# FINAL REPORT

## ON SHELTER COSTS

Robert A. Krupka

HI-361-RR/3 June 11, 1964

22 p [redacted]

Prepared Under Contract No. OCD-OS-63-122, Task No. 4113D
Office of Civil Defense, Department of the Army

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HUDSON INSTITUTE, INC.
Quaker Ridge Road
Harmon-on-Hudson
New York

# TABLE OF CONTENTS

# SUMMARY

During the course of our studies on optimizing blast shelter programs,* it became apparent that a shelter cost-hardness relationship would be required in order to design programs and measure their performance. This paper presents the results of a limited effort to develop a simple cost function for blast shelters.

As a basis for preparing the relationship, costs, overpressures, space allocations, and other significant items were extracted from several previous shelter design studies. A plot of costs versus usable floor area indicated that the following function was roughly representative of the majority of points:

$$c = 4.2\ p^{.34},$$

where c is the cost in dollars per square foot of bare shelter space and p is the blast rating in pounds per square inch.

This equation was further refined by assuming a space allocation of 8 square feet per space and adding the cost of "fixed" items such as mechanical-electrical equipment, sanitation and water systems, and habitability items. The final cost function reduced to

$$C = 50 + 20\ p^{.5},$$

where C is the total cost in dollars per shelter space. This cost includes overhead, profit and contingencies at 60%, but does not include the cost of land.

*Brown, W. M., The Design and Performance of "Optimum" Blast Shelter Programs, HI-351-RR/2, Harmon-on-Hudson, N.Y.: Hudson Institute, June 11, 1964.

# ON SHELTER COSTS

## Introduction

There is general agreement, today, among civil defense planners that providing protection over a wide range of attack situations may involve a major shelter construction program. To the extent that this is true, it appears desirable to develop planning procedures which will assure maximum performance per new shelter dollar.

Many models[27]* have been devised to optimize shelter programs, particularly blast shelter programs. Generally, these are analytical schemes aimed at arranging the distribution and quality (degree of blast protection) of shelters to minimize expected casualties and thus decrease an enemy's chances of degrading the population by direct attacks, by side effects resulting from attacks at other targets, by miscalculations, or by inaccuracies. The degree of optimization is usually measured in cost-effectiveness terms such as dollars per life (or additional life) saved, dollars required to force a particular level of attack, and so on. Regardless of the type of cost-effectiveness yardstick one chooses or the model for optimizing protection used, it is necessary to know the cost of shelter at any level of hardness.

In this paper, we will briefly discuss some of the variables involved in costing shelters, show some of the previous work done in the field, and attempt to produce a simple shelter cost formula in terms of peak static overpressure (psi).

## Design Variables

### A. Protection Criteria

Beyond satisfying protection requirements against initial and residual nuclear radiations (depth of cover), shelters are required to withstand air slap or ground shock overpressures. This level of protection is usually defined in terms of pounds per square inch overpressure and is taken to mean that no structural failure occurs at this pressure level. Although the structural designer is permitted to allow for some plastic deformation, he is not permitted to allow the materials of design to fail entirely. The result is that, although we think about "sudden death" failure of the shelter structure, this may not be the case at all. In other words, we think of a 10-psi shelter failing 100% at 11 psi when, in fact, it may not fail at all or may fail only partially. The 35-psi corrugated steel arch shelter, for example, may yield at 36 psi and even dish down at 40 or 50 psi, but such deformations (or even translations) do not necessarily degrade the shelter population.**

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*Superscript numerals refer to References, on page 14.

**A small HI effort along these lines is almost finished. It deals

The point we make here is that the overpressure parameter has not been solidly defined, at least as used in vulnerability studies. And the reason this may be important to do is that there may be significant cost differences involved.

Aside from this consideration, structures designed for below-ground installation, by their nature, have some inherent blast protection. That is, it is difficult to design a "0-psi" shelter. Beyond considering built-in protection, selection of the overpressure criterion may be an irrevocable decision, since we may not be able to upgrade the shelter after construction (at least at reasonable cost).

