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FINAL REPORT

THE DESIGN AND PERFORMANCE OF "OPTIMUM" BLAST SHELTER PROGRAMS

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PREFACE

This is the second revision of the original paper on "Optimizing Blast Shelter Programs," HI-302-DP, which with some changes also appears as a contribution to Project Harbor.

The major revisions are contained in the later sections in which are developed costs and effectiveness of blast shelter programs coupled with partial dispersal of population from some of the more congested city areas and with possible "overcrowding" of the shelters.

It is hoped that this paper will provide a reference from which the costs and effectiveness of possible alternative blast shelter programs can be taken. In this way it should be of value not only to the Office of Civil Defense, but also to other elements of the defense establishment, and in particular, should be useful for the study of combined active and passive defense systems.

ACKNOWLEDGEMENTS

Historically the approach of this paper was paralleled by a complementary effort of H. Kahn, which appears initially in HI-202-FR.* Much of the stimulus for this effort derived from discussions with Kahn who also contributed valuable suggestions. Dr. Fred Rockett provided a patient "sounding board" during the development of the subject matter. John Devaney of the OCD deserves a medal for tolerating several presentations of this material with great patience and for his steady encouragement. Lloyd Woodward of the OCD was kind enough to read a draft of this paper with great care and offered many useful criticisms.

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*See Reference 4.

SUMMARY

This paper develops a mathematical model from which the cost of a national blast shelter program for the 213 urbanized areas of the U.S. can be calculated, and from which the effectiveness of the program in providing blast protection for the urban citizens can be quickly found. This paper, by utilizing the idea of equalizing the value of all urban areas as targets (from the enemy point of view), (a) denies the enemy any preferred targets, from the point of view of population mortalities, and (b) provides an important kind of equality of population vulnerability among the urban areas. For any given budget the funds spent for protecting a citizen in a more congested area would be somewhat greater than for those in less congested areas which, normally, would be a less likely target. From a national point of view, it is believed that the design has the advantage of minimizing the number of blast fatalities which an enemy can achieve, and thereby can contribute to the reduction of national vulnerability. To a large extent the basic design is independent of the size and nature of the assumed attack, although this is less true of the later refinements which involve the use of partial dispersal and crowding.

There are three essential elements required in the initial model, which assumes that shelters are to be built in areas where the population normally resides; these are:

1. the mathematical relationship between blast overpressure and lethal area from any nuclear explosion;
2. the population density distribution within the urban areas of the U.S.; and
3. the estimated cost of shelters as a function of the design overpressure.

Each of the above three factors is estimated and expressed in a relatively simple mathematical form, and the results combined to obtain the cost of alternative national programs for the 96 million people (1960) of the largest 213 urbanized areas in the U.S.

It turns out that the results can generally be expressed in terms of a simple vulnerability criterion, β, which represents the maximum number of fatalities expected from a 1-MT explosion. For each of several values of β the cost of urban shelters for a national program is found from the [illegible] and the results presented both in tabular and graphical forms. For a program with a given β, for any attack consisting of an array of megaton weapons W_i, the number of blast fatalities among the sheltered is given by the equation

$$\text{fatalities} \leq \beta \sum_i W_i .$$

[illegible] examples are worked out showing the method of making the calculations and estimating the effectiveness of the program under some hypothetical attacks against population.

By utilizing an option for partially dispersing the population of congested cities, two additional beneficial effects can be attained. First, the requirement for extremely hard shelters in the very congested areas is relieved, a requirement which, in many cases, might be beyond our technological capability. Secondly, since the cost of sheltering in outlying fringe or rural areas is substantially less than that within the cities, if the total budget for shelter construction is held constant, the option can be utilized to obtain either (a) substantial reduction in the cost of a program utilizing a given vulnerability, or (b) a substantial increase in the degree of protection which is obtained. The results, given in Figure 8, show that for a given budget the vulnerability to blast can be reduced between 50% and 80%.

The discussion of costs have implicitly assumed 8 to 10 square feet of space per person. A separate study indicates that this allotment can be substantially modified and thus by "overcrowding" the shelters the cost of the program can again substantially be reduced (or, at fixed budget, the vulnerability can be reduced). Some results based upon a 2:1 overcrowding are shown in Figure 9. By combining (a) optimized design, (b) dispersal, and (c) overcrowding, the figure suggests that [illegible] blast protection can be obtained nationally at a cost between [illegible] and [illegible] billion.

THE DESIGN AND PERFORMANCE OF "OPTIMUM"[1] BLAST SHELTER PROGRAMS

Introduction

There are two words which even many enthusiasts for civil defense tend to avoid--evacuation and blast shelters. The first has an unpleasant memory because it is associated with the abandoned survival plans of the mid-fifties which anticipated evacuation of untrained populations, without special preparations or professional cadres, upon tactical warning given by the DEW line. This concept soon became obviously impractical because of the development of the ICBM and the MT-weapon. However, in other documents (Refs. 3,4) we have argued that various kinds of movements of people could play an important role in crises (e.g., in a strategic warning situation when The New York Times rather than radar reflections or a secret agent gives the warning).

"Blast shelters" have had a bad connotation for a different reason. They are often associated with "fanatics" who want to do too much. We do not wish to enter into an extensive discussion of the pro's and con's of a blast shelter program in this paper. It is indeed a controversy whose resolution will depend upon many strategic, political, and technical factors. However, we have found that there is a better general understanding of the con's than of the pro's. Therefore, it seemed to us to be desirable to start by considering clarifying some of the basic assumptions indicated in the table below.

Each assumption in the table is either believed to be reasonable now or that it can be made reasonable. If this is true, then some of the current arguments against blast shelters are at least partly misleading. However, even if the favorable assumptions are correct, reasonable analysts might still argue against such programs because of

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[1] The discussions in these chapters are not always rigorous, complete, or carefully hedged. We should probably note that technically the word "optimum" in the title is misleading. In fact, systems analysts should rarely use the term, optimum, to describe a policy choice. They generally use some such term as "preferred" indicating only that they do not know of any other system which is clearly more preferable. However, using the term "optimize" does simplify our exposition and since our purpose here is heuristic it seems appropriate to use the word.

technical uncertainties, cost, image, social impact, or arms race considerations. A future decision may rest as much or more on other motives, values, or assumptions than those discussed here. But an amplification of the assumptions below should help clarify the discussion and debate.

TABLE I

Seven Explicit Assumptions

	FACTOR	OUR ASSUMPTION
1.	Cost estimates	Based upon mass procurement, research and development, and intelligent design
2.	Allocation and distribution of shelter	Some reasonable "optimization" process is followed
3.	% occupancy	Emphasizes Beta and Gamma type scenarios (see Reference 4) in the evaluation
4.	Size and character of attack	As in 3 above plus "reasonable" assumptions about Soviet procurement policy
5.	Damage mechanisms	Blast overpressure is critical
6.	Shelter discipline and viability	As indicated by recent OCD studies
7.	Postattack or postwar rescue and survival	Sensible planning and location of shelters and other reorganization plans and preparations

Seven Explicit Assumptions

1. Cost: Most current cost estimates are based on the price that would be charged by a local private contractor who has been commissioned to build one or possibly a few shelters. It is, of course, possible that if a mass shelter program were procured in the United States, that the actual cost would be even higher since competition for labor, supplies, and even contractors might drive the costs up; there are also other effects which might increase the cost over today's. However, we also believe that a properly designed mass shelter program might be possible at half the cost of normal contracting. The major notion is that we should go to firms such as "General Electric" or "General Motors" for our shelters rather than to individual contractors. Almost all current construction in the United States is necessarily tailor-made. There is very little research done because the cost of such research has to be amortized over a single project, and there is relatively little use of specialized and very expensive equipment, because generally such equipment is difficult

to transport and has to be amortized over a small number of jobs. We have made some preliminary investigations into the use of expensive (a half-million dollars and up per item) equipment in the use of construction of shelters and believe that such possibilities as the use of Le Tourneau permanent forms or the mass casting of concrete on the ground (which is then subsequently cut apart and moved to the site) and other techniques could be used to cut the cost of shelters sharply.

The actual costs assumed in this chapter are given by the equation:

$$C = 50 + 20\sqrt{P}, \quad \text{(dollars per shelter space)}$$

where P is the overpressure design point of the shelter. As discussed later in the chapter we believe this equation is conservative, if there is a mass procurement program based on a large research and development effort. (For example, if we are talking about spending about $20 billion on shelters, it would be reasonable to spend up to a billion dollars or even more for prior research and development to increase our ability to put the program in rapidly as well as bringing down costs.) The estimates represented by the above equation do not take account of such possible savings; they are simply at the medium level of what could be expected of contractors today.

One must, of course, always allow for the possibility that these potential savings will be offset by the well-known experience in defense procurement that early engineering estimates have a habit of understating subsequent costs. There also may be internal political and social difficulties in circumventing normal construction techniques.

2. <u>Allocation</u>: We also assume that the allocation and location of different levels of protection, as well as the construction techniques, will be determined mostly by technical and professional considerations and not by local political or bureaucratic constraints. Thus, each "optimum" blast shelter program to be described assumes an array of shelter sizes and hardnesses which are built and allocated in a manner which tries to get "maximum" protection per dollar spent. Thus the program also assumes that there will not be sizable or very difficult problems in siting according to the design criteria. In some programs there will be requirements for partial dispersal or other movement of residents from some of the more congested areas. It is assumed that such movements can be carried out without any unusual difficulties.

3. <u>Per Cent Occupancy</u>: There is a widespread belief that shelter programs must be designed so that the population can be protected with only a few minutes warning--certainly less than fifteen. It has been argued cogently in a number of documents (references 3 and 4) that the warning requirement for a shelter program need not be based on a 15 minute reaction but that hours or even days is more reasonable for the "interesting" range of threats. That is, when one considers the complete range of possible future wars, recent informed judgment seems more and more to accept the thought that within this range nearly all the possible attacks would be those in which, through a combination of strategic and tactical warning,

the time to take shelter would be quite substantial (from several hours to several days or even weeks). Indeed it has been argued that even in most of the exceptions, for example wars which might begin with an unsuspected enemy strike against the ZI, in most of the country the population centers would not be targeted by the first missile wave, since it generally would be to an enemy's advantage to damage the quick-reacting military targets first. Thus it appears that in the large proportion of possible attacks there would be both strategic and tactical warning available for the country and that in almost any case a large portion of the population could expect to receive at least a significant amount of tactical warning (hours) which could provide sufficient time for reaching shelter. This, of course, would not be true for all possible scenarios. A desirable basic concept is that, wherever it is inexpensive to do so, we should try to get a capability for protecting people on a few minutes notice, but we should not be willing to let costs increase by much more than 5 or 10%, or performance to go down in Beta-3 and Gamma-type scenarios, in order to get improved performance for the Alpha or Beta-1 type scenarios.[1]

We also assume that much of the information and training that the population would need can be disseminated during the crisis period. That is, while we specifically wish to design the program to have some reasonable capability with completely untrained and uneducated populations, we believe this would be far less than the best that could be achieved. This reduction of completed capability is deliberately accepted in order not to impose responsibility for peacetime civil defense preparations upon the average civilian. (However, it should not be difficult to educate children by introducing civil defense practices into schools even in normal times.) During a crisis period, as discussed in Reference 3, a large number of techniques are available to get the information out rapidly. And, of course, if the government ever actually does decide to spend several billions or tens of billions of dollars on shelter programs, then this fact should make others take it seriously. It is to be expected that the response of the average American will be one of acceptance and cooperation.

