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FINAL REPORT

ON SHELTER COSTS

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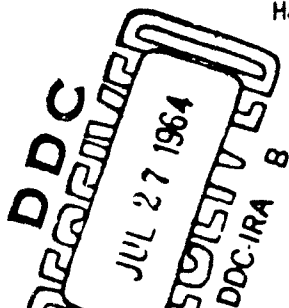Office of Civil Defense, Department of the Army

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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).
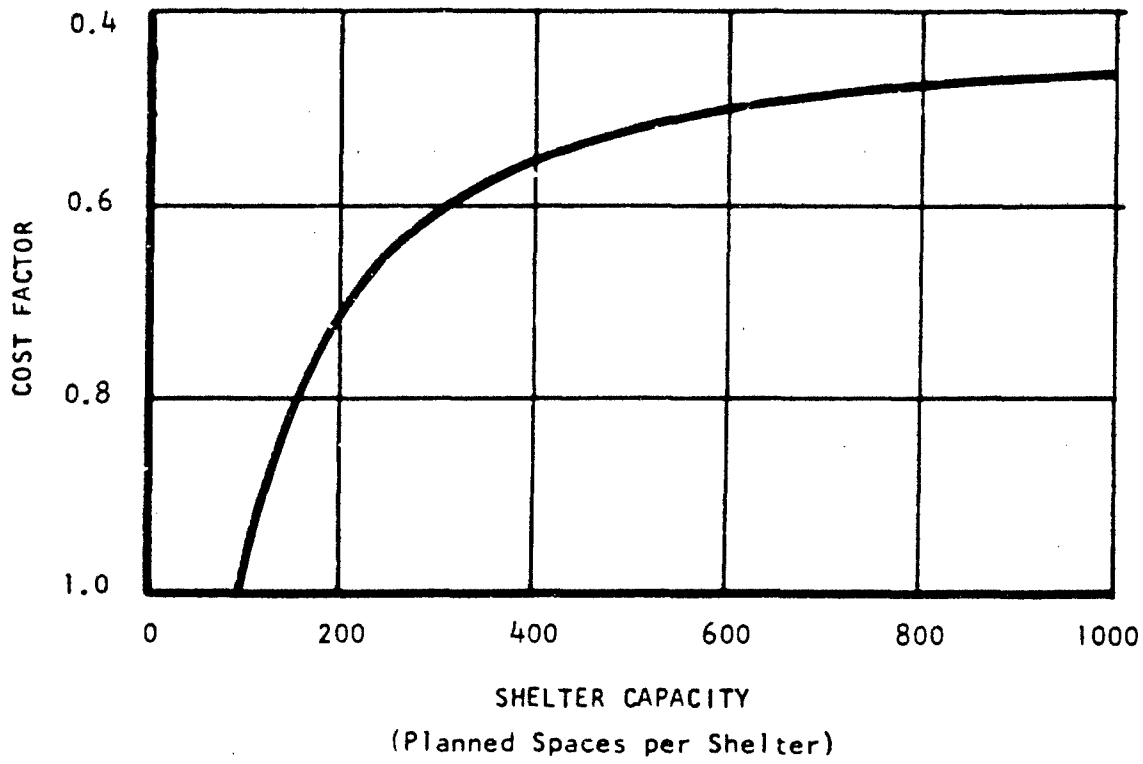
SHELTER CAPACITY
(Planned Spaces per Shelter)

FIGURE 1

will be willing or able to take. From the engineer's point of view, habi-
tability 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, let-
ting 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 opti-
mum 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 uti-
lization. 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 con-
crete structure will result in least cost and least uncertainties in assign-
ing psi ratings. The reason for this is two-fold: 1) because it is a fa-
miliar 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 contingen-
cies 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 pro-
gram. 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

