2 of 3

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FINAL REPORT

OVERCROWDING POTENTIAL

By

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HI-361-RR/4 June 11, 1964

30 p #2.00 hc
#0.50 mf

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

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TABLE OF CONTENTS

Page

Summary . . . ii

Introduction . . . 1

Some Background . . . 1

Implications . . . 2

An Example of Overcrowding Performance . . . 4

Ventilation and Heat Dissipation . . . 13
- A. Ventilation and Closure Capability . . . 13
- B. Heat Dissipation for Extended Occupancy . . . 18
- C. Water . . . 21

Conclusions . . . 23

References . . . 25

LIST OF TABLES

Table

1 Area Allocations . . . 5

2 Example of Occupancy Performance . . . 11

3 Typical Environmental Data . . . 19

4 Atlanta, Georgia (1960 Data) . . . 20

5 Overcrowding Performance (Environmental) . . . 20

6 Well Water Use . . . 22

LIST OF FIGURES

Figure

1 Anthropometric Data . . . 6

2 1,000-Person Shelter (Nominal Capacity) . . . 7

3 Free-Standing Bunk (5-High Version) . . . 8

4 Free-Standing Bunk (5-High Version) . . . 9

5 Bunk Crowding . . . 12

6 Possible Scheme for Overloading Bunk System . . . 12

7 Closure Performance - Surface Area Per Occupant vs. ΔT (Shelter Air Temperature minus Soil Temperature) . . . 17

OVERCROWDING POTENTIAL

Introduction

Almost all of our contemporary research in the fields of active-passive defense, arms control, and other areas involving defense posture requires cost and performance data for blast and fallout shelters. Many research projects (especially those concerned with designing and optimizing active-passive defense programs) require such data in detail (cost vs. hardness, time to construct, etc.) and the results often turn out to be very sensitive to variations in the basic data.

This paper will present some thoughts and conclusions of a limited investigation of one facet of shelter performance (and dependent cost variations). This is habitability or "overcrowding" potential (our synonym as used herein) and is an arbitrary performance parameter which denotes the possibilities of using shelter space and utilities beyond their "normal" capabilities. Thus, for a shelter designed for 1,000 persons, we will say that it can accommodate 1,500 persons, or have an overcrowding potential of 50% if--and then say something about requirements or performance at this level of occupancy.

It should be noted that the entire subject of shelter habitability requirements is still somewhat controversial, especially with regard to the amount of space that _must_ be allotted to each shelter occupant. In terms of survival, it is known from privation experience with people in slave ships, concentration camps, and the like, that people can survive very crowded conditions. Of course, we do not propose that shelter living would or should be that harsh. We do propose that as long as adequate shelter is not available, serious consideration be given to the potential of shelter crowding as a life-saving expedient up to (and even beyond) the point of severe discomfort.

Some Background

The recent history of space allocations in civil defense studies is interesting in terms of the changing attitudes about habitability. In a Panero study to OCDM completed in January 1959,[1] for a shelter nominally rated for 1,728 persons, the following variations are given:

Type of Occupancy	Area Allocated/Person
Comfortable	21 square feet
Standard	14 square feet
Overcrowded	9.5 square feet

Quoting from their final report:

> The comfortable spacing allows sit-up conditions for the occupants of bunks. Standard occupancy provides cramped sit-up conditions. Overcrowded is based on the minimum spacing

permitted on troop ships and also implies the use of practically the whole shelter area for sleeping.*

A USNRDL report dated 6 October 1959[2] includes the following:

> Most shelter cost estimates have assumed an arbitrary space allocation of about 10 to 12 sq. ft. per person. This amount of space can provide reasonable living conditions for an extended occupancy if some ingenuity in outfitting the shelter is exercised....compared with a current OCDM recommendation to provide at least 12.5 sq. ft. (per person).

An occupancy study in a simulated shelter conducted by the American Institute for Research in 1960[3] concluded:

> Although no precise conclusions can be drawn from the informal 20-hour test with 5.9 (sq. ft.) and 42.8 cubic feet per occupant, the consensus of participants and observers was that the capacity for a manageable group had not been reached but was being approached.

A recent occupancy study conducted by the University of Georgia[4] allotted 8 square feet of bare space per person (no bunks or seats) and concluded this to be sufficient for a two-week stay. A shorter test using children was run at 6 square feet per child. This was also deemed adequate.

And finally, a recent Panero report[5] shows an arch configuration arranged to provide bunking or seating for everyone, plus utilities (toilets and storage area), for a gross area of 4.9 square feet per person.

Albeit these examples are too few in number to establish a trend towards fixing space allocations, they are representative of the apparent change in thinking about adequacy. Today, most shelter designers would probably consider the Panero "comfortable" type of occupancy extravagant and even the "standard" type very adequate indeed.

Implications

In calculating the over-all cost of shelter systems, costs are usually assigned on a per capita basis for structural and entrance items, environmental control, sanitation, water, habitability items and, in some cases, carbon dioxide absorption and oxygen systems for possible button-up conditions. Generally, the costs assigned for structural and entrance items are by far the largest and increase as the strength (psi rating) of the shelter increases.

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*Our underlining, to emphasize that the prudent design and the use of furniture (bunks) as currently proposed reduces the impact of such statements. Also, people aren't like troops.

