figure 16. This is the adjusted area A′.

Part b) of Figure 16 is the plot of Xo vs A′ for the determination of roof contribution Co and the equivalent roof mass thickness, Xo′.

Once A′ is determined, go horizontally in Part b) until the total overhead mass thickness line is reached. This point is the roof contribution Co line. If we remain on this vertical line, the true value of Co will be maintained in the problem. To determine the value of equivalent roof thickness, Xo′, go vertically to the area of the building. The area of the building is the area used with the Pf charts and is that area from which ground contamination is excluded.

Example: A = 1500 sq ft Z = 30′
Xo = 150 psf
Xw = 200 psf

From 1500 on Part a), a line is drawn through 30′, intersecting the left band ordinate of Part b) at 170. Go horizontally until the Xo = 150 line is reached. Note that the Co value is .0031.

Go vertically to A = 1500, and read out Xo′ = 172 psf. From Figure 2 with Xw′ = 200 and Xo′ = 172, the Pf = 100.

Note that in this problem, the actual value of Co was not needed nor used. The value was extracted only for instructional purposes. The procedure used in this simple problem can be applied to more complicated ones. There is only one rule to remember when solving for Xo′ and that is: *Find the Actual Roof Contribution, Co. With Co and Building Area To Be Used in the Problem, Find the Value of Xo. This Is the Equivalent Roof Mass Thickness Xo′.*

2. Intermediate Area Problems

For adjusted roof areas less than 1000 sq ft, the roof lines slope sharply to the left. For accuracy, we should interpolate for roof areas as well as ground areas. The following problems illustrate this.

Example: A = 400 Z = 10′
Xo = 100
Xw = 200

From Figure 16, the following values of Xo′ are obtained:

Xo′ (100) = 55 psf
Xo′ (1000) = 110 psf

The corresponding Pf values from Figures 1 and 2 are:

Pf (100) = 43
Pf (1000) = 47
Pf (400) = 45 (linear interpolation)

Note: The method of section 1 for solving this problem, i.e. using a value of Xo′ = 100 for both A = 100 and A = 1000 and then interpolating, yields a value of 55. Such large differences will only result for small areas between 100 and 1000 sq ft. Above 1000 sq ft, the value of Xo′ will be essentially constant, and only one value of Xo′ is needed for interpolation).

3. Core Type Problems

In many practical shielding problems, the shielded space is protected by interior partitions. These interior partitions not only provide a barrier to ground contributions but also act as a barrier to portions of the roof contribution. In these cases, the standard procedure is to compute the roof contribution in two parts. The area of the roof not screened by interior partitions is called the "Core Area," and the portion of the roof screened by interior partitions is called the "Peripheral Area."

The general principle of solving for Xo′ applies for this type of problem. The total roof contribution, Co, is determined and is used with total building area to determine Xo′. In this case, however, Co is determined by adding the peripheral roof contribution to the core roof contribution. In determining the roof contribution from the periphery, Part c) is used to include the barrier effect of interior partitions. For the periphery then, the value of roof mass thickness which is used to determine the periphery roof contribution is:

$$Xop = Xo + \Delta Xo(Xi)$$

Where Xop is the equivalent periphery roof mass thickness.

$\Delta Xo(Xi)$ is the additional mass thickness required to account for the interior partition barrier. (Part c.)

To solve for Xo′, use the following steps:

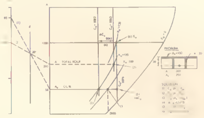
1. Solve for Co for the core area (Ac′, Xo).
2. Solve for Co for the total roof area. Include the interior partition effect (A′, Xop).
3. Solve for Co for the core area as if it was effected by interior partitions (Ac′, Xop).
4. The difference between steps 2 and 3 is the contribution from the periphery.
5. Solve for total Co (add step 4 to step 1).
6. Determine Xo′ from figure 16 by using Co and total area of building A.

Example: Let A = 1,000 sq ft
Ac = 200 sq ft
Xi = 20 psf
Xo = 100 psf
z = 20 ft find Xo′

Figure V–1 indicates schematically the solution to this problem. Each step is labeled to correspond with the following steps:

1. Solve for Co for the core:
   Using nomogram: A=200; Z=20′; Xo =100: Co=.0035
2. Solve for Co from the entire roof but include the effect of interior partition barrier:
   a. From part c) obtain ΔXo=25 psf
   b. Using nomogram: A=1000; Z=20′; Xop=125: Co=.0063
3. Solve for Co from core area but with interior partition effect:
   Using nomogram: A=200; Z=20′; Xop =125: Co=.0022
   An alternate procedure is to move along the Xo=125 line until you intersect the Ac′ line.
4. Obtain ΔCo: ΔCo=(2)−(3)=.0063−.0022 =.0041
5. Add this peripheral contribution (ΔCo) to the core contribution to get Co
   Co=(1)+ΔCo=.0035+.0041 Co=.0076
6. Determine Xo′ by going vertically to A With Co=.0076; A=1000; Xo′=135
   Xo′=135 psf ANS

Figure V-1 SAMPLE ROOF CORE PROBLEM



As a general rule of thumb, if the adjusted core area exceeds 1000 sq ft or if the interior partition mass thickness exceeds 100 psf, the peripheral roof contribution will be negligible.

4. Eccentric Roof Areas

For many practical problems, the best shelter area is located in the central corridor of a building. This corridor will likely be quite eccentric and using the total area of the CORRIDOR AS IF IT WERE SQUARE could lead to serious error. The areas far from the detector will not contribute very much to the total roof contribution.

Part d) of Figure 16 has been included to correct for eccentric roof areas. The abcissa of this chart is the eccentricity ratio, e, or simply the ratio of width to length, W/L. The ordinate is a multiplying factor which is applied to the actual roof area to obtain an "effective contributing" area. This effective area is always smaller than the actual area.

The correction factor F(A) is limited to eccentricities of 10 to 1 (e=0.1). If the roof has an eccentricity ratio of less than 0.1 use only that portion of the corridor or roof area which will yield an eccentricity ratio of 0.1.

For example: suppose that we are analyzing a corridor 10′ wide and 150′ long. The eccentricity ratio for this corridor is .067. To increase the e ratio to 0.1, we simply reduce the effective corridor length to 100′. In effect we are neglecting roof contribution from the corridor roof beyond 50′ from the detector for this problem. Even for thin roofs (Xo=25 psf) such contribution is negligible.

Using an e=0.1 then, and an area of 1000 sq ft, we would obtain F(A)=.34 from Part d). Applying this to the 1000 sq ft, we obtain an effective contributing area of 340 sq ft for the core part of the roof problem. From this point, proceed as in the core type problem demonstrated in the previous section.

5. Basement Roof Problems

The basement protection factor charts (figs. 5–9) are based on a detector to roof distance of 17′ as shown on figure II–1. Two methods can be used to solve for basement protection factors. The first method uses the aboveground charts and table II to correct for the basement location (the floor above the detector). In this case, the equivalent roof mass thickness is determined as described above.

If we wish to use the belowground charts (figs. 5–9) chart 16 must be corrected to allow for the basement standard distance of 17′. This is done by computing an equivalent roof area for the basement, Ab.

$$Ab = A\,(10/17)^2$$
$$= 0.346A$$

This can be accomplished easily with the nomogram, part a). Area Ab is determined by drawing a line through A and Z=17′. For basement cases, exit on Ab instead of A.