Other effects requiring consideration are mass fires and gross contamination of the ventilating system. Protection against these effects usually requires that the shelter include a system which will support life without reliance on outside air for a time.

B. Operational Criteria

Operational items which influence per capita shelter costs include size or capacity, time of occupancy, environmental conditions, access, and space allocation.

There are many factors which influence the choice of shelter capacity. Among these are population density and mobility, alert or warning time, availability of real estate, and construction peculiarities. Regardless of these items, there is a large cost difference between small (around 100 persons) and large (500-1000 and up) shelter units. Figure 1, based on a recent study, indicates that 100-unit shelters cost about twice as much per person as 500- to 1000-person units.

Time of occupancy will determine food, water, sanitation, and auxiliary power fuel costs. Environmental conditions will determine the cost of ventilation and heat dissipation (metabolic) packages. These are critical shelter items which (at least for low-psi spaces) may cost as much as the bare shelter space.

Allocation of space is another important variable. Some studies have considered 10 or 12 feet per person as minimum. Others show 7.5 or less may be ample. Aside from psychological considerations, it can be shown that, with 10-12 tiered bunking, 2 or 3 square feet per person can be allocated. It is all a matter of the efficiency of the configuration plus scheduling space use and the shelter planner's idea of the sort of conditions people

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with questions concerning the strength of contemporary designs and the accuracy of the so-called "cookie-cutter" method of measuring blast failure. Preliminary results suggest that, under ideal conditions, shallow buried structures might take up to a 100% increase in overpressure before significant failures would occur (5 shelters destroyed out of 100) and up to an additional 20% increase in overpressure before almost all would fail (95 out of 100).

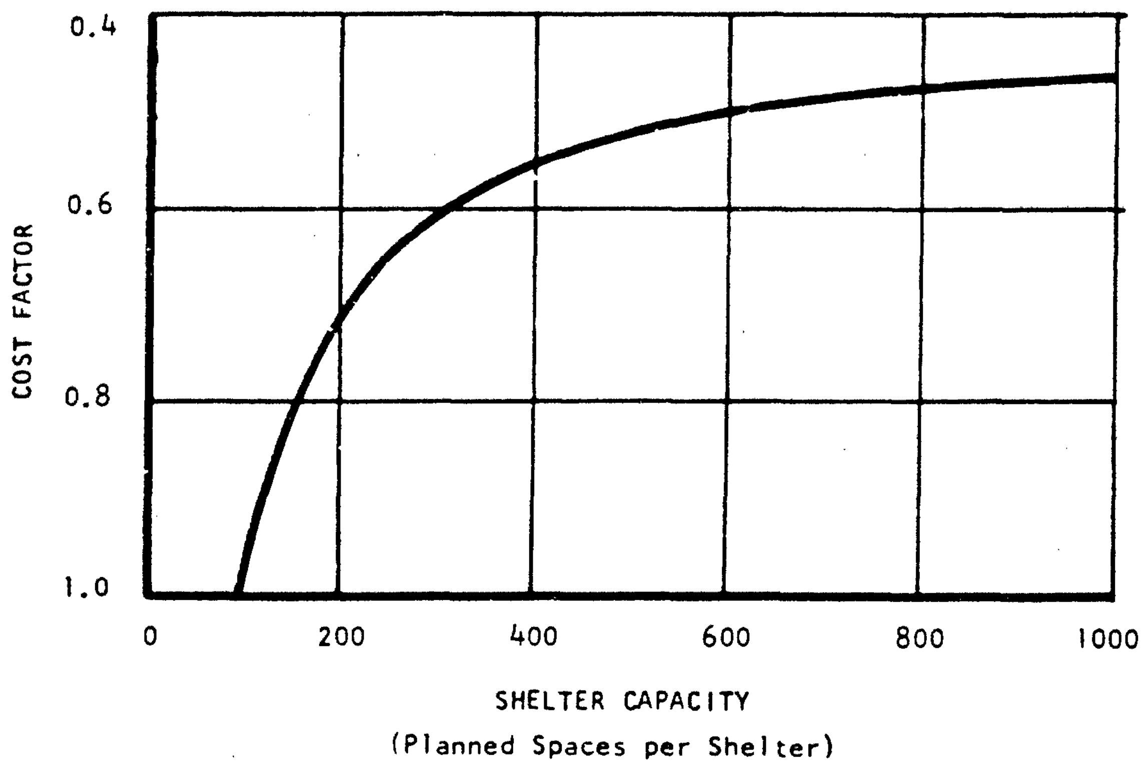
0.4
0.6
0.8
1.0
COST FACTOR
0
200
400
600
800
1000
SHELTER CAPACITY
(Planned Spaces per Shelter)