4. <u>Size and Nature of the Attack</u>: Probably the largest uncertainties involve this question. We mentioned earlier that most people in the late '50's who tried to estimate the kind of missile attack the United States might face in the early '60's, assumed that there might be hundreds of Soviet missiles when, according to various reports, the Soviets only had tens. On the other hand, the Soviets did procure hundreds of IRBM's. This might have been due, as much as anything else, to a lag in Soviet doctrine. If this is true, it must also be realized that other future lags and inefficiencies are also possible. In addition, the Soviets today seem to be extremely pressed for funds for capital investment to raise their standard of living and to keep up their rate of growth. Thus while it is perfectly possible for them to build a very large missile force as in the Alpha or Beta-1 scenarios and launch all or a major portion of these forces at civilian targets, it is also quite possible that their forces could be smaller and/or used with some restraint.

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[1] See Reference 4, pp. 140-147 for discussion of these scenarios.

In this respect, we might also take note of the history of preparations for conventional warfare in Europe. For many years, there was a systematic overestimation of the Soviet capability (175 divisions), one so large as to make it seem that even major efforts by the Europeans would be useless in the face of the overwhelming threat. Today, we are now willing to argue that even current NATO forces in Europe might be about a match for the current Soviet forces that are actually available. (For example, see Reference 5.)

In any case, no matter what the Soviet preparations are, there are always a range of possible wars in which the attacks would not be totally devastating. For example, can we design a blast shelter program in which no more than 20% of the people might be blast victims of a 3000 MT counter-city war. While an urban attack ten times this size would completely overwhelm the system our judgment must be that this kind and size of war would be extremely unlikely.

5. Damage Mechanisms: We rely here on the Effects of Nuclear Weapons (Reference 2) and other publications.[1] We have taken account of the major damage mechanisms and believe that it is not likely that the ones we have not thought of will prove to be serious. It is assumed that people not casualties of the prompt nuclear effects have been provided sufficient supplies and protection to avoid the dangers of the intense radiation threats of the first few weeks.

6. Shelter Discipline and Viability: Depending on the details of the war and the variation of events at different locations the necessary occupation of blast shelters could vary anywhere from less than a day to more than two or three months. We will start by assuming that existing research by the OCD on the ability of people to stay in shelter for lengthy periods can validly be extrapolated to the wartime situation and that we would not experience any unusual difficulties beyond our ability to anticipate and calculate. We would, for example, assume from the research that food and water resources can be shared equitably and rationed intelligently during the shelter stay and that psychological and social problems would create discomfort and irritation but not increase the casualties by a large amount.

7. Postattack and Postwar Rescue and Survival: We refer here less to the common image of individuals trapped beneath collapsed buildings than to our postattack ability to get people out of shelters to more permanent and viable locations, or in getting additional supplies to people in shelters when they have to stay there for a lengthy period. That is, even if the shelter occupants survive all of the immediate weapons' effects, there remains the problem that some fraction of these shelters will be isolated. Some may be covered by rubble caused by the collapse of nearby buildings, trees, etc., or the roads to the shelters may be blocked. In effect, this is a postattack reorganization and rescue problem that could be much affected by the preparations made to anticipate these problems. In particular, they are probably sharply affected by the actual location of the shelters. Here again, appealing to our notion that people would

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[1] For example, see Project Harbor draft report.

usually be able to move at least small distances before the attack, we would argue that the shelter locations should be chosen with an eye to the possibility of postattack and postwar rescue and aid, as well as the normal location of population. In other words, we would advocate consideration be given to the placement of blast shelters along major highways, in the outskirts of downtown areas, or generally in places which are unlikely to be blocked by debris.

We will not discuss here the problem of survival after the initial postattack period, i.e., the problem of recuperation and reconstruction. This question is, of course, quite critical as it would do little good to protect people if they cannot survive in the postwar world. But it is also clear that current hypothesis that one cannot survive in a postwar world is "theory"--as opposed to the also theoretical but much firmer notion that one is more likely to survive the immediate effects of the war if he is in a 100 psi shelter than if he is not.

THE MODEL

Assumptions in the Calculations

A number of simplifying assumptions will be made in our model which are believed to be reasonably consonant with reality. These are:

1. That the cities are large: this means that only a small area or fraction of the sheltered population are vulnerable to a single weapon. (This assumption can be eased somewhat as shown in the later discussion.)

2. That the sheltered population is distributed "smoothly" over the city (that is, the population density varies relatively slowly), approximately in proportion to existing residential densities. (The utility of relocating a portion of the population during the shelter-taking period will be discussed separately--see section on "Small Cities.")

3. That the sheltering policy is (a) one of minimizing (on a national basis, for any given budget) the expected number of blast mortalities from attacks which are designed to maximize casualties in full knowledge of the shelter program; and (b) one which attempts to remove, by program design, preferred population targets from a malevolent enemy.

4. That for analytical purposes a "cookie-cutter" definition of blast resistance is satisfactory (e.g., a 100-psi shelter collapses at 100.1 psi and is undamaged at 99.9 psi).

5. Very good fallout protection ($PF \cong 500$) would be available to the rural population not protected by blast shelters. The cost of this fallout protection is not included in our calculations.

6. A final assumption, which is seemingly more arbitrary than the others, and which is made here without proof or even discussion[1] is that the optimum distribution of shelters is related to the proper choice of two design parameters, α and β, where:

α = maximum number of dollars that would be spent to provide shelter for one citizen.

β = a specified level of blast vulnerability to a 1-MT weapon. Any target that would otherwise yield more than β lives to a 1-MT weapon is protected (subject to the above α limit) until the β criterion is met.

In principle, for any given total budget both α and β can be determined, the shelter system can be designed, and the approximate vulnerability to various optimized attacks calculated.

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[1] A more rigorous description of the "optimization" technique and some of the caveats will be discussed in a forthcoming Hudson Institute report.

Required Protection

Assumption 6 introduces a criterion for sheltering the general population which removes from the enemy most especially attractive targets, in terms of expected mortalities. This criterion results in a program which is designed to restrict the mortalities in a lethal area, A, resulting from the explosion of a "standard" 1-MT bomb against a sheltered population of quasi-constant density, ρ, to satisfy the relationship, $\rho A \leq \beta$; where β is the chosen design criterion for vulnerability. (Then, by virtue of the scaling laws, from a bomb of W-MT the total number of mortalities would be $\leq \beta W^{2/3}$.) This suggests that we might be able to determine for each local population density, ρ, a sheltering hardness, P, such that the above equation would be satisfied.

The requirements for such a program are shown in Figure 1, which plots the needed blast protection as a function of population density for a "typical case" in which the vulnerability, β, is taken to be 20,000 per 1-MT bomb. It is seen from the figure that the sheltering requirements are somewhat different, depending upon whether one is considering a groundburst or an airburst attack. However, a reasonable linear approximation of the two cases is given by the formula,

$$P = 150\ \rho/\beta \qquad (1)$$

(the formula using $P = 160\ \rho/\beta$ is a better representation of the optimum airburst case, but we have chosen to use an equation more representative of both cases). The figure, drawn from data in Effects of Nuclear Weapons, shows the results up to 200 psi. It would be reasonable to extrapolate the approximation to about 300 psi. However, above 300 psi a significant divergence from a linear approximation appears because in this range the relationship between overpressure and distance is given approximately by Pr^3 = const. (while the formula, $P = 150\ \rho/\beta$, is equivalent to a relationship Pr^2 = const.). In this paper we will, as a first approximation, ignore this 300-psi limit, anticipating that a realistic program would not involve many shelters much above this degree of protection. (That is, the error introduced into the subsequent estimated cost of a national program will be small.)

It should be noticed that ρ/β is the interesting parameter in Figure 1. If we had changed the scale to show a population density of twice that in the figure, then we would get the same curve by choosing the criterion, β, twice as great, or in this case 40,000 per 1-MT bomb. Thus, after choosing any particular β, the axes can be rescaled to read directly the required P for any density, ρ.

Shelter Costs

A shelter program which aims at optimizing the amount of protection for a given budget requires some information about the cost of the shelters as a function of their hardness. It is clear that other considerations

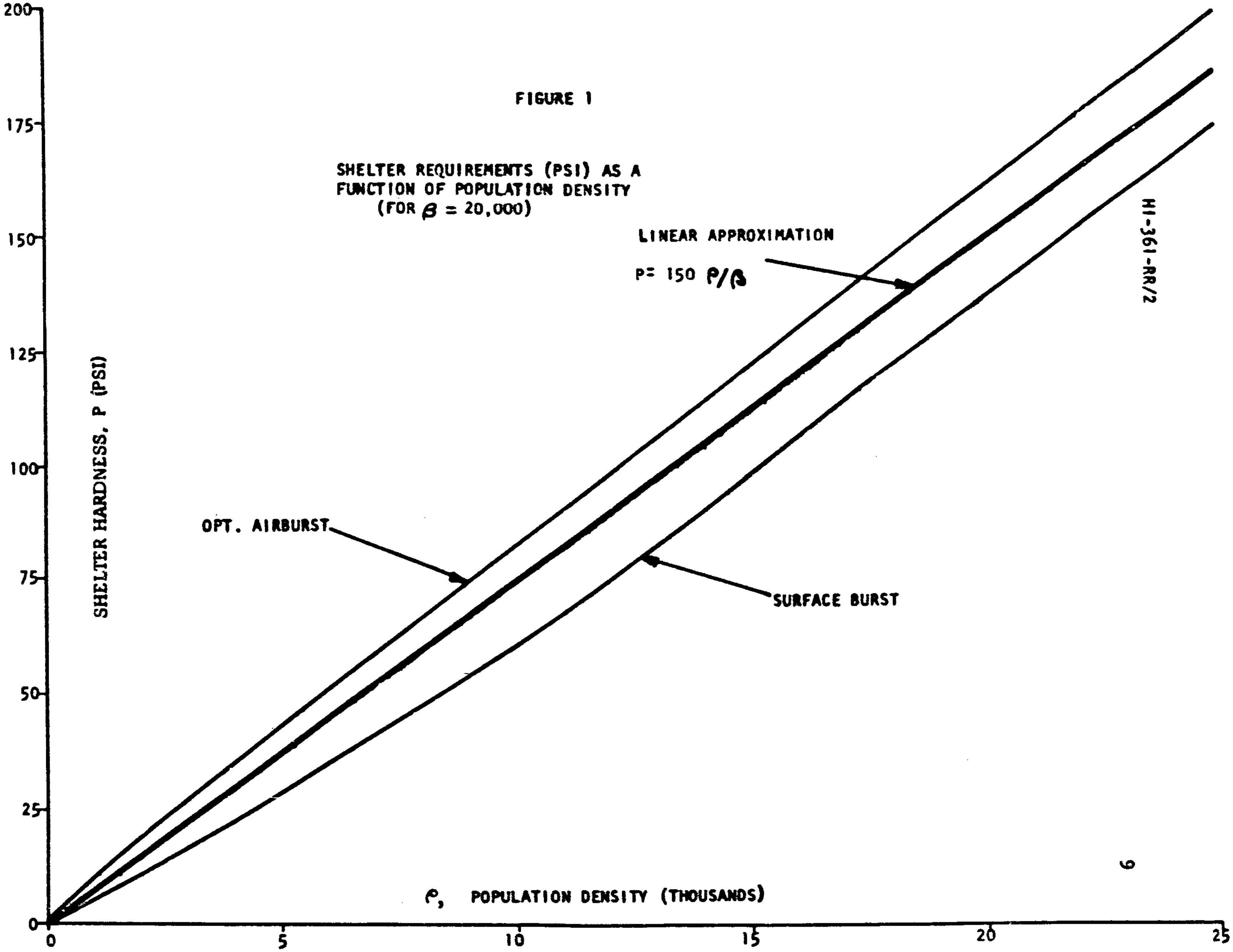

FIGURE 1

SHELTER REQUIREMENTS (PSI) AS A FUNCTION OF POPULATION DENSITY (FOR $\beta = 20,000$)

would also affect shelter costs, considerations such as the condition of the soil, the actual shelter capacity, the number of square feet allowed per person, the chosen design for the shelter, etc. We have shown in Figure 2, six analytic curves which purport to relate cost to shelter hardness. Five are linear and one is non-linear. All of the curves could be justified under various assumptions, but the cost curve (in dollars per shelter space)

$$C = 50 + 20\sqrt{P}. \qquad (2)$$

will be chosen for our analysis in this paper. It is based on some Hudson Institute research on estimated costs of shelters (Reference 7). It estimates, for example, that 100-psi protection costs $250 per shelter space and for large shelters is conservatively consistent with both research estimates and existing experience. These estimates take account that the average cost of a shelter of any given psi will vary according to the size and special conditions under which the different psi shelters are likely to be installed. A comparison of the chosen curve with the costs estimated by Project Harbor[1] is given in Figure 3. Should future cost estimates be changed, the calculations can easily be amended. In any event, either the linear or square-root relationship can be readily handled.