With this value of Ab and the true roof contribution, Co, enter figure 16 and determine Xo′ (see Example p. 9).

EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

W= 50 L= 100 A= 5000
Wc= 20 Lc= 50 Ac= 2000
Z= 17 A′= 1730
H= 3 Ac′= 346
Ap= Xo= 100
Me= Xe= —
Xi= 50

EQUATIONS

$Xw' = Xe'(Ap) + Xi + \sum \Delta Xw$

$Xo' = Xo(A,Z) + \Delta Xo(Xi)$

SKETCH

40′ 20′ 40′ 50′ 100 50 50

EQUIVALENT WALL MASS THICKNESS Xw′

Factor	Fig.	Sector #1	Sector #2	Sector #3	Sector #4
Xe′(Ap)	10 11				
Xi	—				
ΔXw(A,H)	12				
ΔXw(Me)	13				
ΔXw(FC)	1				
* ΔXw(Xf)	14				
* ΔXw(Ex)	15				
Xw′					

EQUIVALENT ROOF MASS THICKNESS Xw′

1730, 107 Co(A′, Xo+ΔXo)	.0160
346 107 −Co(Ac′, Xo+ΔXo)	.0103
Co(Periphery)	.0057
346 100 +Co(Ac′, Xo)(Core)	.0135
Co(Total Roof)	.0192
Area=	5000
Xo′=	101

$\Delta X_o(X_i) = 57\,psf$ (Fig M)

$X_{op} = X_o + \Delta X_o(X_i)$

$= 50 + 57 = 107$

$X_o' = 101\ psf.$

* For Basement Case

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EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

W= L= A= 1000
Wc= 40 Lc= Ac=
Z= A′= 62.5
H= Ac′=
Ap= Xo= 100
Me= Xe=
Xi=

EQUATIONS

$Xw' = Xe'(Ap) + Xi + \sum \Delta Xw$

$Xo' = Xo(A,Z) + \Delta Xo(Xi)$

SKETCH

40′

EQUIVALENT WALL MASS THICKNESS Xw′

Factor	Fig.	Sector #1	Sector #2	Sector #3	Sector #4
Xe′(Ap)	10 11				
Xi	—				
ΔXw(A,H)	12				
ΔXw(Me)	13				
ΔXw(FC)	1				
* ΔXw(Xf)	14				
* ΔXw(Ex)	15				
Xw′					

EQUIVALENT ROOF MASS THICKNESS Xw′

Co(A′, Xo+ΔXo)	—
−Co(Ac′, Xo+ΔXo)	—
Co(Periphery)	—
62.5 100 +Co(Ac′, Xo)(Core)	.0046
Co(Total Roof)	.0046
Area= A_B=346	346
Xo′=	147

$A = 1000$

$A' = 1000\left(\frac{10}{40}\right)^2$

$= 62.5$

$A_B = .346 \times 1000$

$= 346$

$X_o' = 147\ psf$

* For Basement Case

VI. Complex Applications

The Equivalent Building Method was originally developed to provide "ball park" estimates. With engineering judgment, the protection factor charts can still be used for estimating purposes. Problem 14, for example, required a twelve page Engineering Manual solution for a value of 47; a quick estimate yielded a Pf of 47; the Equivalent Building "wall by wall" analysis gives a value of 50.

Complex applications are best solved by using a "wall by wall" analysis with appropriate fictitious buildings similar to the Engineering Manual method. One must remember, however, that the Equivalent Building Method yields an answer which has both an overhead contribution and a ground contribution. When the protection factors are modified by an azimuth sector, the overhead contribution is also affected by the same azimuth fraction. It is important to make certain that important parts of the roof contribution are not omitted. Problem 14 is a good example of the correct procedure. In this problem, certain sectors had a negligible Cg because of many intervening partitions, however, the contributions from the roof over these azimuth sectors could not be ignored. This was easily handled by assuming that the walls for these sectors were infinitely thick. The protection factors obtained for each contributing sector are combined by inverting (or changing to reduction factors), multiplying by the azimuth fraction, and then adding. The azimuth fractions can be divided by the Pf to obtain the same result. Once the total reduction factor is known, this is inverted to obtain the protection factor.

In complex applications it is not uncommon to have 15 or 20 separate azimuth fractions since an azimuth fraction is used whenever the conditions within a structure change. Changes are caused by doorways and interior partitions. The protection factor charts are helpful in combining sectors. For example, if the overhead mass thickness for a particular building is 100 psf, and the gross area of the building is 10,000 sq ft., Figure 3 tells us that all sectors with wall weights equal or greater than 250 psf can be combined because the resulting Pf will be the same.

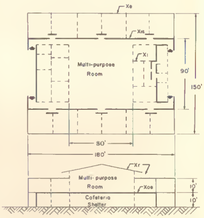
VII. Design Procedure

The Equivalent Building Method lends itself to preliminary design of fallout shelter since it provides the architect or engineer with a quick method of determining the effect of changing the various parameters concerned. We are concerned here only with the design of the shielding required and not with structural design methods. A designer is concerned with obtaining the most protection for the least money. Since the protection factor is a complex function of radiation contributions from various sources, determining the economic shield for a particular application can be a most complex process. To indicate how the Equivalent Building Method can be used to solve such problems, an example will be demonstrated.

Figure VII–1 is a simplified sketch of a two story school building with 24 classrooms. The classrooms surround a central area which houses the administration and service areas. In the center of this area on the first floor is the cafeteria. The second floor has a clerestory section over a multi-purpose area. The service area includes office space, lavatories, machinery spaces, etc. If we use the cafeteria area for shelter, what wall and roof thicknesses should be used to obtain the most economic shield?

Figure VII - 1

ECONOMIC DESIGN PROBLEM



The following assumptions will be used for this problem:

1. Reinforced concrete will be used as shielding material. Inplace costs are: walls, \$50/cu yd; ceiling, \$80/cu yd.

2. The following material would normally be used if no shelter was included:

a. North-South exterior walls (classroom walls) would be 8" concrete faced with 4" brick. $X_e = 140$ psf. 60% of these walls will be window area, with sill height at 3 ft.

b. East-West walls would be 12" concrete block with no windows. The clerestory will have windows all around. $X_e = 85$ psf.

c. The interior partitions supporting the clerestory will be 12" concrete block, $X_i = 85$ psf. All other interior partitions will be lightweight concrete block, $X_i = 22$ psf.

d. The East entrance to the school contains office space with exterior walls light metal framing and glass, $X_e = 0$.

3. The dotted lines indicate interior partitions. The heavy lines indicate the position of shelter shield. The shelter ceiling covers the service area. The following data has been taken off the sketch:

a. Area of school = 27,000 sq ft.

b. Area of shelter = 13,500 sq ft.

c. North and South wall area including baffles = 4,500 sq ft.

d. Area of baffles, North and South = 900 sq ft.

e. East and West wall area = 2,640 sq ft.

Problem: Determine wall and ceiling weights for shelter area which can be placed at least cost. Determine cost per sq ft of shelter space over and above cost without shelter and compare to \$2.50/sq ft shelter incentive allowance. Pf = 100 required.

Assuming that concrete weighs 4,000 lbs/cu yd, we can write the following cost equation:

Cost = Cost of interior walls (NS) + Cost of exterior walls (EW) + Cost of Shelter Ceiling.

