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Basic Concepts for the Design of Nuclear Shelters and the Calculation of Wall Thickness Against a Nuclear Explosion of 20 kT

Dr. Salam J. Al-Maliky
Environmental Engineering Department, College of Engineering
Al-Mustansiriya University, Baghdad, Iraq

Abstract

Of the major aspects in dealing with the design of nuclear shelters, such as the engineering designs (archetectural and civil), location, prevailing meteorolgical conditions, methods and technologies of ventilation and air conditioning, supplies, degree of burial, wall thickness…etc., the last two aspects are chosen in this paper.

This paper results the preference for the nuclear shelter to be under ground for maximum protection. That will reduce the effect of over pressure on the exposed roofslab, and remove the effect of the dynamic pressure altogether. Also the effects of radiation would be reduced, allowing simplification of the design process and reducing the material cost compared with a similar partially or wholly above ground shelter.

Two types of concrete were tested as shielding materials through the use of the computer program CADRE, in addition to the use of program BMIX to calculate some of the variables needed for the essential program, to calculate the wall thickness required to reduce the radiation dose exerted from a nuclear explosion of 20 kT (about 1 km away) to a safe value inside the shelter (2 mrem/h).

الخلاصـــــــة

من بين الاعتبارات الرئيسية التي يتوجب الاخذ بها عند تصميم ملاجئ نووية، مثل التصاميم الهندسية (المعمارية و المدنية) واختيار الموقع و دراسة الاحوال الجوية السائدة و اساليب و تقنيات التهوية و التكييف و التجهيزات و المستلزمات الحيوية و عمق الدفن (الغمر) و سمك الجدار..الخ.، تم اختيار العنصرين الاخيرين لاغراض هذه الدراسة.

يخلص البحث الى تفضيل ان يكون الملجأ النووي تحت الارض للحصول على الحماية القصوى. يؤدي ذلك الى تقليل الضغط المسلط على السقف، و كذلك استبعاد تاثير الضغط الديناميكي. كنتيجة لهذا الاجراء يتم تقليل الاشعاع الواصل للملجأ، مما يسمح ببساطة التصميم وتقليل كلفة المواد مقارنة مع الملاجئ المماثلة المدفونة جزئيا او الواقعة كليا فوق مستوى السطح.

تم اختبار نوعين من الكونكريت كمواد تدريع و باستخدام البرنامج الحاسوبي CADRE، مع الاستعانة ببرنامج BMIX لحساب بعض المتغيرات المطلوبة للبرنامج الاساس، لحساب سمك الجدار المطلوب لتقليل الجرعة الاشعاعية الناتجة عن انفجار نووي بطاقة ٢٠ كيلوطن (على بعد حوالي ١كم) الى القيمة المقبولة داخل الملجأ (٢ مللي ريم/ساعة).

1. Introduction

The most important phenomena of a nuclear shelter is to [1]:

1. Resist the over pressure and the dynamic pressure (wind).
2. Reduce the effect of radiation.

The main discussion, would be with protection against the effect of radiation, whether from the initial explosion or from the residual fall-out and since α and β-rays are short ranged, the radiations to be shielded against initially are γ-rays and Neutrons, but only γ-rays for residual fall-out.

1-1 γ-Rays Shielding

The attenuation of γ-rays is dependent on mass per unit area of the material in which they pass. So, for low density of a substance it would require a greater thickness than that of high density for the same attenuation. Theoretical and experimental results have led to the concept of "tenth value thickness" as a measure of the effectiveness of a material attenuating γ-rays of a given energy. Tenth value thickness is defined as that thickness of the specified material which reduces the radiation dose (or dose rate) to (1/10) of that falling up (**Table (1)**) [2].

Table (1) Tenth value thickness of various materials for initial and fallout gamma radiation [2]

Material	Density (kg/m^3)	Initial γ radiation 1/10 value (cm)	Fallout γ radiation 1/10 value (cm)
Steel	7850	13.5	9.4
Concrete	2305	45.7	30.5
Earth	1600	66.0	45.7
Water	1000	94.0	66.0
Wood	545	177.8	122.0

1-2 Neutron Shielding

The attenuation of neutrons involves several different phenomena; first, the very fast neutrons must be slowed down into the moderately fast range, which requires a suitable (inelastic) scattering material, such as one containing Barium or Iron. Then the moderately fast neutrons have to be decelerated by (elastic scattering) into the slow range by an element of low atomic weight.

Water is very satisfactory for this, since it's two constituents; Oxygen and Hydrogen, both have low atomic weights. The slow neutrons must then be absorbed by elements of low atomic weight. Also sufficient γ-attenuating materials must be included to minimize the escape of γ-rays created as a result of neutron capture [4].

2. Shielding Materials

The general requirements for radiation shielding materials are [3]:

1. High density, for maximum efficiency of shielding against γ-radiation with minimum thickness of shielding material.
2. The density should remain constant, and the material should be homogeneous in all sections of the shield.
3. A sufficiently large current of hydrogen (generally in the form of water chemically combined in the shielding materials) for the moderation of neutrons .
4. The material should not be subject to decomposition or weakening under the influence of radiation.
5. A high content of heavy elements for moderating fast neutrons and also for absorbing secondary γ-radiation resulting from the moderation.
6. Constructional strength and stability, as in most cases the radiation shielding is load bearing member. At the same time the shielding should not have joints, upon which leakage may occur.
7. High fire resistance (if the material is inflammable the rate of combustion must be low self extinguishing when the source of heat is removed).