FIGURE 1

will be willing or able to take. From the engineer's point of view, habitability and environmental control items can be furnished regardless of the population density. And, if the choice for the shelterees is between severe living conditions or no shelter, overcrowding may be acceptable.[28] For the shelter designer, this may serve as a kind of criterion--that is, to select the configuration, equipment, and management scheme to include an overcrowding capability. For example, he might design on the basis of 10 square feet per person, single-shift bunking, but have the option of, say, doubling the capacity by dumping some bunks and triple-shifting, letting the people out of bunks stand or sit on the floor. All sorts of schemes of this type are possible and may be especially utilitarian during the construction of a high-quality (blast) shelter program.

Construction and Other Variables

A. Configurations and Materials

Should it be a corrugated steel arch? A concrete arch? A flat-slab reinforced structure with steel columns of sheer walls? How about a steel cylinder or a tunnel in rock? Or maybe a shallow dome? How about a cone or a sphere? All of these shapes have been studied and several seem optimum even at the same level of hardness, depending on the computation methods used and the material and labor cost one assigns to their construction. In addition, each shape or building scheme is different in terms of space utilization. The result, particularly at high overpressures, is that the most efficient configurations have not been pinpointed. However, there seems to be evidence that up to 60 or 100 psi or so, the rectangular reinforced concrete structure will result in least cost and least uncertainties in assigning psi ratings. The reason for this is two-fold: 1) because it is a familiar construction shape; and 2) because it is an efficient space user.

B. Estimating Procedures

General estimating procedures in the construction business go something like this: the final building design goes through a quantity take-off in which the specific amounts of steel, concrete, reinforcing bar, etc., are listed and assigned material costs and erection man-hours. This is further refined by assigning labor costs for the various specialities and adding the purchase price of manufactured equipment. To this total the contractor adds his expected profit and overhead, and adds something called contingencies to cover unforeseen construction difficulties. Contingency hedges against increased costs due to ignorance, strikes, accidents, ground water, poor concrete, and a host of other gremlins that invade a construction program. If the job is familiar, the contractor might limit the contingency item to 10% or 15% of the estimated cost. For early underground shelter construction this would be more like 15-30%.

Similarly, the overhead and profit figure in normal construction runs around 25-30%, with overhead rarely running less than 20%. On special jobs--and shelter construction is considered special today but would not be t an extended program--the contractor may require the services of special supervisors or testing equipment which would increase his overhead.

Taking all of this into account and adding fees for the original design, it seems that, initially, the overhead-profit-contingency figure could not be less than 40% and is probably closer to 60%. Even with thorough planning before construction and some construction experience the 40% figure would be hard to realize.

## A Blast Shelter Cost vs. Overpressure Relationship

As a basis for preparing a cost vs. overpressure relationship, we prepared a list of several cost, overpressure, space allocation, and other significant items taken from several research sources. These are shown in Table 1. The shelter designs range from small "do-it-yourself" units to large underground rock complexes. In order to compare cost vs. overpressure structural costs were extracted and made comparable by reducing them to per square foot costs and adjusted to 60% overhead, profit, and contingencies where this was possible to do. These costs are shown plotted in Figure 2.