For a first cut at the problem, we will assume that the contribution from the floor above will be negligible. Since the area of the shelter is quite large, we will assume that the "z" distance of 22' will not materially affect X_o'. There is no mutual shielding or height correction to make.

The cost of interior walls (NS) depends on the area of the NS walls, the required weights (X_i), and the unit cost of material, or

$$\text{Cost (NS-walls)} = X_i\, A_w(NS)\, C_w$$

For exterior walls (EW), assuming the walls inside the exterior office space are exterior walls, the equation would be:

$$\text{Cost (EW-walls)} = X_e\, A_w(EW)\, C_w$$

For the ceiling:

$$\text{Cost (ceiling)} = X_f\, A_r\, C_r$$

If the costs (C_w, C_r) are costs in \$/lb, these can be obtained by dividing the cost per cu yd by the 4,000 lbs/cu yd. The product of mass thickness and area is lbs of material and our equation gives us costs in dollars.

The wall functional equation which applies to this problem is:

$$X_w' = X_e'(A_p, X_c) + X_i$$

Thus for the North-South walls, $X_i = X_w' - X_e'$. For the East-West walls, $X_e = X_w' - X_i$. For the ceiling, $X_f = X_o' - X_r$. Substituting these quantities into our cost equations, we have the following:

$$\text{Cost} = (X_w' - X_e')A_w(NS)C_w + (X_w' - X_i)A_w(EW)C_w + (X_o' - X_r)A_rC_r$$

For \$ costs, this equation must be divided by 4,000 lbs/cu yd.

Substituting areas and weights from the data of the building and dividing by 4,000 yields:

$$\text{Cost} = 56.3(X_w' - X_e') + 33(X_w' - X_i) + 270(X_o' - X_r)$$

From Figure 10c, for $X_e = 140$ and $A_p = 60\%$, we obtain $X_e' = 77$. For X_i, we have 85 + 22 or 107. For X_r, we have 50. Substituting and adding we have:

$$\text{Cost} = 89.3\, X_w' + 270\, X_o' - 21{,}260$$

The only unknowns in this equation are X_w' and X_o'. These are directly obtained from the Pf charts. Referring to figures 3 and 4 we obtain the following set of combinations of X_w' and X_o' which will produce a Pf of 100.

For Pf = 100, A = 10,000

X_w' =	145	155	165	173	185	210	233	297
X_o' =	250	200	175	160	150	140	135	130

For Pf = 100, A = 100,000

X_w' =	97	103	113	145	153	200	350
X_o' =	250	200	175	150	140	130	127

using the cost equation, we can now construct a cost table (not shown) for both areas. We will interpolate linearly between the two sets of values for our area of 27,000 sq ft. The cost table indicates a minimum cost value for $X_o' = 140$ for both tables. Listing the values from both tables to obtain the required wall thickness, we have:

A = 10,000 Xo′ = 140 Xw′ = 210
A = 100,000 Xo′ = 140 Xw′ = 153
A = 27,000 Xo′ = 140 Xw′ = 199 (use 200)

For the North-South walls then, the interior mass thickness required would be 200–77 or 123 psf. For East-West walls, the exterior mass thickness required would be 200–107 or 93 psf. The shelter ceiling would have to be 140–50 or 90 psf, or 40 psf more than normal construction.

Since the exterior East-West walls would normally be 85 psf, these walls are almost sufficient as is. By filling the hollow blocks with sand or grout, the additional mass thickness would exceed the required 8 psf. The cost would be very small but for purposes of this problem we will compute this cost at $50/cu yd. The North-South walls would have to be 11″ of concrete for the 123 psf required or 101 psf more than normal construction. The added cost of shelter would be:

Cost ceiling =	(140–100)×270 =	$10, 800
Cost NS walls =	(101)(50)(3,600/4,000) =	4, 550
Cost NS baffles =	(123)(50)(900/4,000) =	1, 400
Cost EW walls =	(8)(50)(2,640/4,000) =	264
Total additional cost	=	17, 014

Cost per sq ft = $17,014/13,500 sq ft = $1.26 per sq ft.

Using the values of Xo′ = 140 and Xw′ = 200, we should check the Pf of this structure. This should be done by the Engineering Manual method. Using the EBM, for A = 10,000 the Pf = 95. For A = 100,000, the Pf is 125. For 27,000, the Pf is 101. A check of the contribution from floor above indicates negligible contribution. Xo′ does change from 140 to 142 for a change in Z from 10′ to 22′, but this increases the Pf slightly. Thus the two assumptions used for simplicity do not materially change the economic analysis.

VIII. Engineering Estimate Procedure

The ability to make good engineering approximations is usually directly proportional to the experience in a given field. For estimating protection factors of buildings, the Pf charts plus a few rules of thumb should aid in obtaining good estimates.

If possible, try to bracket the Pf by obtaining maximum and minimum values. If the maximum and minimum are within a factor of two, you have accomplished the purpose of estimating the Pf of a building; i.e., getting within a factor of two. An average of these two values could be used if a single number is desired.

For most problems, using the actual roof mass thickness will give good results. If the "z" distance is large or if the core is small, use Xo. The Pf obtained will be lower than the actual Pf. A check of the Pf chart will indicate the degree of conservativeness that may be involved, and how sensitive the Pf is to the Xo′ in this particular configuration.

For example, suppose that a building has an area of 1000 sq ft with Xo = 100 and z = 40 ft. The walls are 100 psf. Chart 3 tells us that the Pf must be at least 14 (using Xw′ = 100, and Xo′ = 100). With an infinitely thick roof, the Pf would only be 19. Thus a change in z for this example is not very important. However, if Xw = 200, the minimum Pf would be 40 and the maximum would be 160 (for an infinite Xo′). The following rule of thumb works fairly well for a change in z.

Rule for Change in "z": For small areas (A ≅ 1,000), add 1 psf for each foot over standard distance (10′). For large areas (A ≅ 10,000) add 1 psf for each 4 feet over the standard distance.

For the example above, add 30 psf (40–10) to Xo for a total of 130. The estimated Pf would then be 65.

The following additional rules of thumb are useful.

Rule for Windows: Xe′ = Xe(1–Ap)

Rule for Height: Up to 50′, add 1 psf for each foot of height over the standard 3′. For heights over 50′, add 1 psf for each 4 ft over 50 ft. (For 100 ft height, correction = 50 + 50/4 = 62 psf.)

Rule for floor above and floor below correction: Decrease Pf by 10%.

For Minimum Pf: Assume ground floor conditions. Correct for windows.

For Maximum Pf: Follow Xo line to right ordinate. Correct for any large z changes or for small cores.

To correct for core changes, convert the core area into a z change and apply z rule. A 400 sq ft core in a 10,000 sq ft building is the same as a z change of 50 ft. The Xo correction would be 10 psf.

Example: Suppose we have a building with a gross area of 5,000 sq ft. We wish to estimate the Pf on the 7th floor of a nine story building. If Xe = 200, Ap = 60%, Xf = 50 (all floors), z = 27′, and H = 63′, what is the Pf?

Minimum Pf: Assume ground floor conditions. Xw′ = 200×0.4 = 80, Xo′ = 3×50 = 150 psf (3 floors). Average Pfs from figures 2 and 3:

Pf(min) = (11 + 21)/2 = 16

Maximum Pf: Average Pfs from figures 2 and 3 for Xo = 150 at right ordinate:

Pf(max) = (180 + 160)/2 = 170

Since the min and max are not close, we should make a closer estimate by applying rules of thumb.