Shielding materials can be classified into three broad categories according to their function;

2-1 Heavy or Moderately Heavy Elements

These materials are used to attenuate γ-radiation and to slow down very fast neutrons to about 1-Mev by inelastic collisions. Iron, carbon, steel and stainless steel are an example of such materials.

Lead and it's alloys have been used to some extent in nuclear reactor shielding, because of their density and easy to fabricate to attenuate γ-rays with energies in the 2-Mev region, roughly the same mass of lead as Iron is required to remove a specified fraction of radiation [4].

2-2 Hydrogenous Material

The value of hydrogenous materials for the shielding of neutron is determined by its Hydrogen content. The number of Hydrogen atmosphere unit volume expresses this.Water which contains $6.7\times10^{28} atoms/m^3$, in addition to it's low cost make it the best 'probably' neutron shielding material. But its poor absorption of γ-ray, low boiling point under atmospheric pressure, and its susceptibility to decomposition by radiation are some drawbacks to the use of liquid water in reactor shields. On the other hand, water provides ready means for removing the heat generated by radiation absorption.

Concrete is much recommended for shielding material, because it is strong, inexpensive and adaptable to both block and monolithic of constructions. Ordinary concrete of density 2.3 Mg/m^3 generally contains (7-8%) by weight of water when cured. $(ie 1.4\times10^{28}$ Hydrogen atoms/m^3). Thermal macroscopic cross section for fast neutrons of concrete is about (8.5 m^{-1}) and for water (10 m^{-1}). However concrete is much superior to water for the attenuation of γ-rays. This mainly due to the presence of some 50% by weight of high mass number elements such as Calcium and Silicon [2].

3. Fallout Shielding

Another parameter to be studied is the fallout radiation effect to find the contribution made by the fallout to total dose for shelters affected by initial radiation. Fallout is assumed to uniformly cover all horizontal surfaces and the fallout radiation spectrum is taken as that existing (1.12hr) after the explosion. The energy of the emitted γ-radiation from fallout is partially in the range of (0.2-3.0) Mev [5]. For portions protected by a barrier from fallout radiation, several possibilities are taken for γ-rays incident on the barrier, these are [1]:

1. It may pass through the barrier without suffering an interaction (direct radiation).
2. It may interact with an orbital electron of an atom in the barrier, loss all energy and be absorbed.
3. It may act with an orbital electron without loosing all its energy and new photons with lower energy will depart in a different direction (Compton scattering effect).

The third case may occur in the air or in the intervening barrier. The radiation received from the Compton effect in the barrier is the scattered radiation and that received from that effect in the air is the skyshine radiation.

A simple above-ground shelter is taken to be rectangular on plan, isolated on a horizontal plan field, extending infinitely in all directions, having an envelope of uniform mass thickness, and containing no aperatures. The floor at ground level, with radioactive fallout particles uniformly distributed over the entire plane surface outside the building and over the entire roof surface. For this shelter, the sources of radiation reaching a detector 1-m above the shelter floor (the average mid body surface) are shown in **Fig.(1)**.

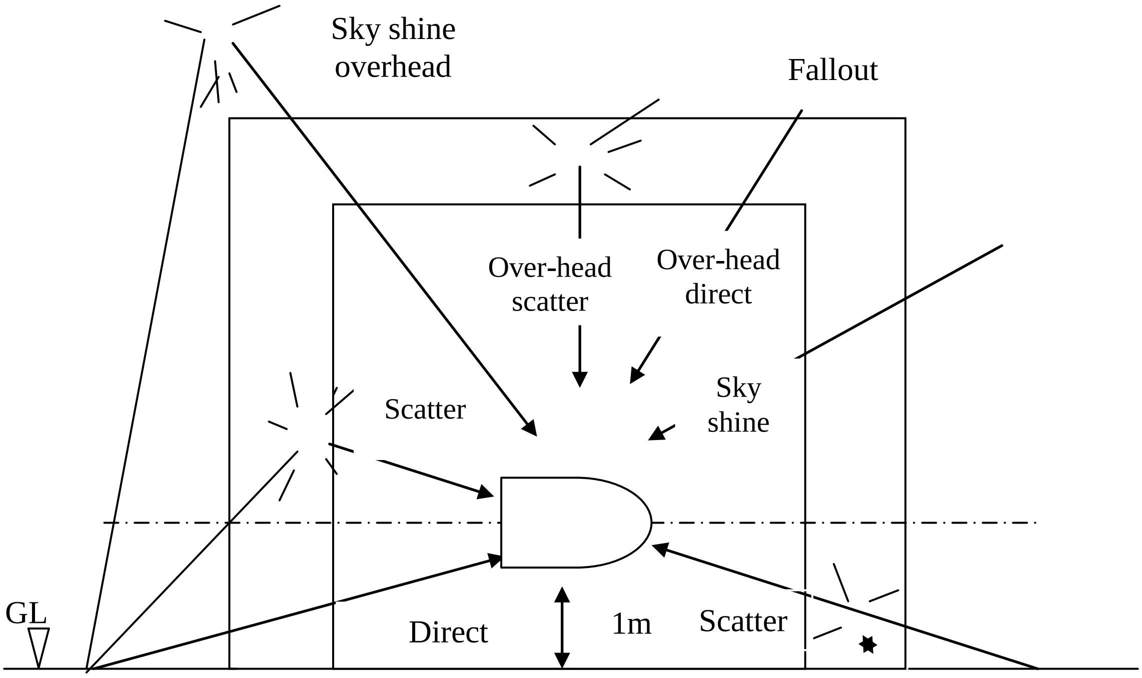


Figure (1) Typical radiation sources reaching a detecter in typical above ground nuclear shelter [4]