The range of costs is roughly bounded by the following relationships:

$$c = 9.3\ p^{.31} \quad \text{upper limit}$$
$$c = 1.8\ p^{.4} \quad \text{lower limit}$$

where c is the cost in dollars per square foot of bare shelter space, including the entrance, and p is the level of blast protection measured in pounds per square inch overpressure. The straight line drawn half-way between the upper and lower limits and roughly representative of the majority of plotted points is defined as

$$c = 4.2\ p^{.34}.$$

Considering large shelters only, we may be able to allow 7.5 or 8 square feet per person without overcrowding. Using 8 square feet, the median cost is then

$$C = 34\ p^{.34} \text{ dollars per person.}$$

Based on an analysis of the tabulated cost information, the range of costs for the "fixed" items is approximately as follows:

| | |
|---|---|
| Mechanical-Electrical System | \$25-75/person |
| Sanitation and Water System | 5-15 |
| Habitability Items | 10-20 |

This gives a range of \$40-110 per person and a mean value of \$75. Considering that these items (at least) are subject to cost reductions through large procurement programs, we will assume that the fixed cost could be maintained at \$40 per person, at least for shelters up to 60 or 100 psi. At higher overpressures we should expect increasing costs due to protecting outside air connections and because we may desire to furnish these shelters with higher quality supporting systems. Based on the estimates given in the Manhattan Shelter Study,[25] the total fixed costs might be as high as $350 per person for deep underground installations.

For continuity purposes, then, let us assume fixed costs of $40 per person up to, say, 60 psi. Above that, let us also assume increasing costs to $350 per person at 2,000 psi. The complete cost function is then

$$C = 40 + 34\ p^{.34} \text{ to } 60 \text{ psi},$$
$$C = 3.2\ p^{.62} + 34\ p^{.34} \text{ above that.}$$

Both relationships are shown continually on Figure 3, along with a more easily remembered equation:

$$C = 50 + 20\ p^{.5}.$$

This equation follows the other fairly well at the lower overpressures and we would recommend its use for simplicity's sake at this time. At the higher overpressures the costs seem to be high even with all the uncertainties involved. However, it is not possible to make a case for this statement, since the available design and cost data for high-strength installations is very meager. In addition, high overpressure designs may involve trade-offs between underground facilities in rock and fabricated structures nearer the surface. This may make a great difference in final cost.

## Limitations

Aside from the general observation that this is not a comprehensive investigation of shelter costs and that the information presented herein should be used with caution, the study has the following limitations (among others):

1. Land costs are not included. Although a significant portion of urban land is available for shelter construction (parks, playgrounds, parking lots, etc.) at no cost, one would expect a large shelter program to include some real estate purchases.* A recent OCD Research Memorandum[26] estimates average land costs for large programs at $2 to $33 per person, depending on location. Of course, one could argue that costs would be incurı only to the extent that the construction program <u>uses up</u> real estate. Tha' is, a plot of ground is not necessarily "destroyed" by putting a shelter under it. In fact, some net benefits might accrue (more parks, playground: parking lots, improvements, development of leasable or salable properties, etc.).

2. The costs do not reflect possible savings due to efficient planni phasing, use of mass-production techniques or standardization.

3. The space allocation is arbitrary. It may be possible to plan for some overcrowding (at least for the initial production of shelters) such t the costs per person sheltered are reduced by factors of 2 or more.[28]

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*Because the available land is not suitable for construction purposes (i.e., it would be less expensive, over-all, to buy suitable land) or beca the available land is not optimally situated with respect to the populatio