Height correction = 50 + 13/4 = 53 psf Xw′ = 80 + 53 = 133 psf "z" correction = (27–10)/4 = 4; Xo′ = 150 + 4 = 154 psf.

Use average of Figures 2 and 3.

Pf(est) = (35 + 65)/2 = 50

Reduce by 10% for floor and ceiling correction:

Pf(est) = 45 ANS (EBM Sol = 43)

IX. Summary

The Equivalent Building Method is not presented as a cure-all for all fallout shelter shielding problems. Rather it has been developed to explore the problem of fallout shielding from a different viewpoint. The state of the art at present can only furnish answers that are within, roughly, a factor of two. This method is within this range.

There are many complex shielding situations which require a tremendous amount of arithmetic to compute the protection factor using the Engineering Manual Method. The complexity does not lend itself to analyzing or obtaining a "feel" for how various changes in the parameters would affect the final answer. The Equivalent Building Method does give a quick method of "seeing" how changes affect the result; how the various parameters influence each other. This Equivalent Method then lends itself to preliminary design as well as analysis since changes can be made easily or a number of possible solutions can be done. The Engineering Manual Method should be used as a final check of any preliminary design. The method also lends itself to the quick bracketing of maximum and minimum answers which may, in many cases, be sufficient for the purposes at hand.

The Equivalent Building Method is based on empirical corrections to the overhead and wall mass thicknesses of a building. These empirical values have been derived by solutions to many problems by using either the Engineering Manual or the Spencer Monograph. Correct use of this method should yield results within 10% of the Engineering Manual Method.

A suggested solution form for the EBM method is shown on page 5.

REFERENCES

1. OCD-Engineering Manual. Office of Civil Defense. Washington, D.C., Draft Version—October 1961.
2. Spencer, L. V., Structure Shielding Against Fallout Radiation from Nuclear Weapons. NBS Monograph 42. National Bureau of Standards, Washington, D.C., June 1962.
3. Effects of Nuclear Weapons—1962. U.S. Atomic Energy Commission-U.S. Department of Defense, April 1962.
4. An Engineer Looks at Fallout Shelter, EMO Manual No. 1, Privy Council Office, Ottawa, Canada.
5. Starbird, Albert W., et al., The Effect of Interior Partitions on the Dose Rate in A Multistory Windowless Building. TO-B 63-6. Technical Operations, Incorporated. Burlington, Mass., January 1963.

TABLE I CORRECTION TO Xw FOR FLOOR AND CEILING CONTRIBUTIONS
(Tabular values are subtracted from Xw).

Area	Xf=20	40	60	80
1,000	5	2½	--	--
10,000	12½	10	5	2½
100,000	10	7½	5	2½

TABLE II CORRECTION TO Xw FOR CONTRIBUTION
FROM FLOOR ABOVE DETECTOR (BASEMENT)

AREA =	100	1,000	5,000	10,000	100,000
Xw=0	255	150	105	107	70
25	190	95	52	60	45
50	180	80	45	50	35
100	170	80	43	45	25
150	170	80	38	40	20

TABLE III CORRECTION TO Xw FOR CONTRIBUTION
FROM FLOOR BELOW DETECTOR

AREA =	100	1,000	10,000	100,000
Xw=0	55	15	-20	-45
50	70	20	- 7	-30
100	82	22	- 3	-18
150	85	30	3	-15
200	90	32	7	-12
250	90	35	8	- 7
300	90	35	10	- 3

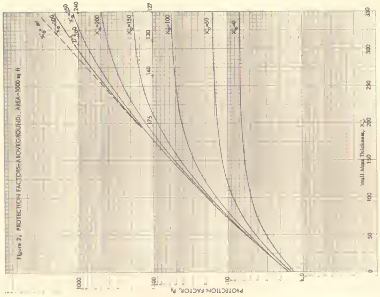


Figure 2. PROTECTION FACTORS-ABOVEGROUND: AREA=1000 sq ft

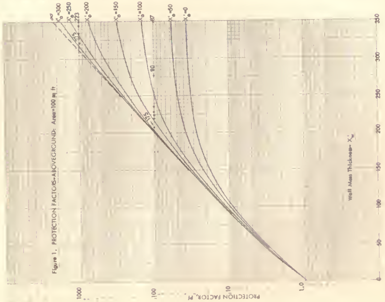


Figure 1. PROTECTION FACTORS-ABOVEGROUND: Area=100 sq ft

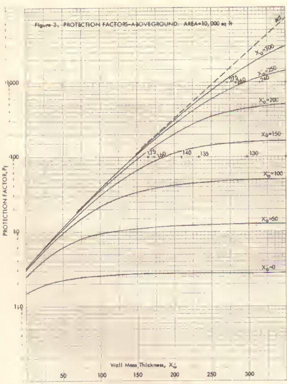


Figure 3. PROTECTION FACTORS–ABOVEGROUND: AREA=10,000 sq ft

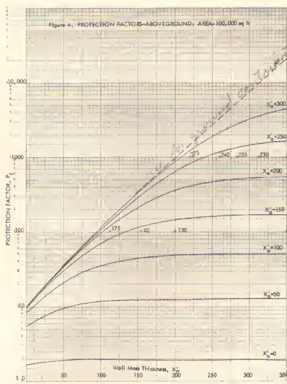


Figure 4. PROTECTION FACTORS–ABOVEGROUND: AREA=100,000 sq ft

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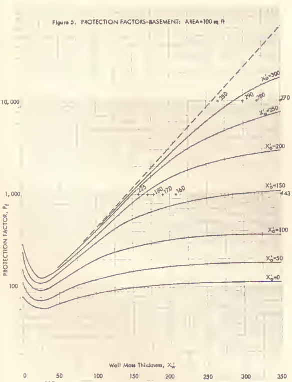