The fallout shielding calculation is based on the following two variables [4]:

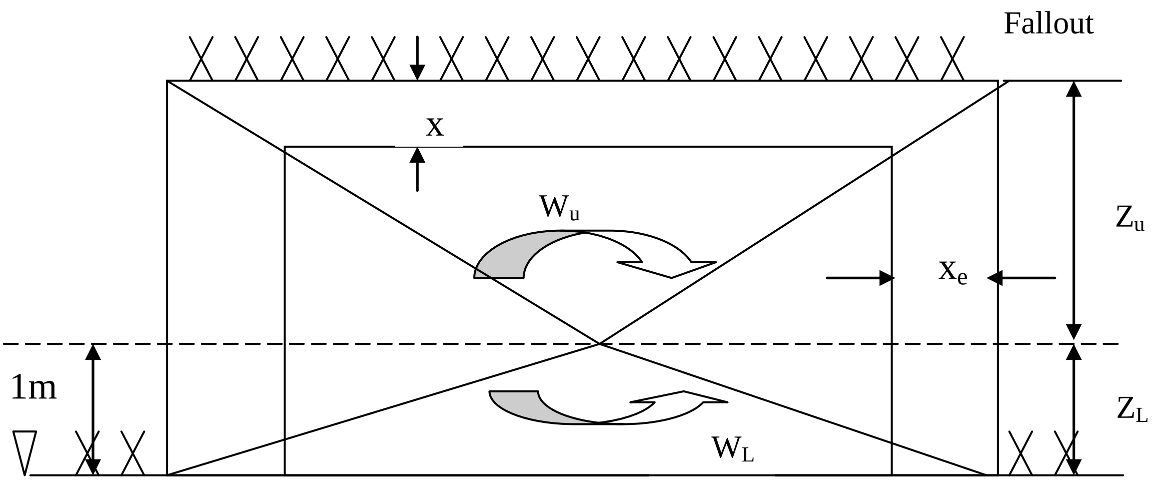
3-1 Geometric Shielding

It is used to determine the directional responses to the various radiation sources and the shape influence of the shielded area, through the action of the inverse square law. The effect is determined by the solid angle fraction (w) of the shielded area (the area which the solid angle subtends on a sphere of unit radius, divided by the area of a hemisphere of unit radius). It can be calculated for the shelter of specifications as in **Fig.(2)** by preparing the Eccentricity ratio (width/length) and the Altitude ratio (altitude/length) to be used in **Fig.(3-a)**.

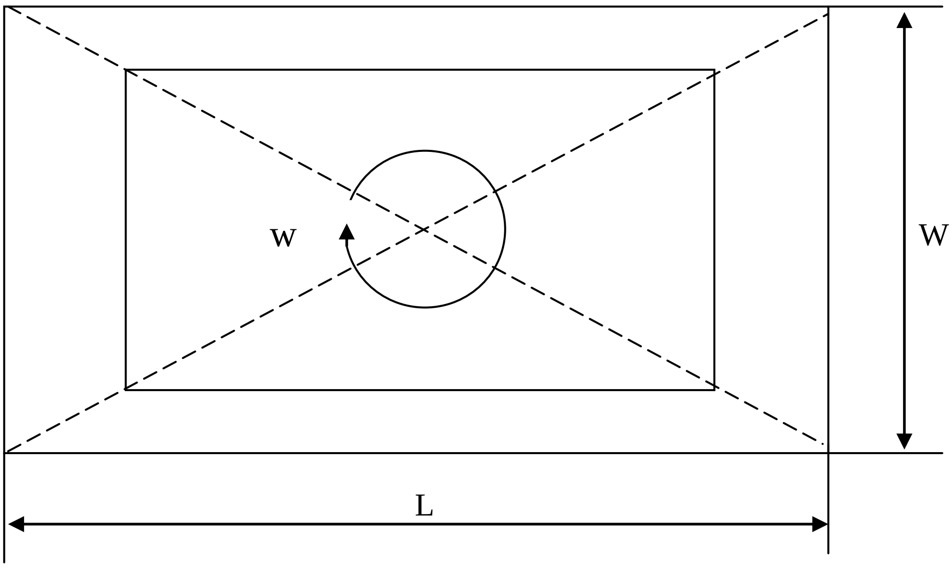
3-2 Barrier Shielding

It is based on the attenuating effect of a dense barrier on incident radiation and depends on the mass thickness of barrier. The protection factor (pf) of the structure shown above is made up from a contribution from the roof (Co) and through the walls (Cg). Both are affected by geometry and barrier shielding i.e.:

$$\mathbf{pf = \frac{1}{Co + Cg}} \quad \dots\dots\dots\dots \mathbf{(1)}$$



- Section -



-Plan-

Figure (2) Section and plan views of a typical shelter [6]

3-2-1 The Over Head Vontribution (Co)

Attention here is focused on radiation that emerges from the underside of the roof barrier and reaches the detector as an overhead contribution. It has the following components **[6]**:

1. Direct overhead contribution.
2. Surface overhead contribution.
3. Overhead skyshine contribution.

The geometric shielding effect is accommodated by calculating the upper solid angle (w_u), along with the appropriate data and reading the value from **Fig.(3-a)**. The barrier shielding is acomodated by calculating the mass thickness of the roof (mass per unit area), X_0 (kg/m^2). These two variables are then used in **Fig.(3-b)** to obtain the overhead reduction factor (Co).