Figure 4 is a plot of required shelter hardness as a function of population density, ρ, for various criteria ranging from β = 1,000 to β = 80,000. The population density ranges up to 36,000 (per square mile) which should be sufficient to cover all parts of the U.S. with the exception of some central parts of New York City. For reference Table 2 shows the average population density of the larger central cities of the United States.

We can represent the cost of each shelter space, C, in terms of ρ and β, by putting together the two equations above to yield the result:

$$C = 50 + 20\,(150\rho/\beta)^{1/2} \qquad (3)$$

It should be clear from equation (3) that if we can specify both β and the density distribution of the sheltered population,the total cost of a program could be determined by adding up the costs of all the required spaces. (We will introduce the α parameter later as an arbitrary limit on the maximum cost per shelter space.)

Population Distribution

In order to apply equation (3) above, to the calculation of the cost of a national program, it will be necessary to determine the population density distribution of the U.S. Table 2 indicates some of the data about population which is available from census material (see Reference 1). This data is somewhat coarse, since the density of population is averaged

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[1] See Project Harbor report (draft).

FIGURE 2

SHELTER COST FUNCTIONS

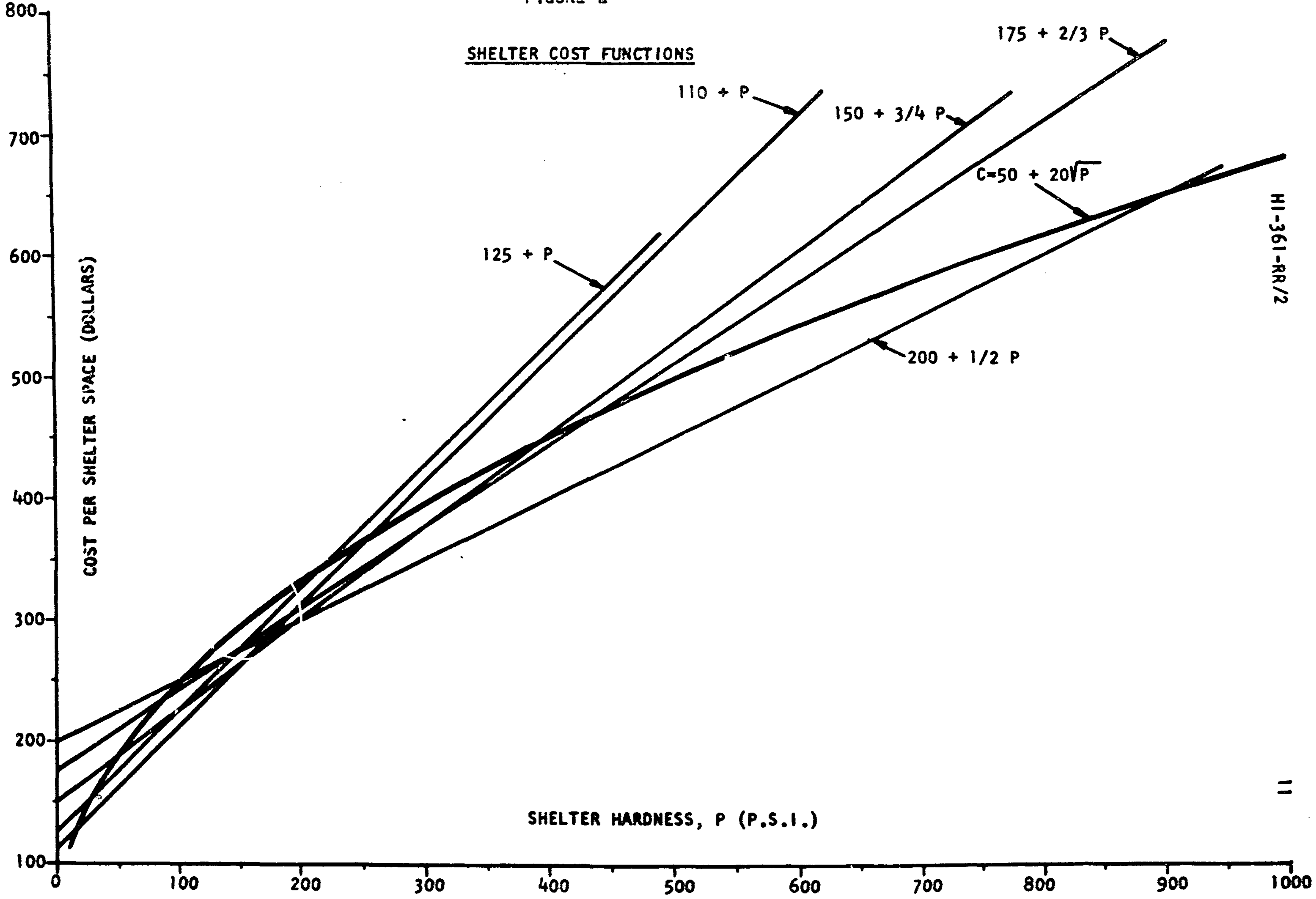


FIGURE 3

COST OF MASS PROCURED SHELTERS

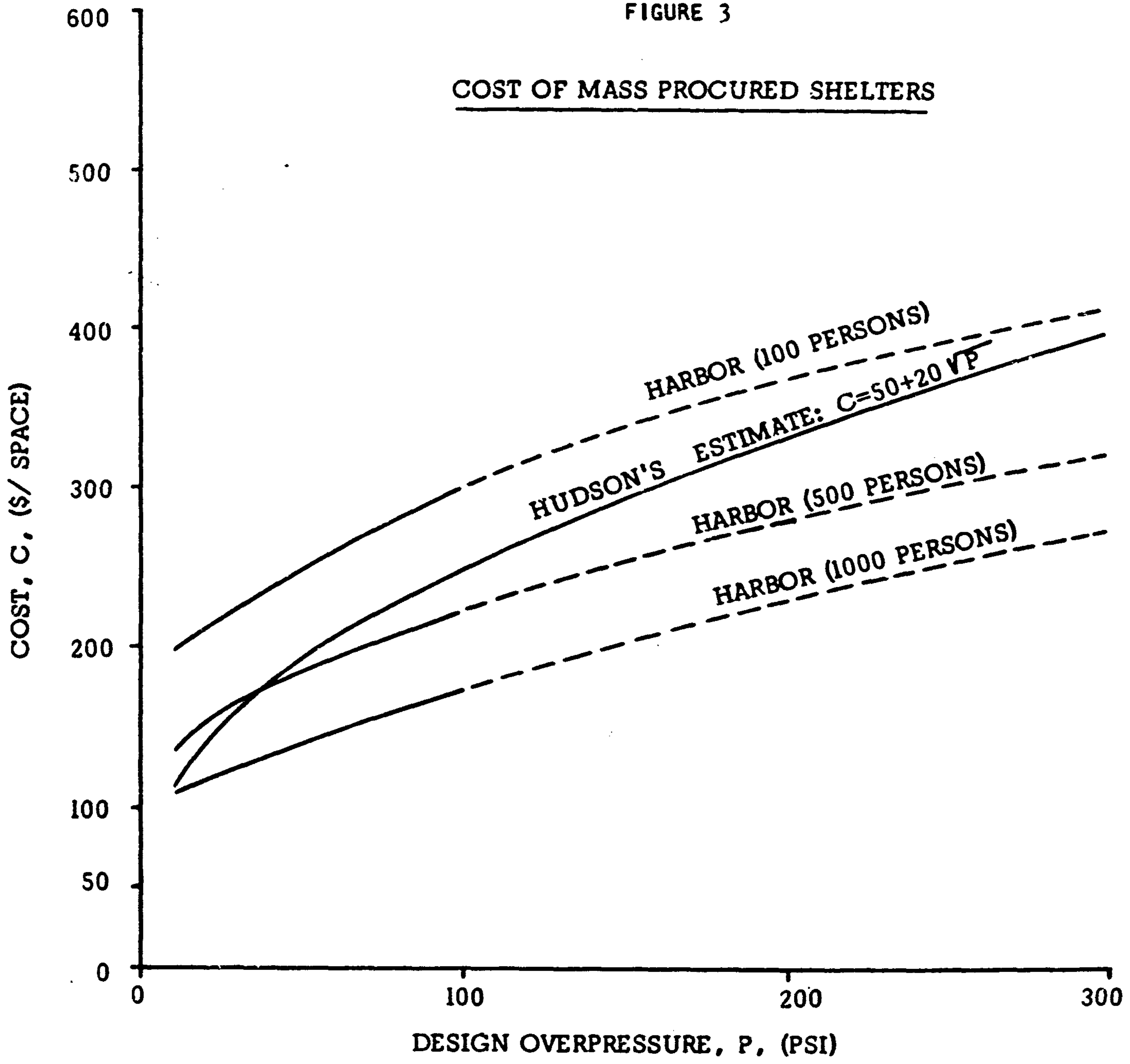
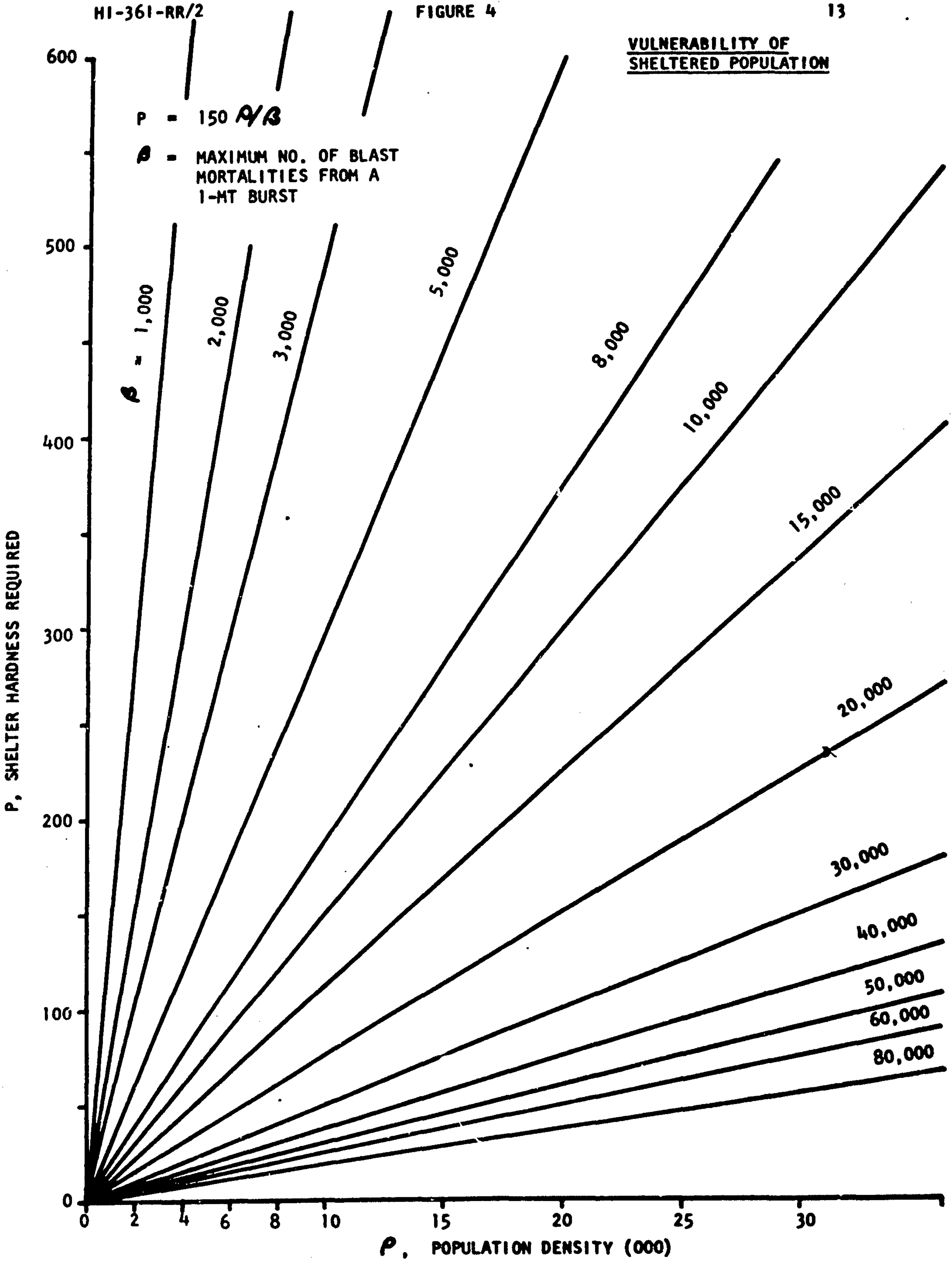