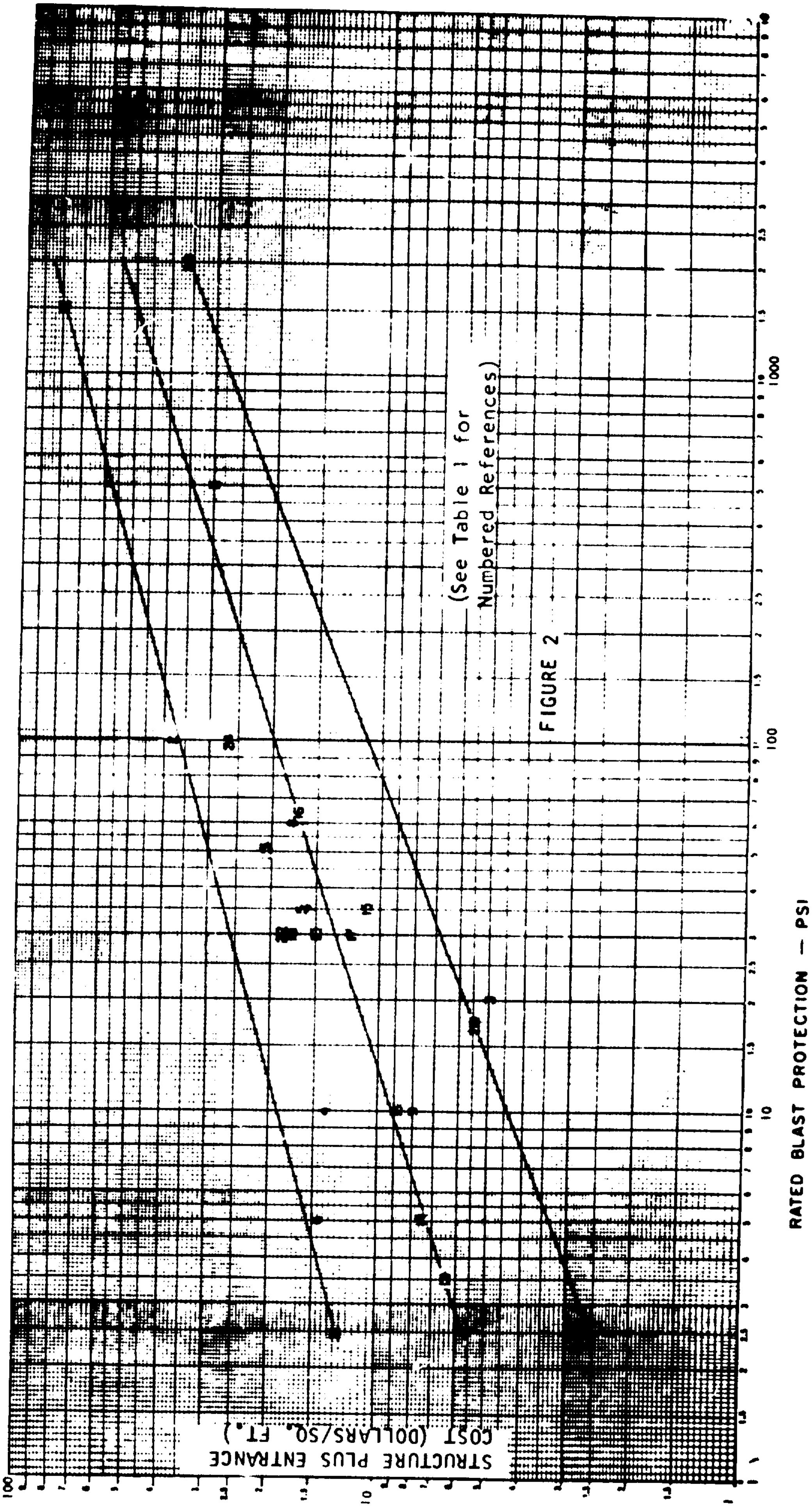
FIGURE 2
(See Table I for Numbered References)
RATED BLAST PROTECTION — PSI
STRUCTURE PLUS ENTRANCE COST (DOLLARS/SQ. FT.)
10
100
1000