Figure 5. PROTECTION FACTORS–BASEMENT: AREA=100 sq ft

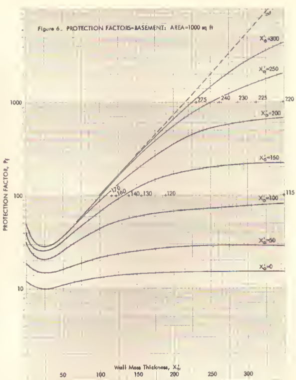


Figure 6. PROTECTION FACTORS–BASEMENT: AREA=1000 sq ft

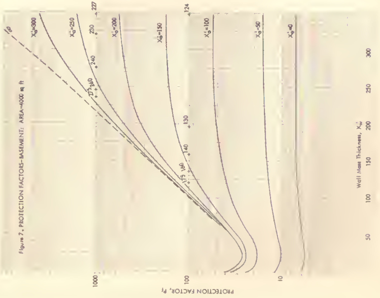


Figure 7. PROTECTION FACTORS–BASEMENT; AREA=4000 sq ft

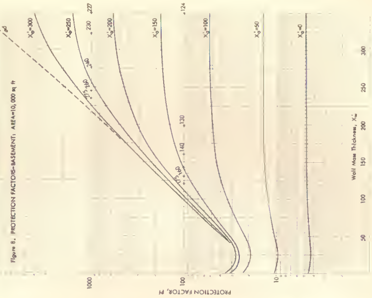


Figure 8. PROTECTION FACTORS–BASEMENT; AREA=10,000 sq ft

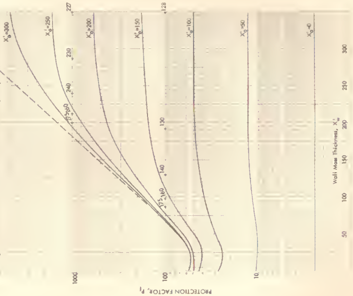


Figure 9. PROTECTION FACTORS–BASEMENT: AREA=100,000 sq ft

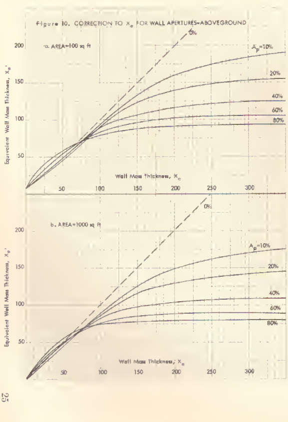


Figure 10. CORRECTION TO X_e FOR WALL APERTURES–ABOVEGROUND
a. AREA=100 sq ft
b. AREA=1000 sq ft
A_p=10%
20%
40%
60%
80%
0%
Equivalent Wall Mass Thickness, X_e'
Wall Mass Thickness, X_e
50
100
150
200
250
300

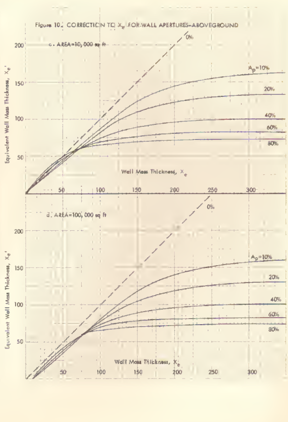


Figure 10. CORRECTION TO X_e FOR WALL APERTURES–ABOVEGROUND
c. AREA=10,000 sq ft
d. AREA=100,000 sq ft
A_p=10%
20%
40%
60%
80%
0%
Equivalent Wall Mass Thickness, X_e'
Wall Mass Thickness, X_e
50
100
150
200
250
300

Figure 11. CORRECTION TO X_e FOR WALL APERTURES–BASEMENT

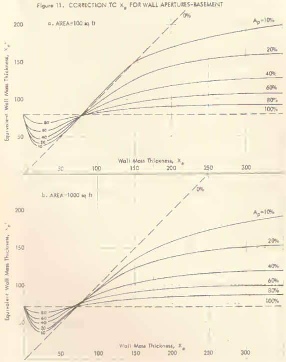
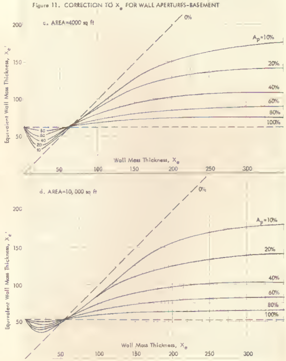


Figure 11. CORRECTION TO X_e FOR WALL APERTURES–BASEMENT



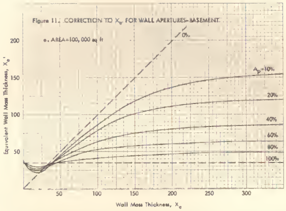


Figure 11. CORRECTION TO X_e FOR WALL APERTURES–BASEMENT

Figure 12. CORRECTION TO X_w FOR HEIGHT OF DETECTOR, H'

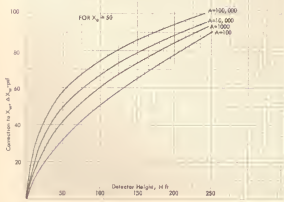
ADD VALUES TO CURVES BELOW

For $X_e = 0$

HEIGHT / A=	100	1000	10,000	100,000
20	6	14	28	53
40	10	21	38	51
60	11	29	42	49
80	10	33	43	47
100	10	36	45	47
150	10	42	46	47
200	9	45	49	47

For $X_e = 25$

HEIGHT / A=	100	1000	10,000	100,000
20	0	3	5	10
40	5	5	6	11
60	6	8	6	12
80	7	9	6	11
100	5	9	6	12
150	4	8	6	10
200	0	5	6	10



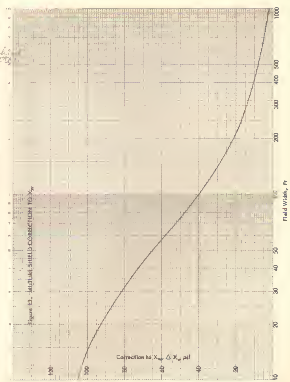


Figure 13. MUTUAL SHIELD CORRECTION TO X_w

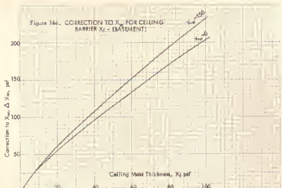


Figure 14a. CORRECTION TO X_w FOR CEILING BARRIER X_f – (BASEMENT)

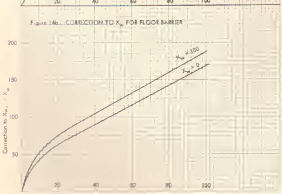


Figure 14b. CORRECTION TO X_w FOR FLOOR BARRIER

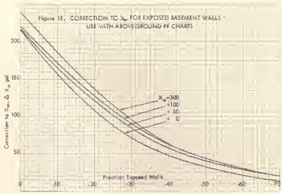


Figure 15. CORRECTION TO X_w FOR EXPOSED BASEMENT WALLS - USE WITH ABOVEGROUND PF CHARTS

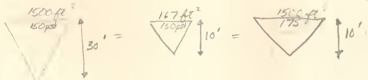
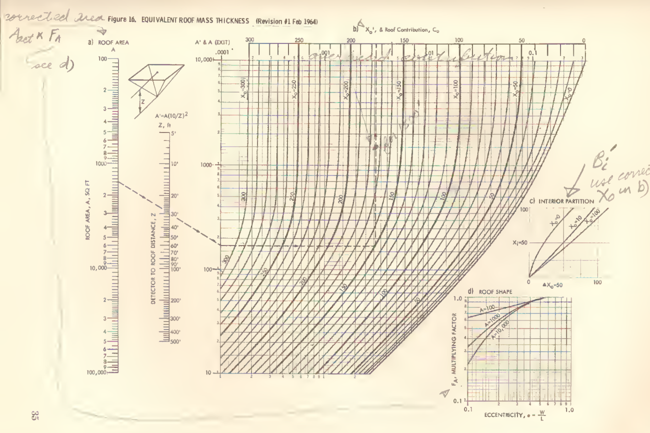


Figure 16. EQUIVALENT ROOF MASS THICKNESS (Revision #1 Feb 1964)



SAMPLE PROBLEMS

The Equivalent Building Method will he demonstrated by a number of typical examples. Most of these prohlems have heen worked out in other publications by the Engineering Manual. Where this is the case, the answers will he compared. The notation (EM=25) means: Engineering Manual method protection factor is 25. Several design problems are worked out indicating the use of this method for such prohlems.

These sample prohlems are organized as follows: (1) Descriptions of the 14 prohlems, (2) solution of prohlems 1–8, (3) quick estimates for the complex problems 9–14, and (4) complete solutions for problems 9–14.

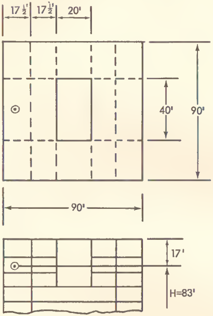
When possihle for short prohlems, one solution form has been used for more than one prohlem to conserve space. All problems are worked out "long hand" to differentiate solution form from solution.