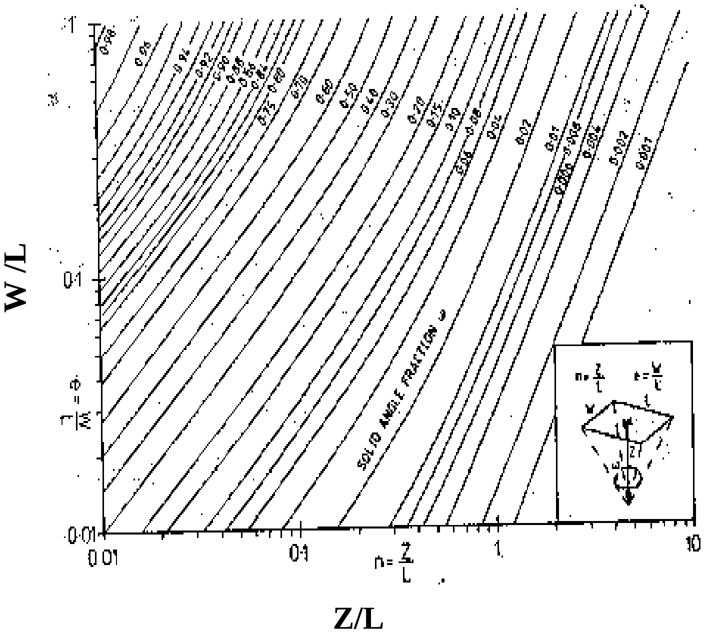


Figure (3.a) Values of solid angle fraction vs. shelter`s dimensions [6]

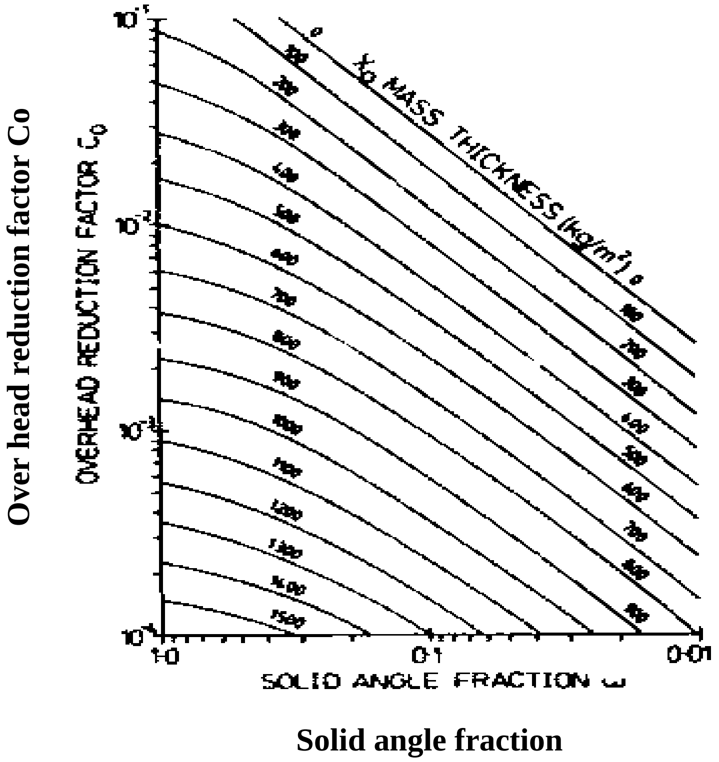


Figure (3.b) Overhead reduction factor vs. solid angle fraction [6]

It should be noted that whether the shelter roof is at/or below ground level the overhead contribution, Co, is the only appreciable source of radiation and will determine the protection factor for the structure.

3-2-2 The Ground Contribution (Cg)

Considering **Fig.(1)**, the radiations are emerging from the inner surface of the exterior wall barriers. The centrally located detector responds to these radiations as they arrive from all angular locations. All the radiations reaching the detector through the walls originate from the fallout particles on the contaminated ground plan and the aggregate is the ground contribution. **Figure (4)** gives an impression of the components of the ground contribution [4].