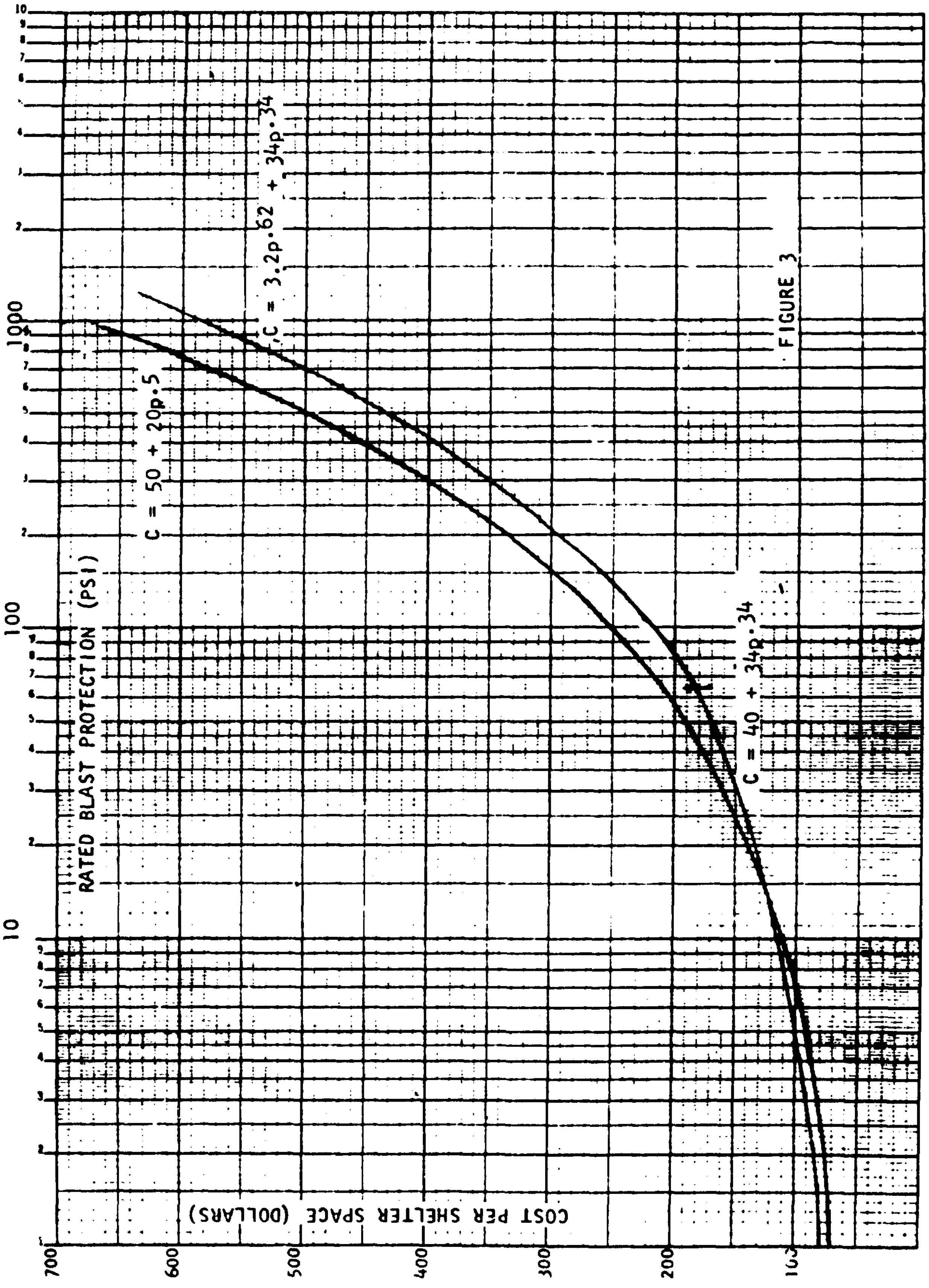
FIGURE 3
$C = 3.2p^{.62} + 34p^{.34}$
$C = 50 + 20p^{.5}$
$C = 40 + 34p^{.34}$
RATED BLAST PROTECTION (PSI)
COST PER SHELTER SPACE (DOLLARS)
1000
100
10
700
600
500
400
300
200
100