FIGURE 4



VULNERABILITY OF SHELTERED POPULATION

TABLE 2

POPULATION AND DENSITY OF U.S. CITIES (1960)*

Residents per sq. mi. (thousands)	Central Cities Only	Population (millions)	Subtotal (millions)
23.3	N.Y., Newark	8.74	
15.4	Philadelphia	2.00	
15.4	Trenton	.11	
14.6	Boston	.70	
12.9	Chicago	3.90	
12.9	Charleston	.07	
12.4	Washington	.76	16.23
12.3	St. Louis	.75	
12.0	Detroit	1.67	
11.9	Baltimore	.94	
11.6	York	.05	
11.2	Pittsburgh	.60	
11.0	San Francisco	1.11	21.35
10.8	Cleveland	.88	
10.8	Providence	.29	
10.4	Harrisburg	.08	
10.2	Reading	.10	22.70
9.3	Hartford	.16	
9.2	Wilkesbarre	.06	
8.7	Bridgeport	.16	
8.7	Rochester	.32	
8.6	Syracuse	.22	
8.5	Miami	.29	23.91
8.4	New Haven	.15	
8.1	Milwaukee	.74	24.80
7.3	Minnesota Class A (> 1M)	.80	
6-8	7 cities Class B (1/2-1M)	3.10	
6-8	7 cities Class C (1/5-1/2M)	1.26	
6-8	3 cities Class D (1/10-1/5M)	.31	30.27

* See Reference 1.

over the entire central city, an area too large for our purposes. However, we can use this data together with an examination of some of the local areas to put together an approximation from which calculations can be made.

We have made a crude estimate of population density distribution, derived from the census numbers given in Reference 1, which is not to be taken too seriously but will do in the absence of more detailed studies. Table 3 gives this estimate of the population associated with various densities for the 96,000,000 residents (1960) of the 213 urbanized areas which have a population of 50,000 or more in their central cities (Reference 1). This Table is a rough model of the urbanized areas in which the density of 80,000 per square mile relates to Manhattan, and the densities of 40,000 per square mile include portions of Brooklyn, Bronx, Queens, and nearby areas in New Jersey.

TABLE 3

ROUGH POPULATION DENSITY MODEL (1960)
OF THE 213 LARGEST URBANIZED AREAS

Density of Population, ρ_i (thousands/sq.mi.)	Number, n_i, of Residents (millions)
80	2
40	4
20	6
15	4
10	6
8	7
6	8
5	10
4	15
3	20
2	10
1	4
	TOTAL: $N = \sum_i n_i = 96$

The Results

If we assume the distribution in Table 3 is a sufficiently accurate representation of the sheltered populations, then we can compute the cost of sheltering these 96,000,000 people. Combining previous equations, the formula for the total cost of a program is easily found to be:

$$T = 50N + 20 \left(\frac{150}{\beta}\right)^{1/2} \sum_i n_i \rho_i^{1/2} \qquad (4)$$

The n_i and ρ_i, for our purpose, can be taken from Table 3, and N is the total population to be sheltered. Using N = 96 (million), and computing from the Table above,

$$\sum_i n_i \rho_i^{1/2} = 248 \qquad (5)$$

we get for the total cost of a program for these 213 areas:

$$T = 96 \times 50 + \frac{245 \times 248}{\beta^{1/2}}$$

$$\cong 4{,}800 + \frac{60{,}000}{\beta^{1/2}} \text{ (in \$ millions)} \qquad (6)$$

Where β is expressed in thousands (e.g., use 8, for β = 8,000).

The cost, T, for a national program which shelters these 213 areas depends on the choice of β; the calculations for a range of β's are given in Table 4 below.

TABLE 4

COST OF BLAST SHELTERS FOR 213 URBANIZED AREAS

Vulnerability, β (thousands)	Shelter Required (psi) at:			Total Cost ($ billions)
	$\rho = 3{,}000$	$\rho = 10{,}000$	$\rho = 30{,}000$	
1	450	1500	4500	64.8
2	225	750	2250	47.2
3	150	500	1500	39.4
4	112	375	1120	34.8
5	90	300	900	31.6
8	56	187	560	26.0
10	45	150	450 *	23.8
15	30	100	300	20.3
20	23	75	225	18.2
25	18	60	180	16.8
30	15	50	150	15.8
40	11	37	112	14.3
50	9	30	90	13.3
60	7.5	25	75	12.5
80	5.6	19	56	11.5

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*The shelter requirements above the dotted line fall outside the limits of the assumptions of the model used in this paper.

The results from this model, shown in Table 4, indicate the blast protection available at various costs. Since, for an attack against these protected areas, the maximum number of blast mortalities is proportional to β, the Table shows that the blast vulnerability can be decreased by a factor of 40, while the cost of shelters increases roughly by a factor of four. This variation is primarily to be attributed to the form of the cost function which gives increasing marginal returns both because of the fixed first term (50) and the square root in the second term--see equation (2). The somewhat surprisingly low costs given by the model follow from the population distribution function (Table 3) which shows the bulk of the urban population at a density of approximately 4000/square mile, which was lower than the "intuitive" estimate.

In any event, the model suggests that shelter in the urbanized areas which might be deemed to offer "excellent blast protection" can be purchased at costs of about \$20-40 billion. For example, the \$31.6 billion program, indicated by the model for a criterion, $\beta = 5{,}000$, suggests (see problem 3) that a malevolent attack of 9,000 megatons (900 10-MT weapons) directed against the protected areas would be limited to about 20 million blast casualties. (It should be added, though, that with this criterion the program might well be extended to smaller towns--perhaps down to those of 10,000 population. This extension to an additional 20-30 million people might increase the over-all cost from 10-20%.)

It was indicated earlier that the maximum number of blast fatalities is given by the expression,

$$M = \beta \sum_i W_i^{2/3} \qquad (7)$$

This upper bound estimate assumes perfect enemy bombing (no misses, no overlaps, no part of the lethal area over rivers, lakes,...) and needs to be modified to obtain a more reasonable estimate. Clearly for sufficiently large attacks the expression must soon be grossly wrong as it could be larger than the total population. A useful formula which is equivalent to equation (7) for smaller attacks but which makes an allowance for CEP and overlaps is given by the following expression for estimating blast fatalities

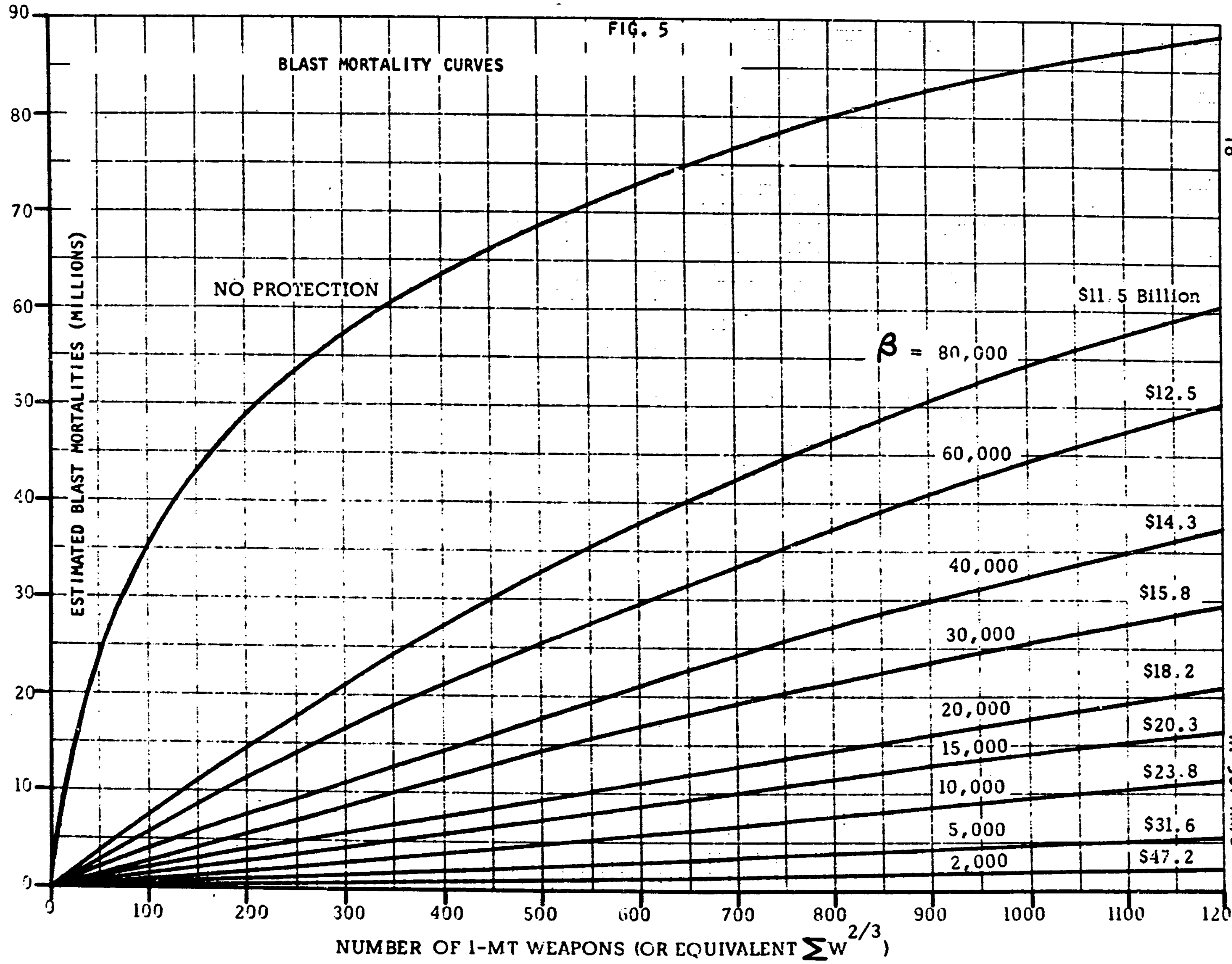
$$F = N\left(1 - e^{-\beta/M}\right) = N\left(1 - e^{-(\beta/N)\sum_i W_i^{2/3}}\right) \qquad (8)$$

where N is the population at risk.