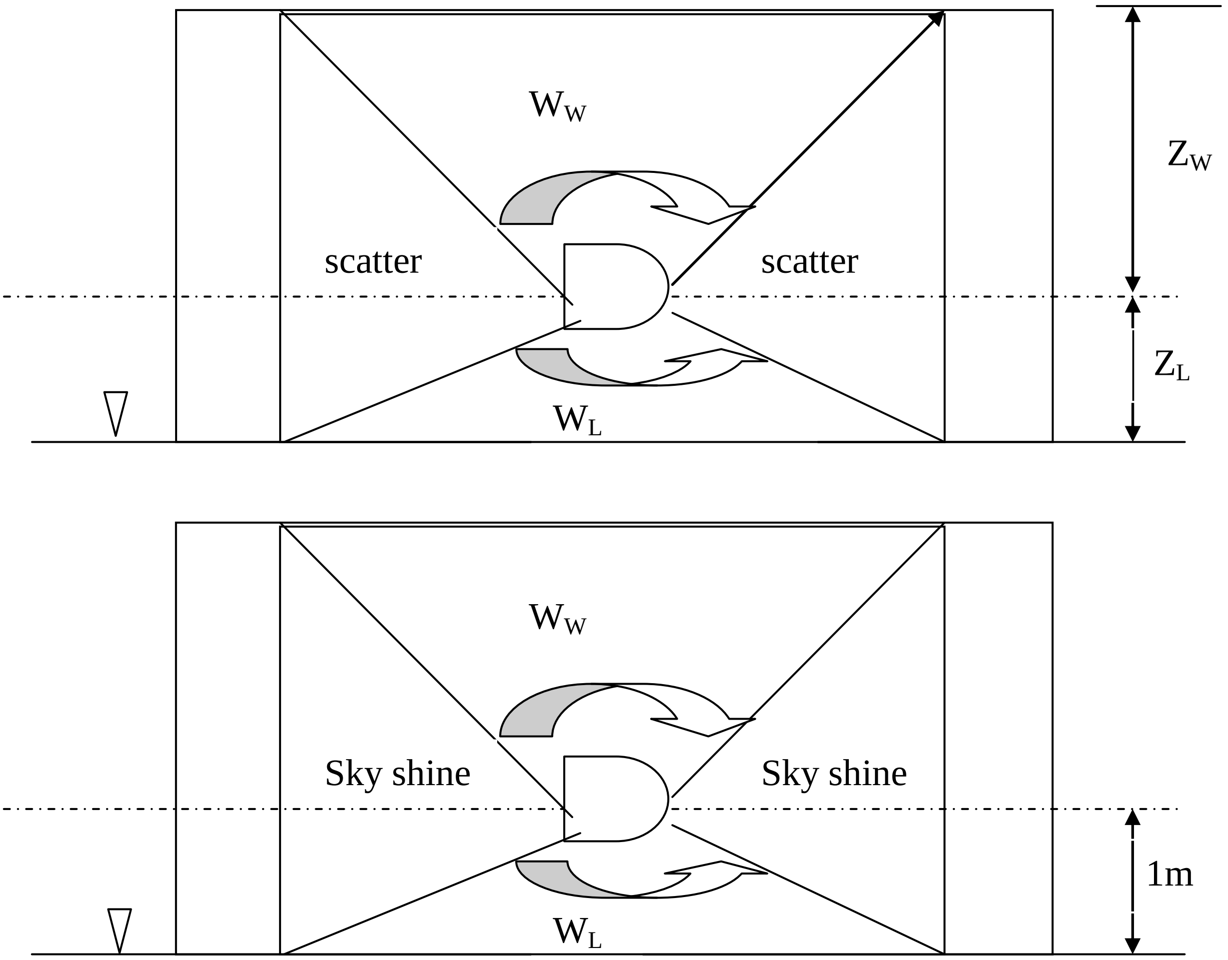


Figure (4) Components of the ground contribution [4]

3-3 Partially Buried Structure

The cases shown in **Fig.(5)** are common in shelter construction. In (a) all the concepts discussed or involved with the fallout shielding are to be taken, the normal way.

In (b) the floor is below the ground level but the plane of the detector is still above the contaminated ground plane. Thus the lower solid angle fraction is increased and the effect of the direct contribution is reduced. Theoretically there are contributions through the earth and buried wall section. Particularly from those sources immediately adjacent to the structure but in practice these are small compared to other contributions and can reasonably be neglected.

In (c) the detector plane is at the ground plane, thus all the direct and scatter contribution has been eliminated from the lower wall segment. In (d) the structure has been further depressed with a resultant decrease in skyshine and scatter contributions from the upper wall segment. This is the most complicated one as partial solid angle fractions are involved in the plane above the detector, but the expression for the geometry factor for ground contribution Cg is easily constructed as the following [4]:

$$\mathbf{Cg=\{Ga(Wu)-Ga(W'u)\}(1-Sw) + \{Gs(Wu)- Gs(W'u)\}E.Sw} \quad \ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where:

G_a: Geometry factor for skyshine radiation through that portion of a wall of a building lying above the detector plane.

G_s: Geometry factor for scattered radiation through that portion of a wall of a building lying either above or below the detector plane.

S_w: Scatter fraction, that portion of the total radiation reaching the detector that has been scattered in the walls.

E: Shape factor

$$= \frac{\mathbf{1+e}}{\mathbf{(1+e^2)^{0.5}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

In (e) the entire wall is buried and the only contribution is that from the overhead sources. If the structure is further depressed as in (f). The effect is essentially one of adding overhead mass thickness by virtue of increased earth cover.

