COST OF RADIATION SHIELDING.

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SUMMARY.

Characteristic cost factors are defined depending on material, shield geometry and attenuation properties for a particular radiation.

These cost factors are calculated for a series of materials, geometries and types of radiation.

Dimensions and cost of a typical pulsed neutron source shield are estimated for various materials.

INTRODUCTION.

In view of the increasing number of materials that have been proposed for radiation shielding, the need arises for cost calculations based on shield volume as dictated by the material's radiation attenuation characteristics.

1. SHIELD VOLUME CALCULATION BASED ON ATTENUATION LENGTH.

Let us assume the material's shielding properties with respect to a given type of radiation can simply be described by a characteristic attenuation length (or mean free path) L, after which the radiation intensity is decreased by a factor e. This attenuation length will of course vary with the type and energy of the radiation. In some cases, when the energy of the radiation varies with penetration, the attenuation is not purely exponential; however the exponential approach can be used in most cases as a first step for volume and cost determination.

Let us therefore assume that the number N of mean free paths required is given to start with. The shield thickness is then NL in the direction of propagation of the radiation. The volume is determined by the geometry of the shield, which depends on the directions the radiation is coming from and the objects to be shielded.

Basically one can distinguish between three shield geometries: plane, cylindrical and spherical. In a first pass one can consider the case where the plane wall has a thickness equal to NL, the cylinder has a radius NL and the sphere a radius NL. As characteristic shield volumes, one is naturally led to take the volume per unit surface NL of the plane shield, the volume per unit axial length 3.14 N^2L^2 of the cylindrical shield, and the total volume of the spherical shield (4/3) 3.14 N^3L^3.

Let p be the price of the shielding material per unit volume in $\$/m^3$. The shield cost figures to be used for comparisons between materials will then be the above typical volumes multiplied by p.

One sees that, N being given in advance, the costs for these geometries are proportional to ρL, ρL^2, ρL^3, which we call the "cost factors" and depend on the type of material for each geometry. The cost factor is thus a function of the price of the material per unit volume and the attenuation length (or mean free path) that the particular type of material can achieve for the particular radiation. It therefore only depends on the material itself and is a figure of merit for the material (given the geometry), the lowest cost factor being the best.

The cost of the shield can easily be derived once the cost factor of the particular material for the relevant geometry is known (table 1).

In the case of cylindrical and spherical shells of thickness NL the volume and cost formulae are more complicated and the cost factors become dependent on the shield efficiency N. They are given in table 1 for completeness sake.

2. COST COMPARISON FOR VARIOUS RADIATIONS AND MATERIALS.

What will be compared will be the cost factors defined in the previous section for plane, cylindrical, spherical geometries, i.e. ρL, ρL^2, ρL^3. This will be done for various materials, such as concrete, steel, iron oxide mortar (including 50% by weight elemental iron), tungsten, lead, and for various kinds of radiation, including high energy neutrons (above 60 MeV), fusion neutrons (14.5 MeV), reactor neutrons (from 8.3 MeV to thermal) and gamma rays of 1 MeV. The properties of each material with respect to these kinds of radiation are different and, combined with the price, lead to a different choice of material for minimum cost for each kind of radiation (assuming space considerations do not dictate the choice of the material).

Table 2 gives the cost factors for the various kinds of radiation and materials considered.

For neutrons above 60 MeV, regular concrete is less expensive than the other materials for all geometries. If space is a consideration, the iron oxide mortar attenuation length lies half way between regular concrete and steel and the material is much less expensive than steel. Tungsten and lead seem prohibitive from the cost point of view.

For 14.5 MeV neutrons, the same observations as above apply.

For reactor neutrons, especially at 1.5 MeV and down to thermal energies, iron oxide mortar beats both regular concrete and steel by a large margin, both in cylindrical and spherical geometries. It is therefore the ideal material for all nuclear reactors and fission devices. Iron oxide mortar should also be preferred for all installation where the shielding is dominated by evaporation neutrons i.e. for accelerators of protons up to 60 MeV, deuterons, alphas and heavy ions, and for electron accelerators whose shielding is dominated by giant resonance neutrons, i.e. all medical or industrial electron accelerators.

For 1 MeV gamma rays, the least expensive material is regular concrete, then come iron oxide mortar, steel and lead, if space has to be saved.

Table 1: Calculation of Radiation Shield Costs for Various Geometries.