Applying equation (8) to the 213 largest urban areas ($N \cong 96{,}000{,}000$, 1960 population) permits the calculation of U.S. vulnerability to be made for a range of programs with different β. The results of these calculations are shown in Figure 5 along with a curve for the vulnerability of the unprotected population (Reference 6).

FIG. 5

BLAST MORTALITY CURVES

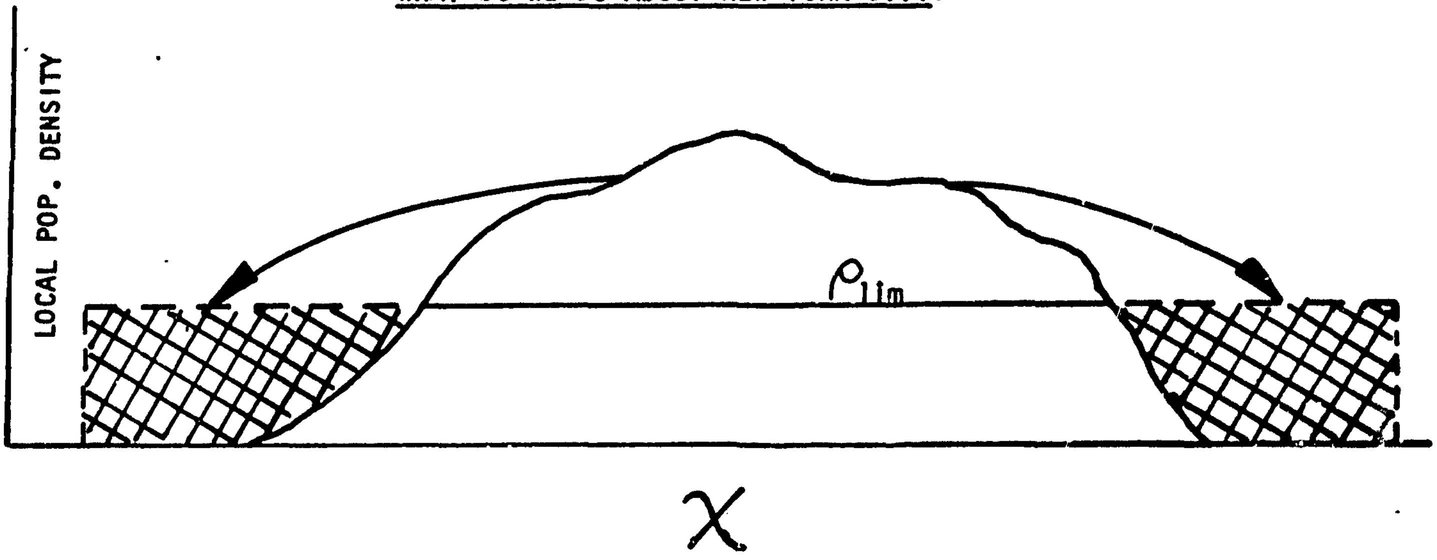


Special Problems of New York

It will be observed that in many of these programs the high population density found in New York City and vicinity requires extremely hard shelters (>300 psi) which in practice might be constructed only with great difficulty, or which could entail an unacceptably high cost per space (greater than α). This requirement for New York could be somewhat alleviated if a partial dispersal to prepared suburban (or rural) shelters were an integral part of the program design (see Figure 6). The number of people to be so dispersed would depend upon the selected criteria, α and β.

FIGURE 6

WHAT DO WE DO ABOUT NEW YORK CITY?



These shelter programs would then work best when prior to an actual population attack there is a period of strategic or tactical warning (as in the Beta-3 or Gamma scenarios) to enable such a dispersal to take place, especially if it is also assumed that preparations for the movement are part of the civil defense program. It should not be unreasonable, in our judgment, to estimate that with a moderate degree of preparation, boosted by emergency civilian mobilization, that up to seven million people could easily relocate from New York City to the outlying suburban areas within 24 hours (perhaps in less than half that time), an interval which could be sufficient for many situations in which population centers are not priority targets even after the war has been started.

Limitations

1. **Cost per shelter**: A reason for putting an upper bound α, on the cost per space is that a point may exist where more lives can be saved by improving the general level of shelter program (that is, choosing a smaller criterion, β) and either accepting a number of unprotected people or providing them with a dispersal option. This determination can often be made without excessive labor using cut-and-try methods as subsequent illustrations try to demonstrate--see Illustrative Problems, especially problem #2, in Appendix A.

Suppose 300 psi was the hardest shelter that could be built because of the α cost limitation. That is, our policy was not to spend more than $50 + 20\,(300)^{1/2} \cong \$400$ per shelter space. Using equation (1), at 300 psi we obtain a limiting density of protected population, $\rho_{lim} = 2\beta$. That is, the maximum density of shelter spaces would be 2β per square mile. If we consider a program based upon $\beta = 8{,}000$, then all the cities will be sheltered completely except those in which $\rho \geqq 16{,}000$ exists. Shelters would be installed in these, but in areas where $\rho > 16{,}000$, the density of shelter spaces provided would be equal only to 16,000, that is to ρ_{lim}. In our distribution (Table 3) this would mean that (64/80) x 2 + (24/40) x 4 + (4/20) x 6 = 5-1/4 million people would not be provided shelters in their residential areas. Nearly all of these would be from New York City. However, this 300-psi limit would also reduce the estimated cost of the complete program by \$3.6 billion--a part of which (it might be argued) could be used to create a capability for dispersal of these people to shelters within or beyond the urban fringes. Such shelters, say, at an average of \$200 per space would cost \$1.05 billion resulting in a net reduction of about \$2.5 billion except for the cost of preparations for the dispersal. This national urban shelter program, then, including space for the potential evacuees, would cost about \$23.4 billion.

In this example, with $\beta = 8{,}000$, the maximum number of blast mortalities, M, calculated for an optimal population attack in which 4,000 megatons were directed at these urban centers (assuming 200 10-MT, 400 4-MT, and 400 1-MT weapons) would be:

$$M = \beta \sum_i W_i^{2/3} = 8000\,(200 \times 4.64 + 400 \times 2.52 + 400)$$

$$= 18.7 \text{ million}$$

This example is intended to show how cost limitations upon shelters might be compensated for by a dispersal program. Indeed it generally follows that, to the extent dispersal is judged feasible and desirable, the costs of the corresponding shelter program would be reduced, since for a given β, the dispersed shelters can be made less expensive by virtue of decreased hardness requirements.

2. Blast mortalities: The design of the program is such that for a given array of weapons deliverable against the 213 urban targets, the number of blast mortalities the enemy can expect is limited by program design, as expressed by the criterion, β. The maximum number of mortalities from an array of weapons, W_i (megatons), is estimated by

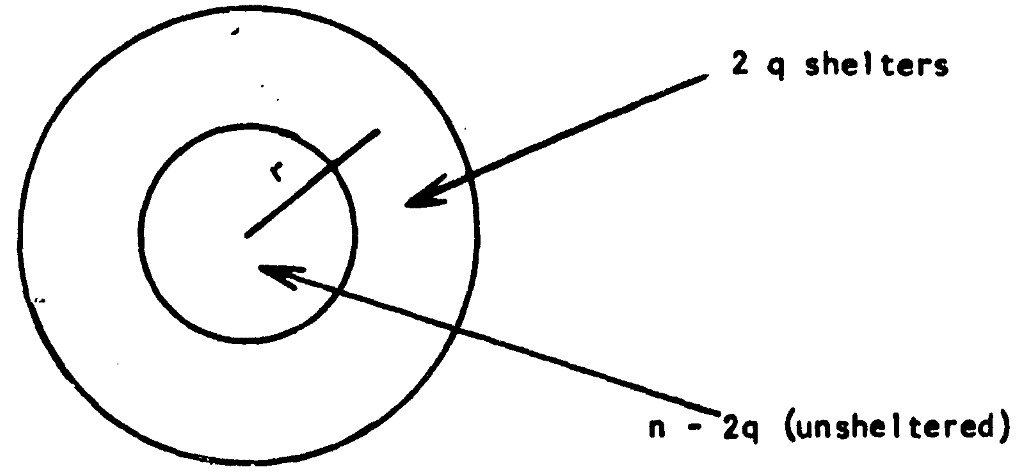
$$M = \beta \sum_i W_i^{2/3}$$

and the total can be quickly summed. However, the number of blast mortalities would often be expected to be less than the maximum because normal C.E.P. variations can cause the lethal area of some weapons to be reduced because of (1) the nearby location of a river, lake, ocean, or other uninhabited space (e.g., railroad yards), and (2) the possibility of overlapping circles when the GZ's are sufficiently close.

It is expected that some minor erratic fluctuations in population density (which in principle could be exploited by an enemy with perfect targeting) would not present important difficulties because of the tendency for these variations to be ironed out by the C.E.P. of the allocated weapons.

Small Cities

If the smallest weapon expected to be used against U.S. targets were 10 MT and the program design had chosen $\beta = 15{,}000$, then $\beta W^{2/3} = 15{,}000 \times 4.64 = 69{,}600$, the maximum number of fatalities per weapon. Therefore no shelter would be required for all urban areas of this total population or less, thus reducing the cost of the program. Moreover for population centers greater than this, but somewhat less than twice this population, only part of the population would need sheltering (and indeed could be chosen at the fringes of the city where the shelters would be less expensive). If the population of a city were $n = 69{,}600 + q$, then no more than 2q shelters need be built at the outer annular ring in order to maintain the criterion, β. In an attack upon the area the central unsheltered population and 1/2 the sheltered might be lost to a 10-MT weapon, while at least q would be expected to survive.



In this calculation the hardness of the shelter at a distance, r, from the center of the city might be determined by maximum overpressure at a distance, r, from a 10-MT explosion.

In practice this problem would be somewhat more complex than stated above but assuming knowledge of the enemy's deliverable strategic weapons, a solution can often be developed for particular cities.

Shelter Size

The principle requirement for the number of occupants, n, of each shelter is $n \ll \beta \bar{W}^{2/3}$ where $\bar{W}$ is the smallest enemy weapon anticipated.* If this criterion is met the shelters cannot themselves provide special targets and the enemy will see a "continuous" population distribution. For β as low as 3,000 and $\bar{W}$ as low as 1 MT, shelters may still be built at 1,000-person capacities since 1,000 is considerably less than $\beta \bar{W}^{2/3} = 3{,}000$. However, in this case, the planned distribution of the shelters would need to avoid inadvertent clustering.