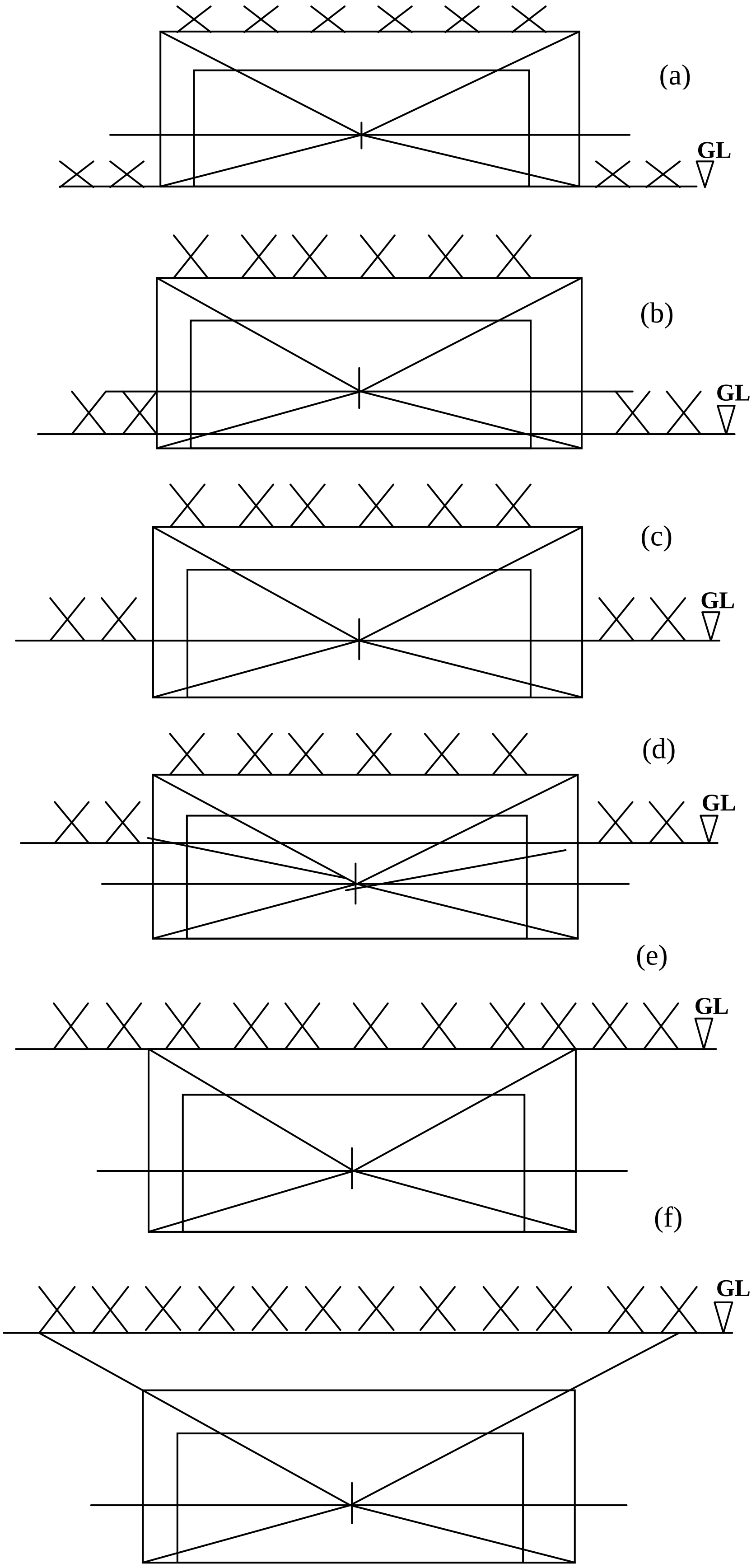


Figure (5) Effect of burying structure on detector response [4]

4. Wall Thickness Calculations

One of the mostly recommended computer programs for the nuclear reactors shielding is the program CADRE [4] (a simplified CADRE flow chart is shown in **Fig.(6)**).This program gives the estimation of the thickness of a multi-layer shield necessary to reduce the dose rate coming from the source (nuclear reactor core) to a given dose rate at the other surface (exterior wall of the nuclear reactor).

Due to the transmission of the explosion power in all directions (spherically) the fraction of power reaching the shelter is:

$$S(x) = \frac{S * A_s * e^{-\mu * x}}{4 * \pi * x^2} \quad \ldots\ldots \quad (4)$$

where:

S (x): Source strength at (x)cm from point zero (power.cm^{-3} s^{-1}).

x: Distance between the source & shelter (cm).

μ: Attenuation coefficient of air (cm $^{-1}$).

A_s: Source surface area (cm^2).

The fast neutron flux, (**Fig.(7)**), is calculated first using the expression:

$$\Phi = \frac{S_v^n}{2\sum_R}\left[E_2(b_1) - E_2(b_1 + b_2)\right] \quad \ldots\ldots \quad (5)$$

where:

S_v^n : Fast neutron volume source strength (neutron.cm $^{-3}$ s $^{-1}$)

$$b_1 = \sum_{k=1}^{N} \sum_R^{(k)} z_k \quad \ldots\ldots \quad (6)$$

$$b_2 = 2 * \Sigma_R * Rc \quad \ldots\ldots \quad (7)$$

where:

Z_k : the width of the kth layer (cm).

$\Sigma_R^{(k)}$: the fission neutron removal cross section for the kth layer (cm $^{-1}$).

Σ_R: the average fission neutron removal cross section for the source material (cm^{-1}).

Rc: the source radius (cm).

E_2 (b1), E(b1+b2): the exponential integral function of order 2.