TABLE I

| REFERENCE NUMBER: | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| NOM. CAPACITY | 5 | 5 | 60 | 100 | 100 |
| DESCRIPTION | Timber RR Ties | Rect. Reinf. Concrete | Rect. Steel & Timber | Corr. Steel Arch | Corr. Steel Arch |
| p.s.i. | 60 | 100 | 20 | 10 | 35 |
| SQ.FT/PERSON | 11.4 | 10.7 | 10.0 | 12.0 | 12.0 |
| **COSTS PER PERSON** | | | | | |
| STRUCTURE | $163.00 | $346.00 | $ 50.00 | $156.10 | $188.30 |
| ENTRANCES | Included Above | Included Above | Included Above | 27.10 | 28.90 |
| MECH-ELEC | - | - | - | 33.20 | 33.40 |
| SANITATION & WATER | - | - | - | 10.10 | 10.10 |
| HABITABILITY ITEMS | - | - | - | 22.40 | 22.40 |
| RAD. INSTRU. | - | - | - | .40 | .40 |
| TOTAL INCLUDING OVHD, PROF & CONT | $163.00 | $346.00 | $ 50.00 | $249.30 | $283.50 |
| % OVHD / PROF / CONT | 27 / 10 / None | 27 / 10 / None | ? | 75 | 75 |
| STRUCT & ENT COST-CORRECTED TO 60% O,P,C* (PER SQ.FT) | 16.70 | 37.80 | 5.00 | 14.00 | 16.60 |
| REMARKS | | | Do-it-yourself | Includes food | |

*Where possible

| REFERENCE NUMBER: | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| NOM. CAPACITY | 100 | 100 | 100 | 100 | 100 |
| DESCRIPTION | Rect. Reinf. Concrete | Reinf. Concrete Arch | Reinf. Concrete Arch | Corr. Steel Arch | Corr. Steel Arch |
| p.s.i. | 5 | 35 | 60 | 10 | 30 |
| SQ.FT/PERSON | 8.1 | 10.0 | 10.0 | 12.5 | 12.5 |
| COSTS PER PERSON | | | | | |
| STRUCTURE | $ 84.80 | $113.60 | $123.20 | $ 54.20 | $ 86.70 |
| ENTRANCES | 35.20 | 43.20 | 52.80 | 8.50 | 30.60 |
| MECH-ELEC | 115.20 | 118.40 | 118.40 | 16.50 | 16.50 |
| SANITATION & WATER | - | - | - | 8.80 | 8.80 |
| HABITABILITY ITEMS | - | - | - | 34.90 | 34.90 |
| RAD. INSTRU. | - | - | - | - | - |
| TOTAL INCLUDING OVHD, PROF & CONT | $235.20 | $275.20 | $294.40 | $122.90 | $177.50 |
| % OVHD | 30 | 30 | 30 | 0+ | 0+ |
| % PROF | 10 | 10 | 10 | 0 | 0 |
| % CONT | 20 | 20 | 20 | 0 | 0 |
| STRUCT & ENT COST-CORRECTED TO 60% O,P,C* (PER SQ.FT) | 14.80 | 15.70 | 17.60 | 8.00 | 15.00 |
| REMARKS | High quality environment control system | | | +On basis of unit costs given | |