14. *Complex Building-Upper Story With Interior Well:* What is protection factor for location indicated?

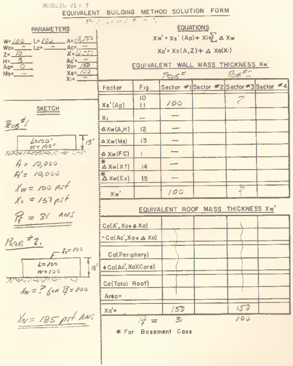
$X_e = 100$ psf $\quad X_i = 50$ psf $\quad X_r = 50$ psf

$X_f = 75$ psf (all floors) $\quad A_p = 0.36$

10′ floor heights $\quad$ Detector 3′ from floor



Sketch for problem 14



PROBLEMS #1 & 2

EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

W= 100 L= 100 A= 10,000
Wc= – Lc= – Ac= –
Z= 10 A'= 10,000
H= 3 Ac'= –
Ap= 0 Xo= 150
Ms= – Xe= 100
Xi= –

EQUATIONS

$X_w' = X_s'(A_p) + X_i + \sum \Delta X_w$

$X_o' = X_o(A,Z) + \Delta X_o(X_i)$

EQUIVALENT WALL MASS THICKNESS Xw'

Prob #1 / Prob #2

Factor	Fig	Sector #1	Sector #2	Sector #3	Sector #4
Xs'(Ap)	10 11	100		?	
Xi	--	—			
ΔXw(A,H)	12	—			
ΔXw(Ms)	13	—			
ΔXw(FC)	1	—			
* ΔXw(Xf)	14	—			
* ΔXw(Ex)	15	—			
Xw'		100		?	

EQUIVALENT ROOF MASS THICKNESS Xw'

Co(A', Xo+ΔXo)				
−Co(Ac', Xo+ΔXo)				
Co(Periphery)				
+Co(Ac', Xo)(Core)				
Co(Total Roof)				
Area=				
Xo'=	150		150	
Pf =	31		100	

* For Basement Case

SKETCH

Prob #1.

L=100'
W=100'
13'

A = 10,000
A' = 10,000
Xw = 100 psf
Xo = 150 psf
Pf = 31 ANS

Prob #2.

Xo=100
L=100
W=100
13'

Xw = ? for Pf = 100

Xw = 185 psf ANS

Problem No. 3 Solution:

This problem asks that we obtain the most economical combination of roof and wall mass thickness. First we write a cost equation.

$$\text{Cost} = (\$75\ A_wX_w + \$100\ A_rX_o)/4{,}000$$
$$= \$75\ X_w + \$250\ X_o$$

Since the building area is 10,000 sq ft we can use figure 3. For intermediate areas, simple interpolation is possible. At the horizontal line for Pf 100 and Pf 1,000, list the combinations of Xw and Xo which are possible. Then construct a cost table to determine the minimum cost.

Xw	*Xo*	*Cw*	*Cr*	*Ctot*
145	250	10, 900	62, 500	73, 400
153	200	11, 500	50, 200	61, 500
165	175	12, 400	43, 700	58, 100
173	160	13, 000	40, 000	53, 000
185	150	13, 900	37, 500	51, 400
210	140	15, 800	35, 000	50, 800*
232	135	17, 400	33, 700	51, 100
297	130	22, 300	32, 500	54, 800

*Minimum.

For part (a) then, the answer would be: *Xw=210, Xo=140*

The same procedure is used for the Pf 1,000 case:

Xw	*Xo*	*Cw*	*Cr*	*Ctot*
265	300	19, 900	75, 000	94, 900
272	275	20, 400	68, 700	89, 100
283	260	21, 200	65, 000	86, 200
295	250	22, 100	62, 500	84, 600
315	240	23, 600	59, 000	82, 600*
350	232	26, 200	58, 000	84, 200

*Minimum

For part (b), the answer would be: *Xw=315, Xo=240*

PROBLEMS #4 & 5

EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

W= ___ L= ___ A= ___
Wc= ___ Lc= ___ Ac= ___
Z= ___ A'= ___
H= ___ Ac'= ___
Ap= ___ Xo= ___
Ms= ___ Xe= ___
Xi= ___

EQUATIONS

$X_w' = X_e'(A_p) + X_i + \sum \Delta X_w$

$X_o' = X_o(A,Z) + \Delta X_o(X_i)$

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1 (Prob #4)	Sector #2	Sector #3 (Prob #5)	Sector #4
Xe'(Ap)	10 11	112		200	
Xi	--				
ΔXw(A,H)	12				
ΔXw(Ms)	13				
ΔXw(FC)	1				
* ΔXw(Xf)	14				
* ΔXw(Ex)	15				
Xw'		112		200	

EQUIVALENT ROOF MASS THICKNESS Xw'

Factor	Sector #1	Sector #2	Sector #3	Sector #4
Co(A', Xo+ΔXo)				
-Co(Ac', Xo+ΔXo)				
Co(Periphery)				
+Co(Ac', Xo)(Core)				
Co(Total Roof)				
Area=				
Xo'=	140		150	

* For Basement Case

SKETCH

Prob #4
$X_o = 140$
$A = 100 \times 130 = 13{,}000$
$A_p = \frac{6 \times 6}{10 \times 13} \times 100 = 28\%$
$X_e = 210$
$P_f = 34$ ANS

Prob #5
W = 60', L = 100'
$X_w = 200$, $X_o = 150$
P_f = [illegible] ANS

P_f = 34, P_f = 86, A = 1300; P_f = 112, A = 13,000; P_f = [illegible], A = 6,000

PROBLEM #6

EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

W= 90 L= 110 A= 9900
Wc= ___ Lc= ___ Ac= ___
Z= 21 A'= 2250
H= ___ Ac'= ___
Ap= ___ Xo= 150
Ms= ___ Xe= 70
Xi= ___

EQUATIONS

$X_w' = X_e'(A_p) + X_i + \sum \Delta X_w$

$X_o' = X_o(A,Z) + \Delta X_o(X_i)$

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1	Sector #2	Sector #3	Sector #4
Xe'(Ap)	10 11	70		70	
Xi	--	—		—	
ΔXw(A,H)	12			—	
ΔXw(Ms)	13			—	
ΔXw(FC)	1 I			47	
* ΔXw(Xf)	14	125		125	
* ΔXw(Ex)	15	—			
Xw'		195		242	

EQUIVALENT ROOF MASS THICKNESS Xw'

Factor	Sector #1	Sector #2	Sector #3	Sector #4
Co(A', Xo+ΔXo)	—		—	
-Co(Ac', Xo+ΔXo)	—		—	
Co(Periphery)	—		—	
+Co(Ac', Xo)(Core)	.0058		[illegible]	
Co(Total Roof)	.0055		[illegible]	
Area= A_B =	3400		9900	
Xo'=	150		150	

P_f = 13[illegible] P_f = 140

* For Basement Case

SKETCH

Prob #6
$X_o = 100$
W = 90, 110', 21'
$A = 110 \times 90 = 9900$
$A' = 9900(\frac{15}{21})^2 = 2250$
A_B = [illegible] = 3400
$P_f = 138$ ANS (Fig 5)