Examples

In order to illustrate some applications of the model, three problems are worked out in Appendix A. The first assumes a 3,000-MT population attack consisting of 300-10-MT bombs and asks what shelter requirements are necessary to hold blast mortalities to within 40 million. The second problem also assumes a 3,000-MT attack, but one consisting of 1,000 3-MT bombs, and the same question is asked. The third problem considers a 9,000-MT attack (900 10-MT bombs) and requires a program in which the blast fatalities would not exceed 20 million. As usual, the problems assume perfect fallout and fire protection for those not in blast areas and that 100% of the urban population gets sheltered. The program costs for these examples are shown to be about 16, 18, and 30 billion dollars respectively.

Possible Errors in Using the Model

1. The linear approximation, $P = 150\ \rho/\beta$ as was pointed out, was an intermediate choice between the optimum airburst and surface burst conditions (see Figure 2). A somewhat more conservative choice would have been the relationship $P = 160\ \rho/\beta$. However, this would have increased the over-all costs shown in Table 4 by no more than 3%.

2. The error in the total program cost will be directly proportional to errors in estimating the cost of shelters. We have previously given a justification for the formula used and hope that this matter can be clarified by further research. As mentioned earlier, a paper supporting use of the formula, $C = 50 + 20\ P^{1/2}$, has been published (see Ref. 7).

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* $\ll$ means much less than.

3. The results are clearly sensitive to the distribution of urban population in the U.S., although from the existing data it is clearly concentrated in the range of 2-8 thousand per square mile. An effort is underway to obtain a more precise distribution.

4. An important defect in the calculation of the cost of programs using the smaller values of β is the limitation of the 213 urbanized areas. Clearly, when β is only a few thousand per bomb it could become necessary to consider extending the program to smaller towns--towns of the size of about 2β. Consequently, if β was chosen to be 5,000 and the enemy was expected to use bombs of, say, three megatons or more, then some type of shelter program would be involved with all towns of 10,000 people or more. This could increase the number of shelters by perhaps as much as 30 or 40%, although generally in the lower cost shelters.

In these smaller towns or in rural areas where a blast threat may exist another option is to plan tactical warning dispersal to nearby fallout shelters. Also, it seems less likely that small areas would be very desirable targets when one considers that not only the population mortalities but indeed a greater degree of property destruction would be desired by a malevolent enemy. Finally, if the number of these towns is much greater than the number of enemy weapons, a complete blast shelter program may be deemed too costly for the potential returns.

5. Since many cities and towns have a natural capability for a rapid dispersal of the population, some costs might be saved by a policy of installing shelters in or beyond the urban fringes. Thus the model may overstate the costs which would be estimated in a real program.

6. In these calculations no attempt was made to take into account the possible dual use of shelter facilities as a cost-reduction measure.

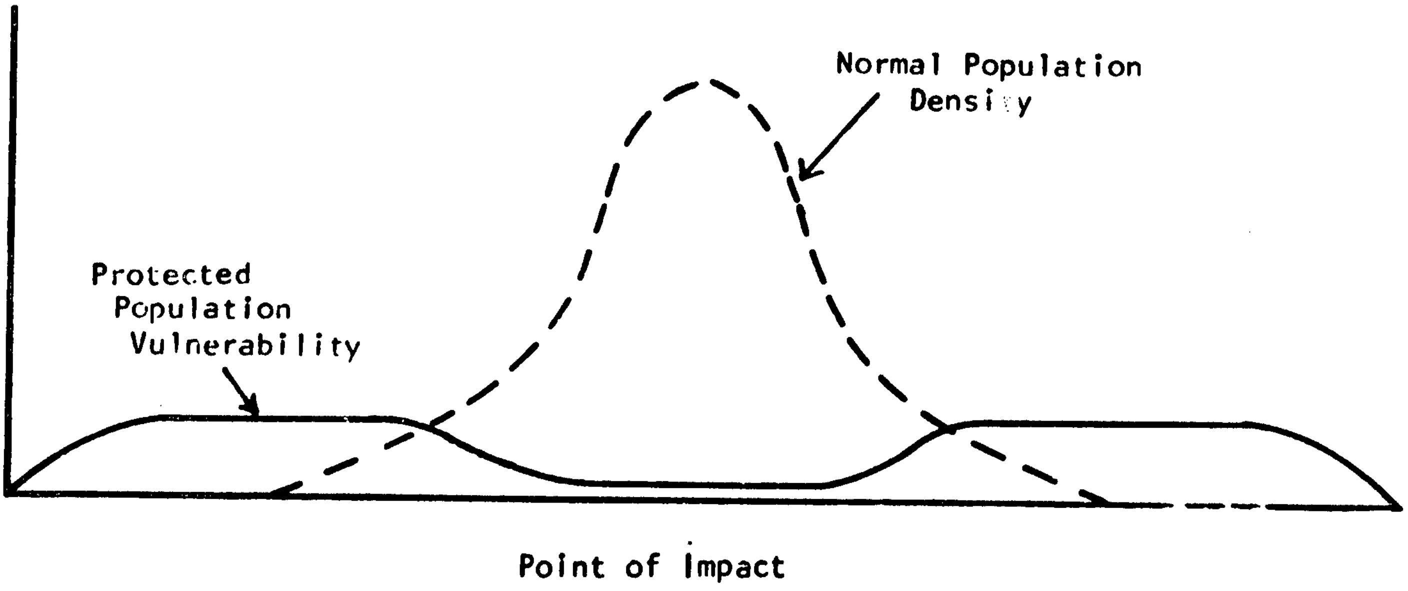
IMPROVING THE MODEL

Suppose through a C. D. blast shelter program we have "flattened" all populated areas to reflect $\beta W^{2/3}$ maximum fatalities per bomb. Then a preferred targeting for a malevolent enemy would be to drop at least one of his weapons on each major populated area, his goal being to maximize property destruction as a bonus to the expected fatalities. He may even have a preference for specific kinds of property (e.g., petroleum, ports, military production, etc.). If we had an acceptable trade-off between lives and property values, as seen by us or the enemy (e.g., suppose he deemed one life equivalent to $20,000 of property), then our sheltering plan could be reoriented to reflect this trade-off. For some designs the population vulnerability might be made relatively smaller than β in areas where property damage is apt to be greater, thus leveling somewhat the combined value of the target to the enemy in terms of people plus property. This approach may only be partially satisfactory, however, because (1) any hypothetical dollar value assigned to a person by us as the enemy's view has a basically large uncertainty, and (2) the great amount of property destruction that a single weapon in the MT range can wreak is often more than can be compensated for by changes in population vulnerability. That is, using arbitrary values of 10^4, or even 10^5 dollars per life, the large central cities are almost always preferred targets, once the population has been protected by a moderate blast shelter program or by an evacuation.

It should be a reasonable judgement that against a highly protected population, $\beta \leqq 5,000$, a malevolent enemy would plan to place at least one bomb on each city in which he can destroy the property as well as the $\beta W^{2/3}$ people, after which he has the option to target population or property with the remainder of his weapons. Because of this consideration the plan for population protection might make the city target somewhat less lucrative by reducing the criteria, β, in the central cities. That is the number of expected casualties can be made less than $\beta W^{2/3}$ by providing either unusually great blast protection or evacuating the centers, or a combination of the two. The vulnerability of population might then appear as shown in the following figure:

FIGURE 7

VULNERABILITY OF A PARTIALLY EVACUATED PROTECTED CITY



As an illustration, consider the following hypothetical plan for a "Gaussian" city of population 1 million whose normal radius (95% of the population) is 8 miles. The original shelter plan was designed to achieve a β of 3,000 and included the dispersal of some people so that after the movement the city would cover a 500 square mile disk (12.6 mile radius). 100 psi shelters were to be uniformly distributed over the disk. The second plan kept the 100 psi shelters but modified the disk into an annulus leaving the first six miles in radius essentially empty. The outer ring of the annulus then had a radius of 14 miles. With this configuration an attacker using a 10 MT weapon has the choice of destroying nearly all of the property but none of the people or some of the property and some of the people by targeting well away from the center of the city.

Clearly another way to give some protection to both the property and the people is by covering the central area with active terminal defense. An effective active defense would reduce the cost of the civil defense portion of a program with a given β. The details of such an over-all defense program would require a reliable way of estimating the cost and effectiveness of active terminal defense measures against the potential threats, one of the difficulties in such a design. The next section discusses one simple-minded way of adding active defense to the over-all defense of the population. More sophisticated approaches will be left for a subsequent study.

Active Defense

1. Assume that we could say that "X" is the fraction of penetrating warheads which could be expected against an area. Then $\beta (X) = \beta / X$ instead of the previous β can become the criterion for designing passive protection. Or suppose a particular β (say, $\beta = 5{,}000$) is a chosen national criterion for blast protection, then if we suppose that there is another limit, $P_{max} = 200$ psi (suitable for $\rho \leq 6{,}700$), defended areas where $\rho > 6{,}700$ can be supplemented by an active defense calculated to permit "X" probability of penetration where $\rho_{av} X = 6{,}700$. For example:

For Manhattan $\rho_{av} \cong 80{,}000$, $\therefore X = \frac{6.7}{80} = .084$ would be required of the active defense.

For N. Y. City $\rho_{av} = 24{,}600$, $\therefore X = \frac{6.7}{24} \cong .27$ would be required of the active defense.

The problem of meeting such requirements for a range of possible attacks would have to be solved by the designers of the active-passive defense system.

Thus active defense can be said to have two protective roles in a shelter-oriented civil defense program:

(1) Reduction of shelter costs and/or dispersal requirements for the protection of people. This is briefly discussed in the above paragraph.

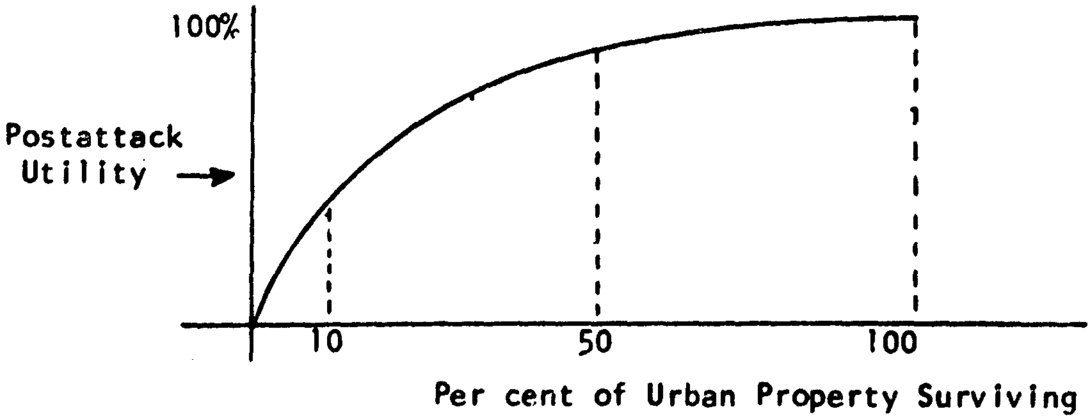
(2) Protection of property. This is our next section.

Protection of Property

Previous portions of this paper have tried to show that surprisingly good protection for population may be feasible by use of blast shelters (and partial dispersal). If, indeed, it is feasible to achieve $\beta \leq$ 2,000 in a C.D. program then, the prospects of using active defense for the same reduction of vulnerability are relatively poor indeed, since its over-all effectiveness in large cities would need to reduce the enemy threat against population by more than a factor of 100 to perform with comparable effectiveness, even assuming the existence of 10 psi shelters in these cities. Currently, no such effectiveness seems to be within reach.