* Where possible

| REFERENCE NUMBER: | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|
| NOM. CAPACITY | 500 | 500 | 750 | 1000 | 1000 |
| DESCRIPTION | Rein. Concrete Horoz. Cylinder | Steel Horoz. Cylinder | ? | Rect. Reinf. Concrete | Rect. Reinf. Concrete |
| p.s.i. | 500 | 1500 | 10 | 5 | 35 |
| SQ.FT/PERSON | 10.0 | 10.0 | 7.5 | 7.5 | 7.5 |
| | | | COSTS PER PERSON | | |
| STRUCTURE | $224.75 | $669.90 | $ 66.00 | $ 49.60 | $ 75.20 |
| ENTRANCES | 43.50 | 52.20 | Included above | 6.40 | 6.40 |
| MECH-ELEC | - | - | 45.00 | 46.40 | 49.60 |
| SANITATION & WATER | - | - | 9.00 | - | - |
| HABITABILITY ITEMS | - | - | 5.00 | - | - |
| RAD. INSTRU. | - | - | - | - | - |
| TOTAL INCLUDING OVHD, PROF & CONT | $268.25 | $722.10 | $125.00 | $102.40 | $131.20 |
| % OVHD PROF CONT | 45 | 45 | ? | 30 .10 20 | 30 10 20 |
| STRUCT & ENT COST-CORRECTED TO 60% O,P,C* (PER SQ.FT) | 29.60 | 79.40 | 8.80 | 7.50 | 10.90 |
| REMARKS | | | No food | High quality environmental control system | |

* Where possible

| REFERENCE NUMBER: | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|
| NOM. CAPACITY | 1000 | 1500 | 2000 | 2500 | 3000 |
| DESCRIPTION | Rect. Reinf. Concrete | ? | Reinf. Concrete | Reinf. Concrete | Reinf. Concrete |
| p.s.i. | 60 | 30 | 30 | 3-4 | 17 |
| SQ.FT/PERSON | 7.5 | 7.5 | 7.0 | 9.5 | 12.0 |
| | | | COSTS PER PERSON | | |
| STRUCTURE | $121.60 | $ 90.00 | $123.45 | $ 43.90 | $ 58.40 |
| ENTRANCES | 8.00 | Included above | Included above | 5.70 | 7.50 |
| MECH-ELEC | 49.60 | 42.00 | 68.75 | 98.00 | 13.50 |
| SANITATION & WATER | - | 9.00 | 14.45 | 19.00 | 10.00 |
| HABITABILITY ITEMS | - | 5.00 | 13.45 | 7.90 | 15.00 |
| RAD. INSTRU. | - | - | - | - | .70 |
| TOTAL INCLUDING OVHD, PROF & CONT | $179.20 | $146.00 | $220.10 | $174.50 | $105.10 |
| OVHD<br>% PROF<br>CONT | 30<br>10<br>20 | ? | ? | 15<br>10<br>5 | ? |
| STRUCT & ENT COST-CORRECTED TO 60% O,P,C* (PER SQ. FT) | 17.30 | 12.00 | 17.60 | 6.40 | 5.50 |
| REMARKS | High quality envir. control system | No food | Dual purpose | No food | No food |

* Where possible

| REFERENCE NUMBER: | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|
| NOM. CAPACITY | 5000 | 5000 | 8000 | 8000 | 4,000,000 |
| DESCRIPTION | Reinf. Concrete | Reinf. Concrete | Steel Arch | Steel Arch | Deep Rock Tunnel |
| p.s.i. | 2.5 | 30 | 50 | 100 | 2000+? |
| SQ.FT/PERSON | 10.3 | 10.9 | 12.5 | 12.5 | ~10 |
| | | | COSTS PER PERSON | | |
| STRUCTURE | $111.70 | $156.50 | $238.00 | $281.00 | $276.60 |
| ENTRANCES | Included above | Included above | 22.60 | 54.00 | 81.90 |
| MECH-ELEC | 22.70 | - | 36.80 | 36.80 | 248.40 |
| SANITATION & WATER | Included above | - | 12.00 | 12.00 | 69.00 |
| HABITABILITY ITEMS | - | - | 34.90 | 34.90 | - |
| RAD. INSTRU. | - | - | - | - | - |
| TOTAL INCLUDING OVHD, PROF & CONT | $134.40 | $156.50 | $344.30 | $418.70 | $675.90 |
| OVHD % PROF CONT | 25 | 25 | ? | ? | ? |
| STRUCT & ENT COST-CORRECTED TO 60% O,P,C* (PER SQ.FT) | 13.80 | 18.40 | 20.80 | 26.80 | 35.90 |
| REMARKS | Dual purpose | Dual purpose | | | 30 - Day Occupancy |

* Where possible

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