Prob. #6 using above
Note we now correct for FC from Table II and use actual area for roof Xo'
$P_f = 140$ ANS (Fig 3)

PROBLEM #7

EQUIVALENT BUILDING METHOD SOLUTION FORM

PROBLEM #7

PARAMETERS

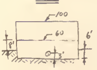
W= 50 L= 100 A= 5000
Wc= ___ Lc= ___ Ac= ___
Z= 23 A'= 946
H= ___ Ac'= ___
Ap= ___ Xo= 160
Ms= ___ Xe= 100
Xi= ___

EQUATIONS

$$X_w' = X_e'(A_p) + X_i + \sum \Delta X_w$$

$$X_o' = X_o(A,Z) + \Delta X_o(X_i)$$

SKETCH



$E_X = 8/14 = .57$

$P_f = 44 \times \frac{1420}{1464}$

$P_f = 43$ ANS

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1 (Pfo)	Sector #2 (Pfu)	Sector #3	Sector #4
Xe'(Ap)	10, 11	100	100		
Xi	--	—	—		
ΔXw(A,H)	12	-	-		
ΔXw(Me)	13	—	-		
ΔXw(FC)	II		43		
* ΔXw(Xf)	14 a	-	145		
* ΔXw(Ex)	15	33			
Xw'		133	288		

EQUIVALENT ROOF MASS THICKNESS Xw'

Co(A', Xo+ΔXo)				
-Co(Ac', Xo+ΔXo)				
Co(Periphery)				
+Co(Ac', Xo)(Core)				
Co(Total Roof)	.0043			
Area=	5000			
Xo'=	165	∞		

A=1000 33 950
A=1400 57 2000
* For Basement Case
A= 5000 44 1420

PROBLEM #8

EQUIVALENT BUILDING METHOD SOLUTION FORM

PROB. #8

PARAMETERS

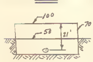
W= 90 L= 110 A= 9900
Wc= — Lc= — Ac= —
Z= 21 A'= 2250
H= — Ac'= —
Ap= 0.8 Xo= 150
Me= — Xe= 70
Xi= —

EQUATIONS

$$X_w' = X_e'(A_p) + X_i + \sum \Delta X_w$$

$$X_o' = X_o(A,Z) + \Delta X_o(X_i)$$

SKETCH



BELOWGROUND CHART
SECTOR #1-COLUMN

$P_f = 130$ ANS (Fig. 8)

ABOVEGROUND CHART
SECTOR #2-COLUMN

$P_f = 132$ ANS (Fig 3)

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1 (Pfo)	Sector #2 (Pfu)	Sector #3	Sector #4
Xe'(Ap)	10, 11	57	57		
Xi	--	—	—		
ΔXw(A,H)	12	—	—		
ΔXw(Me)	13	—	—		
ΔXw(FC)	1	—	49		
* ΔXw(Xf)	14	125	125		
* ΔXw(Ex)	15	—	—		
Xw'		182	231		

EQUIVALENT ROOF MASS THICKNESS Xw'

Co(A', Xo+ΔXo)				
-Co(Ac', Xo+ΔXo)				
Co(Periphery)				
+Co(Ac', Xo)(Core)				
Co(Total Roof)	.0058	0058		
Area= As	3400	4700		
Xo'=	150	150		

$P_f =$ 130 132

* For Basement Case

QUICK APPROXIMATE SOLUTIONS FOR PROBLEMS 9–14

Problem No. 9. Core Building

1. Use approximate arsa of 5,000 vs actual 4,800.
2. Use actual roof and wall thicknesses with no corrections.
3. Use Pf halfway between 1,000 and 10,000 sq ft charts.

Xw=140; Xo=80; For A=1,000 Pf=20
For A=10,000 Pf=25
For A=5,000 Pf=22 ANS (EM=22)

Problem No. 10. Mutual Shield.

1. Use A=1,000 in lieu of actual A=2,000.
2. Neglect effect of mutual shield since it affects only part of one wall.
3. For min Pf assume ground floor conditions:

Xw=60; Xo=100; Pf(min)=6.5

4. For max Pf assume infinite wall thickness:

Pf(max)=55

5. For estimate between min and max correct for height: H=23′, add 20 psf for Xw′=80

Pf(est)=10 (EM=12)

Problem No. 11. Upper Story Building-Windowless

1. Use approximate area of 10,000 vs actual 7,500.
2. For min Pf assume ground floor conditions:

Xw=80; Xo=150; Pf(min)=21

3. For max Pf assume infinite wall thickness:

Pf(max)=165

4. Correct for height. Add 50 pf for H=53′; Xw′=130

Pf(est)=50 (EM=43)

Problem No. 12. Upper Story Building-Windows

1. Use approximate area of 10,000 vs actual 7,500.
2. For minimum Pf assume ground floor conditions and correct for windows.

Xw′=80×0.6=48; Xo=150; Pf(min)=11

3. Max Pf: Pf(max)=165
4. Correct for height; H=53′, Xw′=48+50=98

Pf(est)=31 (EM=35)

Problem No. 13. Complex Building with L-Wing.

1. Neglect contribution from west wing.
2. Use area of remaining building for base, 3,200 sq ft.
3. Use actual wall and roof wsights.
4. Neglect effect of door and mutual shield; they tend to compensate for sach other.

Xw=55; Xo=135; For A=1,000; Pf= 6
For A=10,000; Pf=11
For A= 3,200; Pf= 8 (EM=7)

Problem No. 14. Complex Building with Interior Well,

1. Estimate minimum and maximum Pfs.
2. For min Pf assume ground floor conditions and include effect of windows:

Xw=100×0.54= 54; Xo′=125; Pf(min)=11

3. Max Pf: Pf(max)=95
4. Correct for height, H=83; 50+(8−50)/4=57
5. For wall without intsrior partitions, Xw′=54+57=111

For A=10,000; Pf=31

6. For walls with interior partitions, Xw′=111+50=161 Pf=52
7. Approximately 1/4 of walls have Pf=31 and 3/4 have Pf=52: combine, Pf=31/4+52(3/4)=47 (EM=47)

EQUIVALENT BUILDING METHOD SOLUTION FORM

PROBLEM #1

PARAMETERS

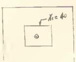
W= 60 L= 60 A= 4800
Wc= 20 Lc= 30 Ac= 600
Z= 7' A'= 9800
H= 3' Ac'= 1220
Ap= 0 Xo= 80
Me= — Xe= [illegible]
Xi= [illegible]

EQUATIONS

Xw' = Xe' (Ap) + Xi + $\sum$ Δ Xw

Xo' = Xo(A,Z) + Δ Xo(Xi)

SKETCH



$X_{op} = X_o + \Delta X_o(X_i)$
$= 80 + 47 = 127$

$A = 1000,\ P_f = 20$
$A = 10{,}000,\ P_f = 25$

$P_f = 20 + 5\left(\frac{3800}{9000}\right)$

$P_f = 22$ ANS (EM=22)

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1	Sector #2	Sector #3	Sector #4
Xe'(Ap)	10 11	100			
Xi	--	40			
ΔXw(A,H)	12	—			
ΔXw(Me)	13	—			
ΔXw(FC)	1	—			
* ΔXw(Xf)	14	—			
* ΔXw(Ex)	15	—			
Xw'		140			

EQUIVALENT ROOF MASS THICKNESS Xw'