However, the shelter program for protecting the urban people has no parallel capability for protecting urban property, the possible loss of which raises the great question of the viability of the postattack economy. In this context the role of active defense could prove to be crucial. Even a "poor" active defense could save, say, from 5-20% of the urban property in an important subset of the range of possible wars in which a hundred or more weapons are allocated to a countervalue phase.

Consider, for example, a general war which escalates out of a period of prolonged international crises, though neither side "intended it to happen." The first exchanges of the war are directed at military targets only until nearly all the forces on both sides are spent or attrited except the submarine missiles and a few "sick" residual land-based missiles. If these remaining weapons were to be used countervalue, then, in the late sixties and early seventies, we could anticipate the possible destruction of several hundred urban centers, including all the major cities, many of which possibly would have been targeted by only one or two bombs. If now we assume the existence of an ABM defense able to attrit 20-50% of the incoming missiles, we might expect, say, 10-20% of the property within the urban areas to survive undamaged including, perhaps, a few of the 50 largest cities. This surviving property could make a tremendous difference to the country, postattack. Indeed if the utility of urban property postattack were measured against the surviving fraction, the curve would probably have the following kind of form.



The figure indicates, as an illustrative estimate, that the first 10% of the surviving property could be worth as much as the next 90%. On this postattack utility basis then, the over-all effectiveness of an active defense system is much increased even if on the linear basis of probability of killing incoming warheads, the system might look weak or uncertain.

Cost of Dispersed Blast Shelter Programs

The calculations up to this point have all assumed that the population is essentially stationary and that the shelters are built where people normally reside (except possibly for the overflow where we relocate people from areas where it is undesirable to build shelters of the required quality, and we use a partial dispersal to avoid creating preferred targets). We now wish to estimate the vulnerability of the population and the cost of three alternative designs which increasingly utilize the option of movement to dispersed blast shelters.

By arbitrary assumption,[1] our model permits the maximum of an 80% movement from any locality in the three cases considered. In Case A, wherever the local population density in an urbanized area is above 4,000, a dispersal is planned which will move the excess people to shelters external to the urbanized area. The population density in the sheltered reception areas will, by assumption, be 4,000 people per square mile, the same as the maximum left in the cities (except in the relatively few instances, however, where the 80% limitation leaves more than a 4,000 density in some areas). Case B will be similar to Case A, except that the cities will be dispersed down to 2,000 per square mile, but not in excess of 80%, and the evacuees will be relocated in the surrounding areas where their density will be 2,000 per square mile. Finally Case C has a similar plan, except that the dispersal is down to a level of 1,000 people per square mile.

To obtain a physical picture of what the relocated population distribution might be for Case C, one can imagine a city of 1 million people which (not atypically) might have an average population density of 6,000 people per square mile (including the urban fringe). After dispersal to shelters, the people have been spread out over an area about 6 times its former size, an area of 1,000 square miles, which is equivalent to a disk about 18 miles in radius.

Table 5 shows the density distribution of people from the 213 urbanized areas after the assumed dispersal has been completed for each of the three cases above. It will be noticed that the maximum density of population becomes 16,000 per square mile; it represents Manhattan, 80% evacuated. The Table (based upon the normal distribution assumed in Table 2) shows that the number of people who would be involved in movement in the three cases are approximately 24, 48, and 67 million respectively.

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[1] This is to allow for maintenance of minimum urban operation, recalcitrants, operational blunders, essential industries, etc.

TABLE 5

Population and Density of Urbanized Areas After Dispersal

Density, ρ_i (000)	Population, n_i (millions)		
	Case A	Case B	Case C
16	.4	.4	.4
8	.8	.8	.8
4	60.8	1.2	1.2
3	20.0	.8	.8
2	10.0	88.8	1.2
1.6	---	---	1.4
1.2	---	---	1.6
1.0	4.0	4.0	88.6
$\sum n_i \bar{\rho}_i^{1/2}$	177.2	136.6	102.5
No. of people moved (millions)	24.4	48.4	67.2

Using our previous estimates of costs for shelter spaces, the next table shows the results of the calculation of the program cost for the 96 million people of the urbanized areas. In each case the cost is calculated for a number of values of the vulnerability criterion, β, varying from 1,000 to 40,000. The total cost is taken from the formula:

$$T = 4800 + \frac{245}{\beta^{1/2}} \sum_i n_i \bar{\rho}_i^{1/2}$$

TABLE 6

Estimated Cost of Dispersed Blast Shelters for 213 Urbanized Areas (96,000,000 people)

β (000)	Total Cost in Billions of Dollars		
	Case A	Case B	Case C
1	48.2	38.3	29.9
2	35.4	28.5	22.5
3	29.8	24.1	19.3
5	24.2	19.8	16.0
10	18.5	15.4	12.7
20	14.5	12.4	10.4
40	11.7	10.1	8.8

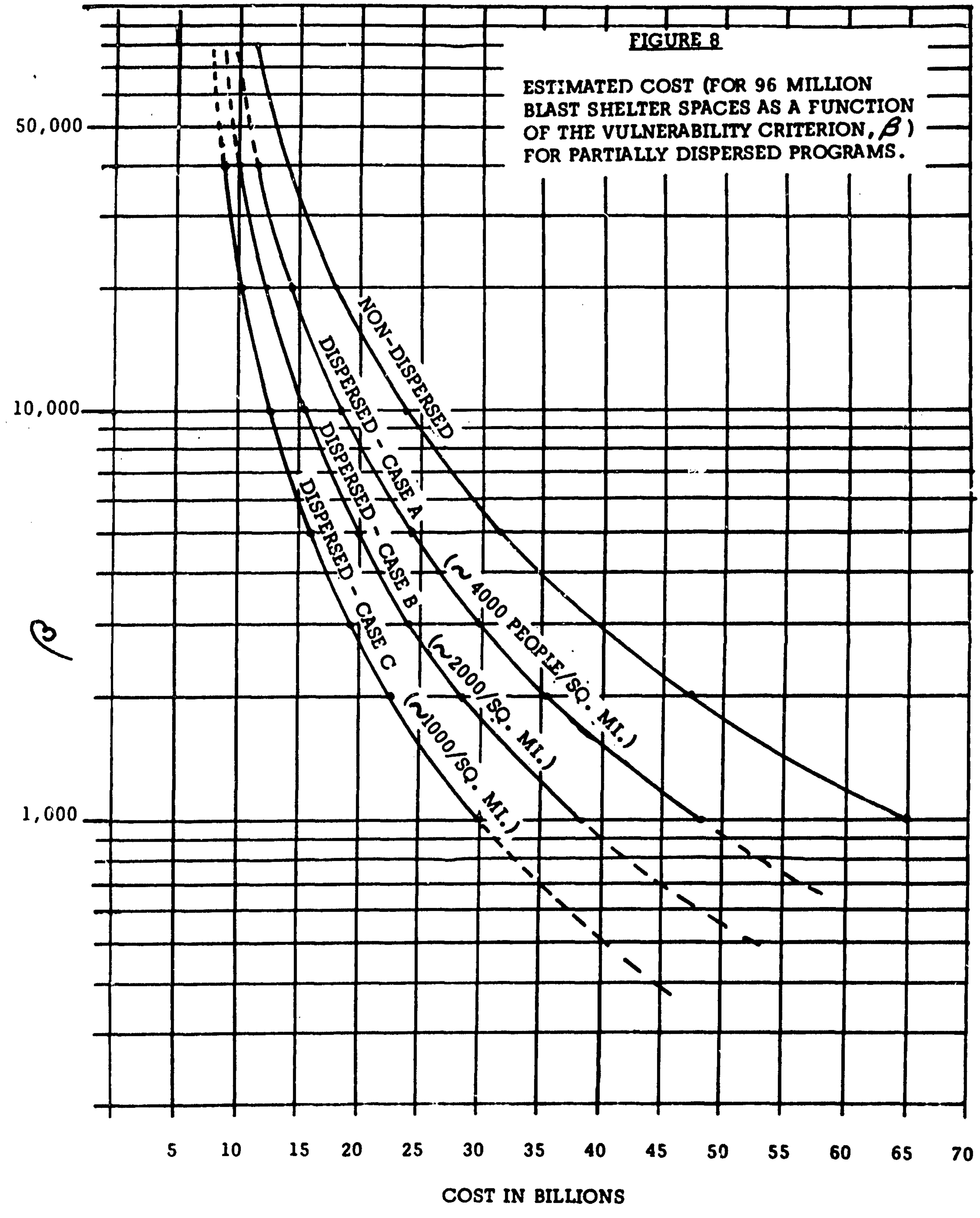

FIGURE 8

ESTIMATED COST (FOR 96 MILLION BLAST SHELTER SPACES AS A FUNCTION OF THE VULNERABILITY CRITERION, β) FOR PARTIALLY DISPERSED PROGRAMS.

It will be noticed from Table 6 (or better from Figure 8) that for a program of a given cost the vulnerability estimate is decreased by about a factor of 3 over the earlier case (Table 4) by dispersing down to a level of 2,000 people per square mile, or is reduced by about a factor of 5 by dispersing to 1,000 people per square mile (each case with the local limit of 80% evacuation).

Also, as Table 6 or Figure 8 show, some "very respectable" programs (β = 5,000 to 10,000) can be achieved by use of this dispersal technique for the relatively "small" budgets of 12 to 16 billion dollars. The strategic justification for the feasibility of planning protective action requiring partial dispersal has been argued elsewhere (Ref. 3,4) and will continue to be examined by the Institute.

Overcrowding Options

The curves shown in Figures 5 and 8 thus indicate the costs and the degree of blast protection which can be achieved by utilizing a blast shelter oriented civil defense program. Even these numbers can be improved substantially (by a factor of 2 or more) by sacrificing some "comfort." This could follow if the shelters which have been described and for which the costs have been estimated are in some sense unnecessarily "luxurious" (or insufficiently austere) in concept. For example, the space generally allotted in shelters, depending on design, has ranged from 7 1/2 to 10 square feet per person. A current paper (Reference 8) attempts to show that the space requirements assumed in these estimates can easily be reduced 50% and in some cases even more, without taking any undue risks with the survivability of the occupants. That is, if we were willing to tolerate a degree of "over-crowdedness" which might be unpleasant (but not lethal), then we could cut the cost per shelter space by a factor of 2 or more. Again, stated the other way, assuming a given budget, it would be possible to achieve a much greater degree of protection by planning a smaller space per person. As an example, if one asked what degree of protection could be achieved in the urbanized areas with $10 billion, one could start with the maximum dispersal posture, Case C of Figure 8, which has a Beta of 21,000. But planning to use an over-crowding option with this same budget would permit the construction of only half as many (or even fewer) higher quality shelters, and thus could achieve the lower vulnerability of a $20 billion program (or more), which is a Beta of 2,800 (or less). Finally, the effectiveness of a $10 billion dispersed and overcrowded design can offer more blast protection than the $40 billion program shown in Figure 5 (which has a vulnerability criterion of 3,000).

Figure 9 compares the performance of two overcrowded programs with two of the non-overcrowded ones of Figure 8. It was assumed in preparing this figure that 5 people can crowd into the space normally allocated for 2 with no significant increase in cost. (See reference 8.)