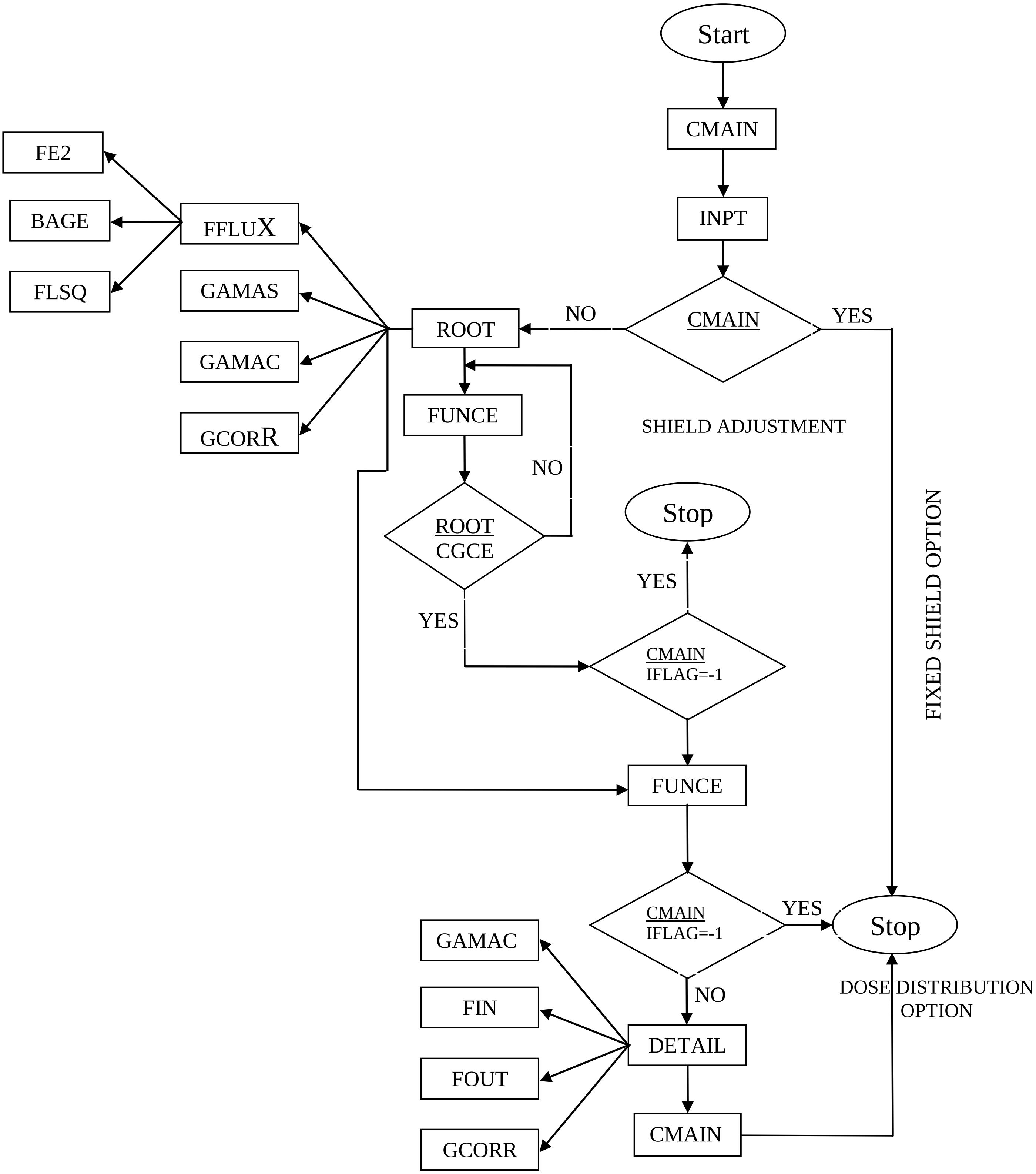


Figure (6) Flow Diagrame of Program CADRE [4]

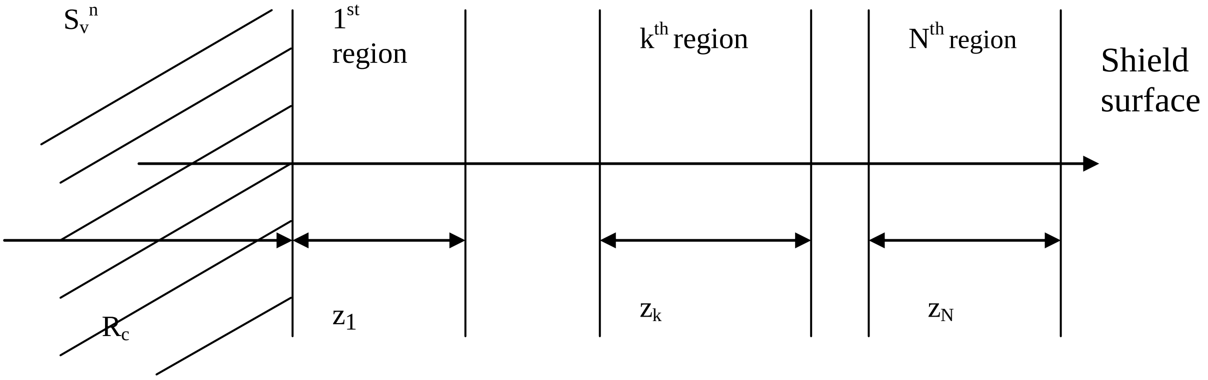


Figure (7) The fast neutron volume source strength, S_v^n, is assumed constant for the explosion source [4]

The thermal build-up factor is [6]:

$$B_{th} = \frac{\sum_R \exp[\sum_R^2 * \tau - h]}{\sum_a [1-(\sum_R * L)^2]} \quad \text{.. (8)}$$

where:

τ: Fermi age parameter (cm^2).

h: Correction constant.

$\sum_a$: Macroscopic cross section for neutron absorbtion (cm^{-1})

L: Diffusion length of neutrons in the medium (cm).