Co(A', Xo+ΔXo) (9800, 127)	.0105			
−Co(Ac', Xo+ΔXo) (1220, 127)	.0100			
Co(Periphery)	.0005			
+Co(Ac', Xo)(Core) (1220, 80)	.031			
Co(Total Roof)	.0315			
Area=	4800			
Xo'=	85			

* For Basement Case

EQUIVALENT BUILDING METHOD SOLUTION FORM

PROBLEM #10

PARAMETERS

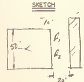
W= 40 L= 50 A= 2000
Wc= — Lc= — Ac= —
Z= 7' A'= 4100
H= 23' Ac'= —
Ap= — Xo= 100
Me= 20' Xe= 60
Xi=
$f_f = 40$

EQUATIONS

Xw' = Xe' (Ap) + Xi + $\sum$ Δ Xw

Xo' = Xo(A,Z) + Δ Xo(Xi)

SKETCH



$\tan\theta_1 = \frac{35}{40} = .875,\ \theta_1 = 41°$

$\tan\theta_2 = \frac{25}{40} = .625,\ \theta_2 = 32°$

$\omega_1 = 73/360 = .203$

$P_f = \frac{.203}{35} + \frac{.797}{10.3}$

$= \frac{35 \times 10.3}{209 + 27.9}$

$P_f = 12$ ANS (EM=12)

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig.	Sector #1 (Pfo, ω=.203)	Sector #2 (Pfg, ω=.203)	Sector #3 (Pfo, ω=.797)	Sector #4 (Pfg, ω=.797)
Xe'(Ap)	10 11	60	60	60	60
Xi	--	—	—	—	—
ΔXw(A,H)	12	27	20	27	20
ΔXw(Me)	13	93	93	0	0
ΔXw(FC)	1	—	17	—	17
* ΔXw(Xf)	14	—	97	—	97
* ΔXw(Ex)	15	—	—	—	—
Xw'		180	287	87	194

EQUIVALENT ROOF MASS THICKNESS Xw'

Co(A', Xo+ΔXo)				
−Co(Ac', Xo+ΔXo)				
Co(Periphery)				
+Co(Ac', Xo)(Core)				
Co(Total Roof)				
Area=				
Xo'=	100	∞	100	∞
use A=1000 P_f=	36	995	11	135

* For Basement Case

35   10.3

PROBLEM #13

EQUIVALENT BUILDING METHOD SOLUTION FORM

PROBLEM #13

PARAMETERS

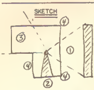
W= ~80 L= ~80 A= ~4800
Wc= – Lc= – Ac= –
Z= 22' A'=
H= Ac'=
Ap= .15 Xo= 135
Ms= Xe= 55
Xi=

EQUATIONS

$Xw' = Xe'(Ap) + Xi + \sum \Delta Xw$

$Xo' = Xo(A,Z) + \Delta Xo(Xi)$

SKETCH



FOR SECTORS ①, ②, ④

A = 40x80
= 3200
A' = 661

FOR SECTOR ③

A = 120x80
= 9600
A' = 1980

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1	Sector #2	Sector #3	Sector #4
		Q = .167	.036	.178	.620
Xe'(Ap)	10, 11	50	0	50	50
Xi	--	–	–	–	–
ΔXw(A,H)	12	–	–	–	–
ΔXw(Me)	13	64	0	0	0
ΔXw(FC)	I	neg	neg	neg	neg
* ΔXw(Xf)	14	–	–	–	–
* ΔXw(Ex)	15	–		–	
Xw'		114	0	50	50

EQUIVALENT ROOF MASS THICKNESS Xw'

	Sector #1	Sector #2	Sector #3	Sector #4
Co(A', Xo+ΔXo)				
-Co(Ac', Xo+ΔXo)				
Co(Periphery)				
+Co(Ac', Xo)(Core)				
Co(Total Roof)	.0075	.0075	.0083	.0075
Area =	3200	3200	6400	3200
Xo' =	140	140	137	140

A = 1000	21	1.5	5.4	5.4
A = 10,000	36	3.0	10.5	10.5
A = 3200/6400	25	1.9	10.3	6.6

* For Basement Case

$P_f^{-1} = \frac{.167}{25} + \frac{.036}{1.9} + \frac{.178}{10.3} + \frac{.620}{6.6}$

$P_f^{-1} = .141$

$P_f = 7.1$ ANS (EM=7)

PROBLEM #14

EQUIVALENT BUILDING METHOD SOLUTION FORM

PARAMETERS

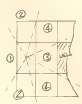
W= 90 L= 90 A= 8100
Wc= 175 Lc= 40 Ac= 700
Z= 17' A'= 2900
H= 83' Ac'= 240
Ap= 36% Xo= 125
Ms= 20' Xe= 100
Xi=
Xf= 75

EQUATIONS

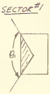
$Xw' = Xe'(Ap) + Xi + \sum \Delta Xw$

$Xo' = Xo(A,Z) + \Delta Xo(Xi)$

SKETCH



SECTOR #1



$\theta_1 = 133°$
$Q_1 = .369$
A = 700
A' = 240
H = 83'

EQUIVALENT WALL MASS THICKNESS Xw'

Factor	Fig	Sector #1	Sector #2	Sector #3	Sector #4
		Q = .369	.205	.207	.229
Xe'(Ap)	10, 11	85	83	80	77
Xi	--	0	50	50	
ΔXw(A,H)	12	51	54	19	
ΔXw(Me)	13	0	0	92	
ΔXw(FC)	I	0	0	0	
* ΔXw(Xf)	14	0	0	0	
* ΔXw(Ex)	15	0	0	0	
Xw'		136	187	241	∞

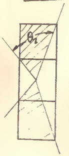
EQUIVALENT ROOF MASS THICKNESS Xw'

	Sector #1	Sector #2	Sector #3	Sector #4
Co(A', Xo+ΔXo)		0023	0027	0027
-Co(Ac', Xo+ΔXo)		0017	0017	0017
Co(Periphery)		0006	0010	0010
+Co(Ac', Xo)(Core)		0067	0067	0067
Co(Total Roof)	.0067	0073	0077	0077
Area =	700	1570	4740	8100
Xo' =	142	140	140	140

* For Basement Case

SKETCH

SECTOR #2



$2\theta_2 = 74^\circ$

$a_2 = .205$

$A = 1570$

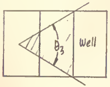
$A' = 540$

$A'_c = 240$

$H = 83'$

$X_{op} = 185$

SECTOR #3



$\theta_3 = 75^\circ$

$a_3 = .207$

$A = 4730$

$A' = 1640$

$A'_c = 240$

$H = 13'$

$X_{op} = 185$

CALCULATIONS

SECTOR #1, $a_1 = .369$

AREA	Pf
100	24
1000	30
700	28

$R_f = \frac{.369}{28} = .0132$

SECTOR #2, $a_2 = .205$

AREA	Pf
1000	64
10,000	85
1570	65

$R_f = \frac{.205}{65} = .0032$

SECTOR #3, $a_3 = .207$

AREA	Pf
1000	90
10,000	120
4730	104

$R_f = \frac{.207}{104} = .0020$

SECTOR #4, $a_4 = .229$

AREA	Pf
1000	150
10,000	130
8,100	135

$R_f = \frac{.229}{135} = .0017$

R_f (TOTAL) $= .0201$

$\therefore P_f = 50$ ANS (EM=47)

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