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

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.
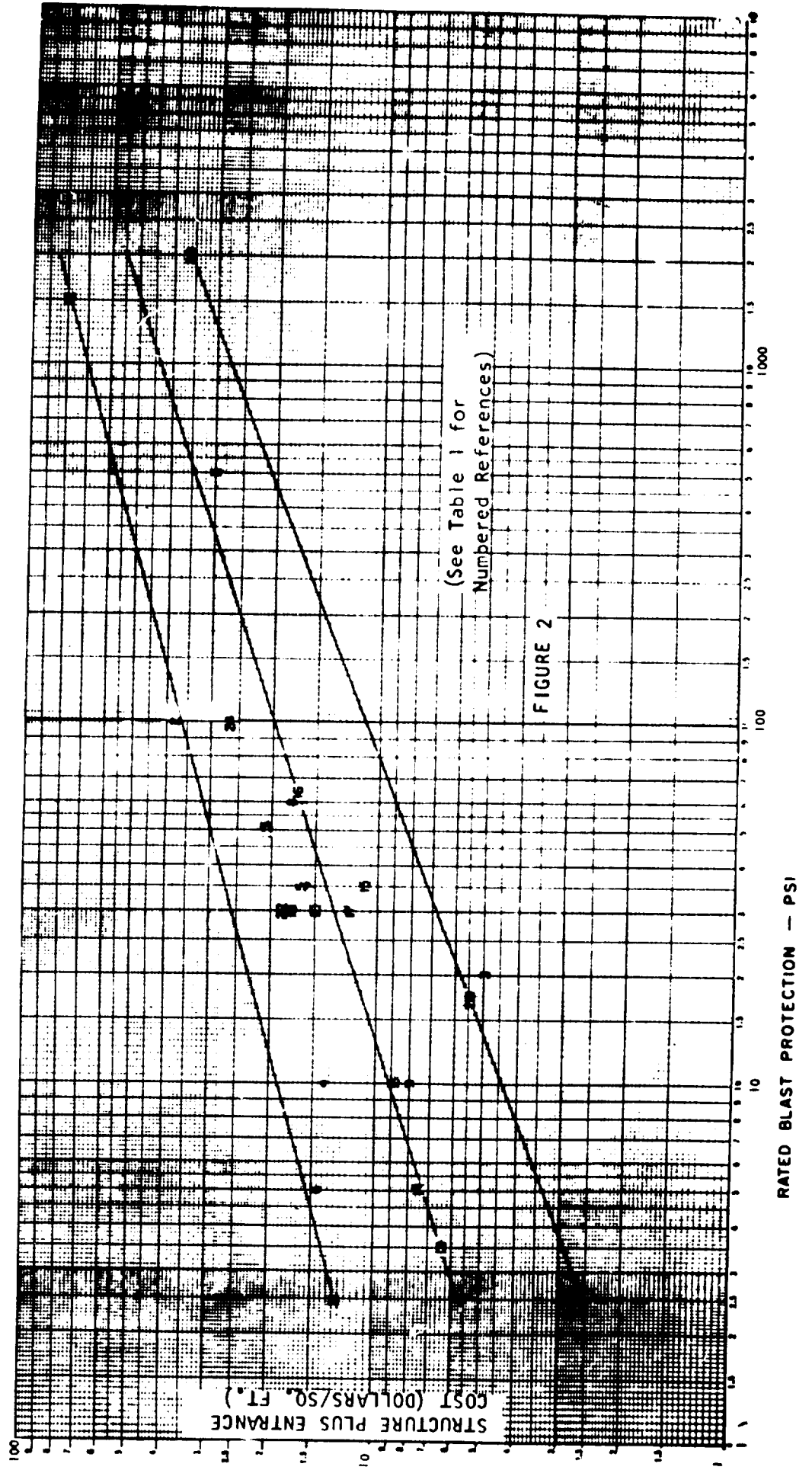
Limitations

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 incurred only to the extent that the construction program uses up real estate. That is, a plot of ground is not necessarily "destroyed" by putting a shelter under it. In fact, some net benefits might accrue (more parks, playgrounds, parking lots, improvements, development of leasable or salable properties, etc.).