	Shield Volume	Shield Price	Cost Factor
Plane Geometry	NL m^3/m^2	$NL\rho$ $\$/m^2$	$L\rho$ $\$/m^2$
Cylindrical Geometry	$3.14\ N^2L^2$ m^3/m	$3.14\ N^2L^2\rho$ $\$/m$	$L^2\rho$ $\$/m$
Spherical Geometry	$(4/3)\ 3.14\ N^3L^3$ m^3	$(4/3)\ 3.14\ N^3L^3\rho$ $\$$	$L^3\rho$ $\$$
Cylindrical Geometry with Coaxial Void of Radius R_o	$3.14\ N^2L^2\ [1 + 2(R_o/NL)]$ m^3/m	$3.14\ N^2L^2\rho\ [1 + 2(R_o/NL)]$ $\$/m$	$L^2\rho\ [1 + 2(R_o/NL)]$ $\$/m^2$
Spherical Geometry with Centered Void of	$(4/3)\ 3.14\ N^3L^3 \times [1 + 3(R_o/NL) + 3(R_o/NL)^2]$	$(4/3)\ 3.14\ N^3L^3\rho \times [1 + 3(R_o/NL) + 3(R_o/NL)^2]$	$L^3\rho \times [1 + 3(R_o/NL) + 3(R_o/NL)^2]$

Symbols:

L: Mean Free Path (Attenuation Length), meter
N: Number of Mean Free Paths Required
NL: Shield Thickness, meter
ρ: Price of Material per Unit Volume, $\$/m^3$
R_o: Void Radius.

3. COST COMPARISON FOR PULSED NEUTRON SOURCE.

A typical pulsed neutron source case will be calculated for a proton beam intensity of $I = 1.5\ 10^{14}$ protons per second (Carpenter, 1978) and a permissible high energy neutron flux outside the shield of $F = 2.5$ n/sec.cm^2 (corresponding to a radiation level better than or approximately 0.5 mrem/h). Let us assume this permissible flux is attained at $R = 6$ m from the source. The product of permissible flux and square of distance per incoming proton is then

$$R^2\ F/I = 36\ 10^4 \times 2.5/1.5\ 10^{14} = 6\ 10^{-9}$$

For this value one derives (Barbier 1980) the number of mean free paths required in various direction as presented in table 3, which also includes the resulting thicknesses for shields made of regular concrete, iron oxide mortar and steel.

The schematics of the neutron shield design are shown in fig. 1. The cavity at the center has been neglected. The proton beam level above ground is assumed to be $h = 1.5$ m. The shield is assumed not to go below ground level. The height above the proton beam is assumed to be equal to the shield thickness at 90° in the horizontal plane, to ensure permanent access to the top of the shield also.

Table 4 presents the resulting parameters and cost of the shield for the various materials. The cheapest shield is regular concrete. The iron oxide mortar shield offers an appreciable reduction in dimensions with respect to the concrete shield at half the price of the steel shield. It should be considered that, due to the propagation of the "iron window" neutrons through steel, a steel shield requires an additional 2 to 3 feet of regular concrete on the outside or distributed within. This circumstance partially offsets the gain in space achieved when using steel.

CONCLUSION.

The choice of the shielding material offers an additional degree of freedom in shield design and an opportunity of substantially reducing shielding costs depending on the radiation to be attenuated.

BIBLIOGRAPHY.

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Table 2: Comparison of Material Cost Factors for Radiation Shields of Various Geometries (continued).

4. Gamma Rays	Regular Concrete	Iron Oxide Mortar	Iron	Tungsten	Lead
Attenuation Length* at 1 MeV L m	0.086957	0.0625	0.0256	0.01111	0.0177
Plane Cost Factor pL \$ /m^2	6.52	24.00	122.15	8,799.1	264.08
Cylindrical Cost Factor pL^2 \$/m	0.57	1.50	3.13	97.76	4.67
Spherical Cost Factor pL^3 \$	0.049	0.0925	0.08	1.08	0.083

* Attenuation Length is 1/ (Narrow Beam Mass Absorption Coefficient x Specific Gravity).

Table 2: Comparison of Material Cost Factors for Radiation Shields of Various Geometries.

	Regular Concrete	Iron Oxide Mortar	Iron	Tungsten	Lead
Price p $/m^3$	75	384	4,764	792,000	14,920
1. Very High Energy Neutrons (above 60 MeV).					
Nuclear Interaction Mean Free Path L m	0.461	0.329	0.1734	0.101	0.178
Plane Cost Factor Lp $/m^2$	34.58	126.36	826.08	79,992.00	2,665.76
Cylindrical Cost Factor L^2p $/m	15.94	41.17	143.24	8,079.19	472.73
Spherical Cost Factor L^3p $	7.35	13.67	24.84	816.00	84.15
2. Fusion Reactor Neutrons					
Attenuation Length* at 14.5 MeV L m	0.091	0.0735	0.056		
Plane Cost Factor pL $/m^2$	6.82	28.24	264.69		
Cylindrical Cost Factor pL^2 $/m	0.62	2.08	14.71		
Spherical Cost Factor pL^3	0.056	0.15	0.82		

* Attenuation Length is $1/\sqrt{3\, S_{scattering}\, S_{absorption}}$, when S refers to the macroscopic cross-section.