Then the thermal neutron flux is obtained:

$$\Phi_{th}(z) = B_{th} * \Phi_f(z) \quad \text{.. (9)}$$

where:

z: Distance between the point in the medium and the source (cm).

This flux is used to obtain the flux of the secondary γ-rays that are converted into dose rate. At last the primary γ-flux is obtained, converted to dose rate, then the total dose rate is obtained by summing all dose rates.

The following relationship is used to calculate the linear attenuation coefficient:

$$\frac{\mu}{\rho} = \sum_k W_k \frac{\mu_k}{\rho_k} \quad \text{... (10)}$$

where:

ρ: Densiry of material ($g.\ cm^{-3}$)

W_k: Proportion by weight of the K_{th} Constituent of the mixture.

After multiplying by the density (ρ), the attenuation coefficient can be calculated for each energy group .

4-1 Program BMIX

This program enables calculations of buildup factors in Finite and multilayer shield configurations. It solves these difficulties using Goldstein's method assuming a simple linear dependence of build-up factor (B) on the attenuating thickness (∝r) in the form:

$$\mathbf{B=\alpha \quad \propto r} \qquad \mathbf{(11)}$$

The program computes an average value of α□ coefficient, which is used for multi-layer slab shields. For each discrete energy of the source photons, the (Z, E)-data table is interpolated to find an average value of α.

5. Wall Thickness Calculation

Since the problem here is to determine the shielding thickness of a shelter wall to reduce the radiation dose rate coming from an exterior source (nuclear explosion about 1 km away from the shelter) to a safe value at the interior side, some modifications are needed for the program CADRE to reverse the directions of radiation (out-to-in).

Some of the input data for program CADRE are listed in **Table (2)**, others such as the removal cross sections ($\sum_R$) referred as REM in the program for shielding materials averaged on all energy groups may be calculated for each type of concret used, by knowing its composition. **Table (3)** shows the composition for Baryte and Portland concrete and the $\sum_R$ for each component.

Table (2) Some parameters needed for the program CADRE [7]

Energy (Mev)	*CFAC	**ETA	
		U-235	Concrete
0.50	0.000094	0.8400E+01	1.000
2.00	0.00299	0.3300E+01	1.000
4.00	0.00477	0.4000E+00	1.000
6.00	0.00631	0.4600E+01	1.000

*CFAC: -Conversion factors for primary γ-rays ($cm^{-2}\cdot s^{-1}$ →mrem/h)
**ETA: - Source weight, or no. of primary γ-rays per fission

Table (3) The properties and composition of two types of concrete [6]

Ordinary (Portland) Concrete				
Element	**Atomic Weight**	**Density in concrete g/cm^3**	**Neutron attenuation**	
			$\sum_R/\rho$ (cm^2/g)	**$\sum_R$(cm^{-1})**
O	16	1.103	0.041	0.0452
Si	28.06	0.2815	0.0295	0.0083
Al	26.97	0.033	0.0301	0.001
Fe	55.85	0.0183	0.02	0.0004
Ca	40.08	0.7712	0.024	0.0185
C	12.01	0.0761	0.05	0.0038
Na	23	0.0116	0.033	0.0004
K	39.10	0.0079	0.0245	0.0002
H	1	0.025	0.602	0.015
Mg	24	0.0426	0.032	0.0014
Total		2.37		0.0942
Barytes Concrete				
Element	**Atomic Weight**	**Density in Concrete g/cm^3**	**Neutron attenuation**	
			$\sum_R/\rho$ (cm^2/g)	**$\sum_R$(cm^{-1})**
Ba	137.36	1.47	0.0124	0.0182
O	16	1.09	0.041	0.0447
S	32.07	0.348	0.0275	0.0096
Fe	55.85	0.307	0.02	0.0061
Ca	40.08	0.159	0.024	0.0038
Si	28.06	0.061	0.0295	0.0018
Al	26.97	0.02	0.0301	0.0006
H	1	0.015	0.602	0.009
Mg	24.32	0.013	0.032	0.0004
Na	23	0.005	0.033	0.0002
Mn	54.93	0.003	0.0202	0.0001
Total		3.49		0.0945

Using the information from **Table (3)**, in equation (10) results the attenuation coefficients listed in **Table (4)**.

Table (4) Attenuation coefficients for each group of energy

Energy (Mev)	MU(cm^{-1})		
	Concrete		U-235
	Portland concrete	Barytes concrete	
0.00	0.2360	0.2312	0.0046
5.00	0.1938	0.1876	0.0469
8.00	0.1840	0.1799	0.0479
0.50	0.2160	0.1989	0.1760
2.00	0.1200	0.1121	0.0480
4.00	0.0810	0.0788	0.0440
6.00	0.2450	0.2129	0.0455

The final results of the required thickness for each type of concrete are listed in **Table (5)**.

Table (5) the required thickness of two types of shielding material as determined by program CADRE

Type of concrete	Thickness (cm)
Barytes concrete	259.52
Portland concrete	262.58

6. Conclusions

The main conclusions of this paper are:

1. The most protective place for a nuclear shelter is below the ground level.
2. A wall (259.52 cm, 262.58 cm) thick, made of Barytes concrete or Portland concrete respectively would guarantee the reduction of radiation dose resulted from a (20 kT) nuclear explosion to a safe value inside the shelter.
3. Program CADRE is an efficient, quick and flexible code for the determination of shielding thickness whether the source is inside (reactor) or outside (explosion or another external source).

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