2. The costs do not reflect possible savings due to efficient planning, 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 that 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 because the available land is not optimally situated with respect to the population

FIGURE 2

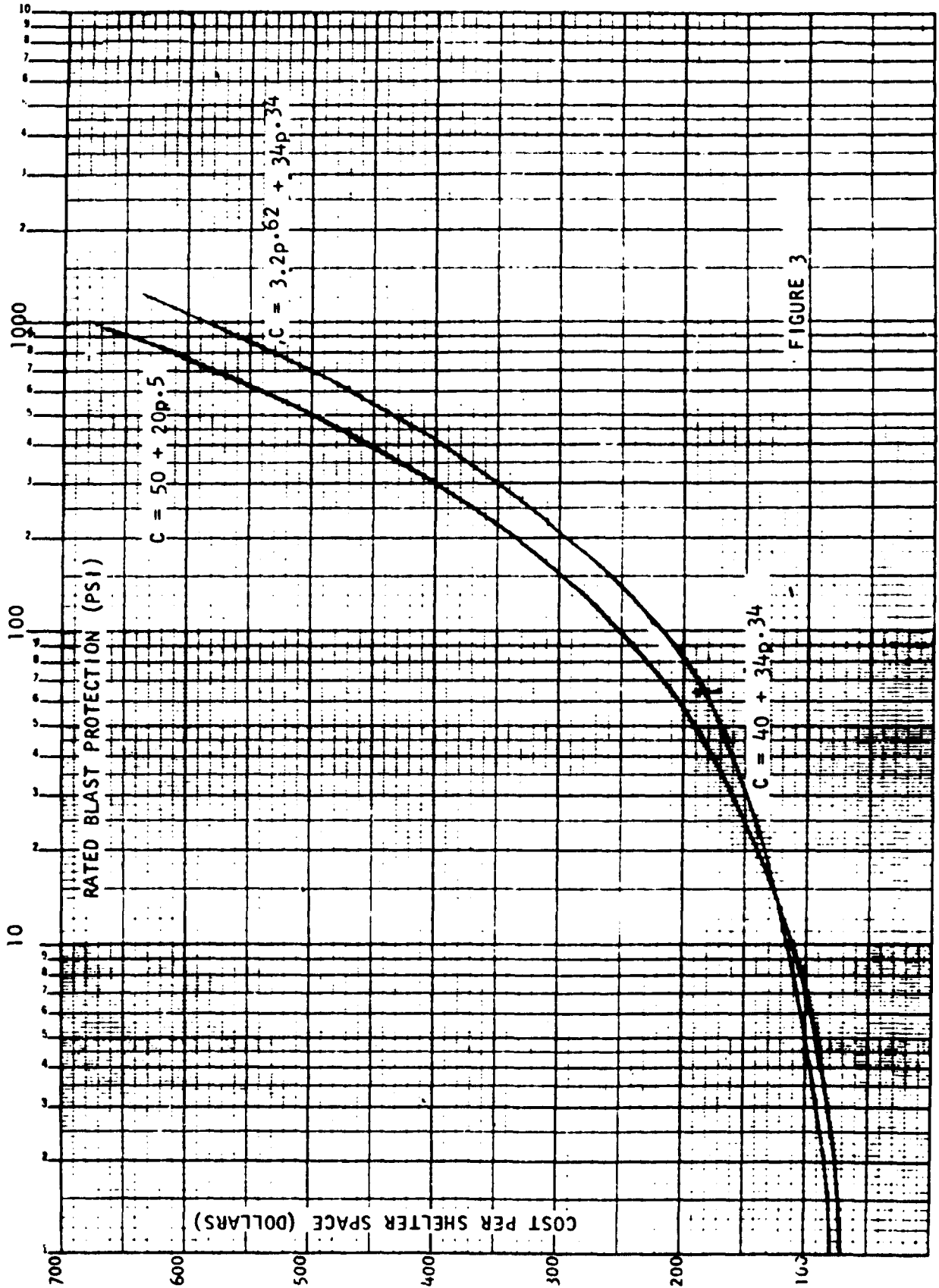(See Table I for Numbered References)

FIGURE 3

The graph shows curves representing:

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

$$C = 3.2p^{.62} + 34p^{.34}$$

$$C = 40 + 34p^{.34}$$

with axes labeled RATED BLAST PROTECTION (PSI) and COST PER SHELTER SPACE (DOLLARS).

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

	1	2	3	4	5
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

	6	7	8	9	10
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

	11	12	13	14	15
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

	16	17	18	19	20
STRUCTURE	$121.60	$ 90.00	$123.45	$ 43.90	$ 58.40
ENTRANCES	3.00	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 % PROF CONT	30 10 20	?	?	15 10 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

	21	22	23	24	25
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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