Table 2: Comparison of Material Cost Factors for Radiation Shields of Various Geometries (continued).

3. Fission Reactor Neutrons	Regular Concrete	Iron Oxide Mortar	Iron
3.1 Attenuation Length* at 8.3 MeV	0.11236	0.081967	0.040816
Plane Cost Factor	8.42	31.36	194.45
Cylindrical Cost Factor	0.95	2.57	7.93
Spherical Cost Factor	0.11	0.21	0.33
3.2 Attenuation Length* at 1.5 MeV	0.49261	0.1046	0.05814
Plane Cost Factor	36.95	40.17	276.98
Cylindrical Cost Factor	18.20	4.20†	16.10
Spherical Cost Factor	8.97	0.437†	0.94
3.3 Attenuation Length* at 0.25 MeV	2.9851	1.2077	0.56497
Plane Cost Factor	223.88	463.86	2,691.5
Cylindrical Cost Factor	668.31	560.21†	1,520.6
Spherical Cost Factor	1,995.5	676.6†	859.11
3.4 Attenuation Length* at thermal energy	0.081301	0.02907	0.013089
Plane Cost Factor	6.0976	11.165	62.356
Cylindrical Cost Factor	0.49574	0.3246†	0.81618
Sherical Cost Factor	0.0403	0.0094†	0.010683

* Attenuation Length is $1/\sqrt{3\, S_{scattering}\, S_{absorption}}$, where S refers to the macroscopic cross-section.

† beats regular concrete.

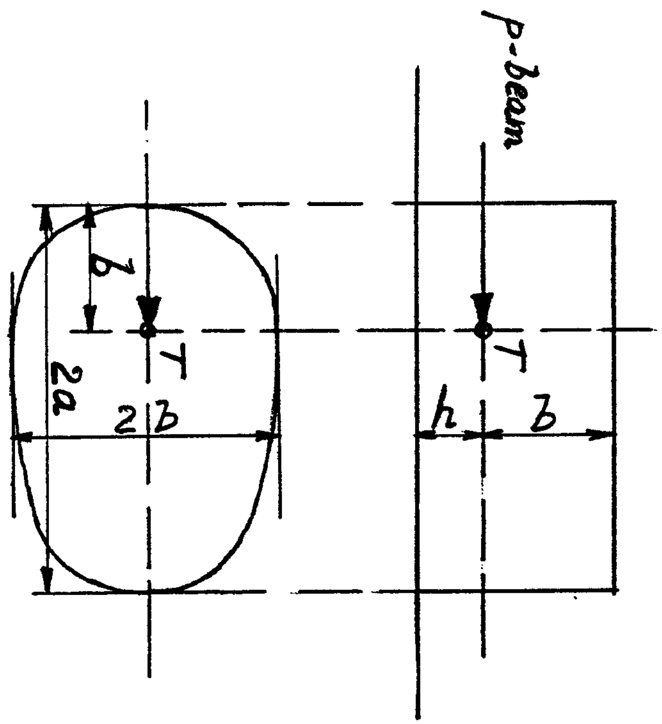

Figure 1: Schematics of Neutron Source Shield Design.

Table 3: Neutron Source Shield Calculation for 1.5 10^{14} protons/sec.

Emission Angle (Degree)	Number N Mean Free Path	Thickness Regular Concrete (m)	Thickness Iron Oxide Mortar (m)	Thickness Steel (m)
7	18.5	8.53	6.09	3.21
28	17.5	8.07	5.76	3.04
53	16.6	7.65	5.46	2.88
90	15	6.92	4.94	2.60
140-180	13.7	6.32	4.51	2.38

Table 4: Parameters and Cost of Neutron Source Shield for 1.5 10^{14} protons/sec.

	Regular Concrete	Iron Oxide Mortar	Steel
Long Half Axis a (m)	7.43	5.30	2.80
Short Half Axis b (m)	6.92	4.94	2.60
Height above ground H (m)	8.42	6.44	4.1
Ground Surface S (m^2)	161.53	82.25	22.87
Volume V (m^3)	1,360.1	529.7	93.77
Material Cost (\$/m^3)	75	384	4,764
Shield Cost (\$)	102,000	203,400	446,720