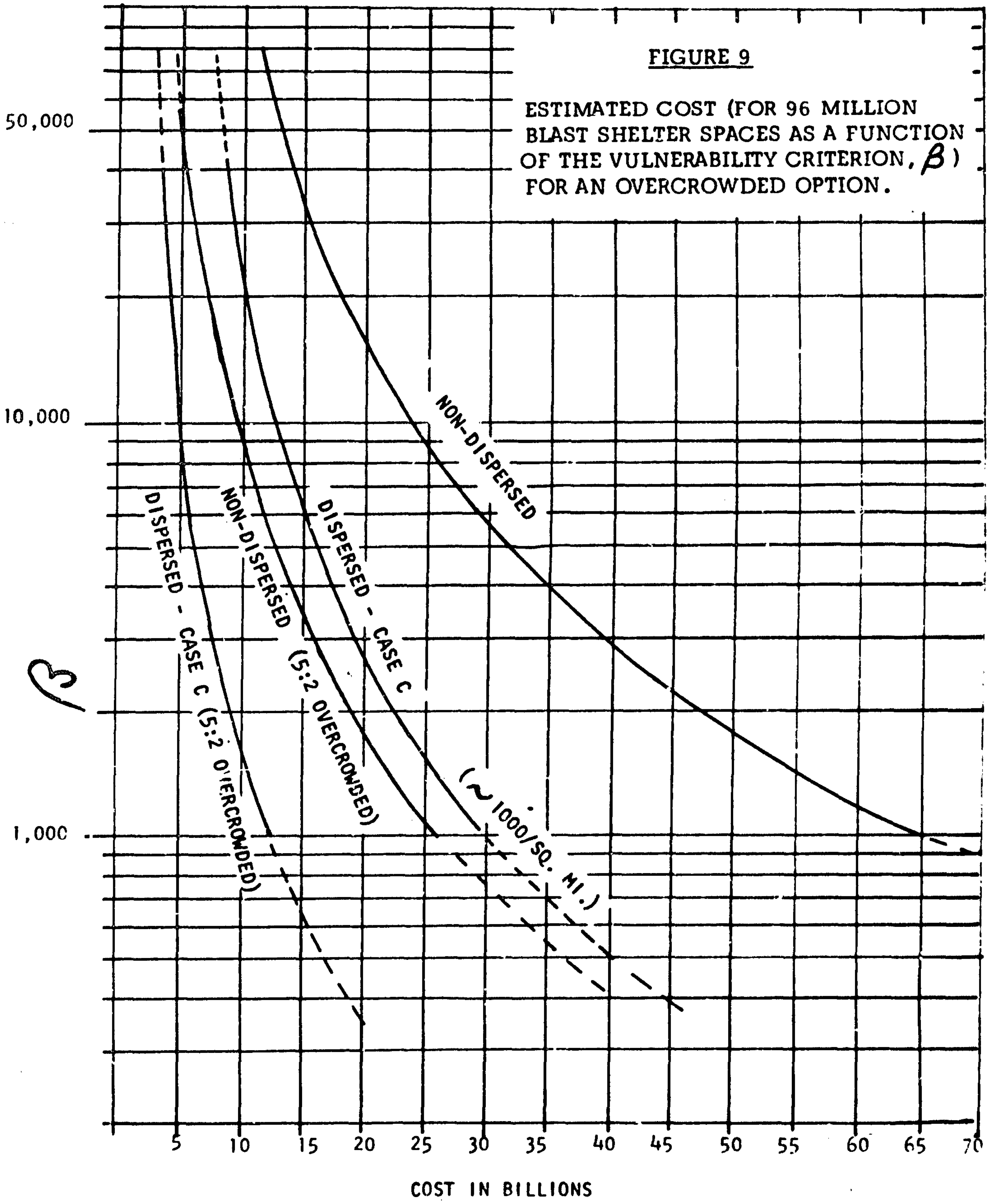

FIGURE 9

ESTIMATED COST (FOR 96 MILLION BLAST SHELTER SPACES AS A FUNCTION OF THE VULNERABILITY CRITERION, β) FOR AN OVERCROWDED OPTION.

CONCLUSIONS

1. Within the limitations of the model described, this report argues that a blast shelter program can be constructed which will provide very substantial protection for the U.S. population against moderate or even large nuclear attacks (1,000 to 10,000 MT) directed against population centers.

2. For the same cost of shelters, the blast vulnerability can be decreased by a factor of 5 by urban dispersal to a density of 1,000 per square mile or by a factor of about 3.5 by a dispersal to a density of 2,000 per square mile.

3. For the same cost, reductions in vulnerability up to about a factor of 5 seem available by "overcrowding" the shelters, i.e. changing the allowable space allotment to approximately 3 or 4 square feet per person.

4. The shelter costs of such programs are in the range of 5-40 billion dollars for nationwide protection involving between 100 and 150 million shelter spaces.

Appendix A

ILLUSTRATIVE PROBLEMS

Alternative Shelter Systems for 96 Million People in 213 Urbanized Areas

Problem 1: Assume threat is 300 10-MT bombs

Case A

Assume maximum mortalities allowable: 40,000,000 or 133,000 per 10-MT bomb. Since $10^{2/3} = 4.65 \therefore \beta = 133{,}000/4.65 = 28{,}800$ and from Table 4, the program cost is approximately 16.0 billion.

Assume \$400 per shelter space is a program limit. Then $P \leq 300$ psi from $C = 50 + 20 P^{1/2}$.

From $P = 150\ \rho/\beta$, 300 psi is sufficient for $\rho \leq 58{,}000$.

$\therefore$ all places except 1/4 of Manhattan ($\sim$1/2 million people) can be sheltered.

Solution:

1) Put 300-psi shelters in Manhattan for 3/4 of Manhattan population. Either leave 1/4 to fate or plan to relocate balance of $\sim$1/2 million Manhattanites.

2) All other shelters are $<$ 210 psi.

3) Saving over the full protection in Manhattan requiring harder ($\sim$400 psi) shelters: $\sim$ 2M (450-396) $\cong$ \$100 Million. (Thus if the cost equation is correct one might ignore the optimization procedure and just put 400-psi shelters in Manhattan.)

4) Total program cost $\cong$ \$15.9 billion (\$16.0 billion if 400-psi shelters in Manhattan).

5) If we wish to rely on the assumptions, then the cost is overstated, since urban centers whose populations are less than 133,000 would need no blast shelters (est., 10 million people and about \$1.3 billion).

Case B

Assume $\alpha \leqq \$250$ (100-psi shelters)

1) 100-psi shelters are sufficient for population densities of 20,000 or less, which is everywhere except Manhattan, Brooklyn, Bronx, and possibly central parts of a few eastern cities such as Chicago and Philadelphia. Roughly 3-1/2 M people would need to be relocated or left to fate (see Table 3).

2) Program cost with relocation to 100-psi shelters will be as above with a saving of about $2 \times (400-250) + 4\,(330-250) \cong \$600$ million. Therefore total cost $\cong \$15.3$ billion.

3) Cost is again overstated by about $1.3 billion for reason given in Case A, that $\sim$ 10M people in smaller urbanized area would require no sheltering.

Problem 2: Assume 1000 3-MT bombs, @ maximum fatalities allowable 40,000/bomb $\therefore\ \beta \cong 20{,}000$.

Case A: Assume $\alpha = \$400 \rightarrow P \leqq 300$ psi

1) This is adequate for $\rho \leqq 40{,}000$, for all of U.S. except 1 M Manhattanites (presumed relocated to $400 shelters in urban fringe). Saving in Manhattan is $2 \times (550-400) = \$300$ million.

2) $\therefore$ program cost (see Table 4) is $18.2 - .3 = \$17.9$ billion.

Case B: Assume $\alpha = \$250 \rightarrow P \leqq 100$ psi

1) This is adequate for $\rho \leqq 13{,}300$

2) From Table 3, number of people above 13,300 density $\cong$ 7 million.

Variation #1: Relocate the above "n" people to 100-psi shelters. Using equation (4) and modifying Table 3 to reflect the relocation, we obtain the total cost,

$$T = 4800 + (45/(20)^{1/2}) \times 223 = 4.8 + 12.2 = \$17.0 \text{ billion}$$

This shows a savings of about 0.9 billion over Case A, if suburban shelters are built for the 7 million people.

<u>Variation #2</u>: Leave n people to fate. Then (assuming $n = 7$ million)

a) The attack will have $40 + n = 47$ million mortalities
b) Costs saved $= 7 \times 250 = \$1.7B$
c) Program cost is \$15.3B.

<u>Variation #3</u>: Leave n people to fate, but decrease β to 16,000 (or 33,000 3-MT bombs) and buy shelters up to $\beta \leqq 13{,}300$, thereby maintaining 40 million maximum fatalities.

a) Maximum $P = 125$ psi (at $\rho = 13{,}300$)
b) Program cost $T = 4000 + 245 \times (174/(13.3)^{1/2}) \cong \$16.5B$

This is a savings of \$.5B over Variation #1.

Problem 3: <u>Assume 9,000 MT attack (900 10-MT bombs)</u>

Criterion: 20 M casualties $\longrightarrow$ 22,000/10-MT bomb, $\therefore \beta \cong 5{,}000$.
Program cost with no α limit is \$31.6B (see Table 4).

Assume: $\alpha = \$475$, then $P \leqq 450$ psi.

1) Shelters available for all $\rho \leqq 15{,}000$; therefore shelters can be constructed for all except ~ 5.6 million people out of a total of 12 million in the most congested metropolitan centers.

2) Relocate the 5.6 million above to suburban shelters at \$475 per space.

3) Program cost $= 31.6 - 8.3 + 5.7 = \$28.0B$.

(Where 8.3 billion is cost of shelters for 12 million people in the most dense areas, if no α-limit exists.)

Appendix B

LINEAR COST FUNCTIONS

Figure 3 shows that certain alternative cost estimates on a linear scale might have been used for estimating the cost of individual shelter spaces. While it is our judgment that these linear relationships are generally less satisfactory than the chosen square root curve, especially at either the low-cost end or the high-cost end, nevertheless it might be useful to make a comparison of national program costs based upon these curves.

The general linear relationship for cost per shelter space is given by the equation:

$$\begin{aligned} C &= A + bp \\ &= A + b\,(150\,\rho/\beta) \end{aligned}$$

The relationship for the cost of a national program involving only the 213 urbanized areas is given by the equation:

$$T = A\sum_{i} n_i + 150\,b/\beta \sum_{i} n_i\,\rho_i$$

Making use of Table 3 we obtain,

$$\begin{aligned} T &= NA + 150\,b/\beta \sum_{i} n_i\,\rho_i \\ &= NA + 128{,}750\,b/\beta \end{aligned}$$

Using this formula we can now calculate the costs of the programs associated with the five linear curves of Figure 3. These results are given in Table 7 below.

TABLE 7

Program Cost Using Linear Shelter Cost Functions

β	(1)	(2)	(3)	(4)	(5)	(6)
1,000	83.6	102.2	111.0	108.6	139.3	64.8
2,000	51.4	59.8	62.8	76.4	75.0	46.2
3,000	41.2	45.4	46.6	54.9	53.5	39.4
5,000	32.1	34.0	33.7	37.8	36.4	31.6
10,000	25.6	25.4	24.1	24.9	23.5	23.8
20,000	24.3	21.2	19.2	18.4	17.0	18.5
40,000	21.8	19.0	16.8	15.2	13.8	14.3
80,000	20.0	17.9	15.6	13.6	12.2	11.6

(1) $C = 200 + 1/2\ P$

(2) $C = 175 + 2/3\ P$

(3) $C = 150 + 3/4\ P$

(4) $C = 125 + P$

(5) $C = 110 + P$

(6) $C = 50 + 20\sqrt{P}$

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