Of course, the structural cost allotted per person is directly dependent on the amount of space or, for some configurations, the amount of volume that is believed sufficient to house the shelterees for a particular time period. The amount of space presently being allotted per person varies from about 10 square feet for current fallout programs, to as low as 7-1/2 square feet for high-quality blast shelters The fraction of the over-all cost that this space represents varies according to the hardness of the structure. This is estimated at somewhere around 50% of the total shelter cost for 10-psi shelters, and roughly 60-70% for 30-psi structures. At 200-300 psi, it may be 75% or more of the total cost.

The costs of the other items are dependent upon other criteria such as shelter stay-time, conditions of temperature both inside and outside the shelter one wishes to design for, the button-up time, and (other) physiological criteria.

Typically, habitability criteria are selected at a high level of confidence. For example, bunk dimensions are based on anthropometric statistics and chosen to exceed the 99th percentile of stature of the adult male population. This might be overdoing the design somewhat since, based on the census data, one would expect at least one-third the shelter population to be children under 14 years of age, and therefore find a goodly portion of the bunking system used below capacity. The same sort of thing comes into play in the selection of optimum headroom, aisle space, distance between tiered bunks, toilet space, door widths, food and water allocations, ventilation equipment, and so on. Thus, in some sense, even the austerely designed shelter has a little "extra" built-in because of the variations in the physiological needs over the entire shelter population.

Beyond deriving space (and cost) savings by accounting for or tailoring to expected requirements,* there is also the possibility of crowding shelters--that is, to the point of putting a strain on the use of space and furniture, on the environmental control system, and on the food and water supply. One might think of doing this for several different reasons. One is that overcrowding may give a fast capability. That is, before all the shelters are built, some fraction will be built; and, if these give a certain minimum acceptable performance, we may indeed have a shelter program. Second, the total blast shelter budget may be limited, in which case one may be willing (or forced) to accept overcrowding. Third, for fixed-budget programs or long-term programs overcrowding may allow the purchase of harder structures which may be very important for their legacy value. Fourth, it might be necessary to plan for overcrowding anyway (at least some shelters) to hedge against short warning times, uncertain population distributions, or errors in system design.

In these connections, there may be some interesting performance possibilities in program phasing. For example, suppose we were interested in providing high-quality protection for, say, 10 million people around counterforce targets and funded a 5-year program to give an average of 30-psi protection. At $160 per space[*] for 30 psi, the total cost is $1.6 billion or $320 million per year. Now, if it is a "normally" designed program, that is, if it is done, finished shelter after finished shelter, it delivers 2,000,000 spaces per year, no more. And, perhaps more important, after 5, 10 or 25 years (if the system is to have some significant lifetime), 30 psi may not be impressive.

---

*Perhaps by building a children's section (small bunks, closer together) or family sections where the children sleep or sit with their parents.

Alternatively, the program might be designed either to get a quicker capability or to get more legacy value or to get both if some overcrowding can be counted on to work. In the first case, it may be possible to plan on tailoring and overcrowding the initial production of shelters to get a significant capability at the end of, say, 2 years (5 people in 2 spaces) and then gradually "uncrowd" them as the program progresses. Or, for maximum legacy value, one might consider buying a much harder program, deliberately planning on overcrowding. Thus, allowing for 5 people in 2 spaces buys 300-psi[**] protection instead of 30 psi. Between these two "extremes" are many other possible programs combining various degrees of overcrowding, hardness, and phasing resulting in different performance levels.

An Example of Overcrowding Performance

Most of the recent work done on overcrowding (including histories of privation situations) has explored and defined the limits of space usage in terms of some physiological thresholds (heat, humidity, water needs, etc.) rather than the limits of using space itself. In some sense, these studies confuse these items. That is, although the environment may well constitute the limiting factors, it might be interesting to address the problem in the following way:

> Given air, water, food, light, and other necessities in abundance and under proper conditions, what performance (in terms of stay-time, health, etc.) might be expected at various levels of shelter loading?

However, lacking such performance data, let us, for the moment, consider the item of space allocation.

Abstractly, there is a limited number of ways for people to use bare shelter space. That is, they may stand, they may sit, or they may lie down. Providing furniture adds two more alternatives, which are sitting on seats and reclining on tiered bunks. Figure 1 roughly shows the amount of floor space and the volume required for the various postures.[*] Using these figures, the area requirements would range from about 14 square feet per person for people in single bunks, down to 1-1/2 square feet per person for standees. Bunking at least four tiers high is more economical than sitting, and tiering bunks nine high is equal to standing.

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[*] Robert A. Krupka, On Shelter Costs, HI-361-RR/3, Harmon-on-Hudson, N.Y.: Hudson Institute, June 11, 1964. $\text{Cost} = \$50 + \$20\sqrt{p}$ where p = psi rating.

[**] This may not be exactly true since additional environmental control equipment may be required to equal the performance of the normal shelter. However, environmental control systems can always be upgraded or increased at reasonable cost. The same cannot be said of 30-psi structures.

As an example of what might be possible in overcrowding a shelter, consider the configuration shown on Figure 2. This configuration is typical of those blast shelters currently thought of as being optimum in terms of size, space allocation, and performance, and is roughly typical in terms of cost.[5] It is a 1,000-person, rectangular, box-type structure made of steel and reinforced concrete. The roof is supported by steel columns, arranged to fit the bunking dimensions. The summary of area allocations is roughly as follows:

TABLE I

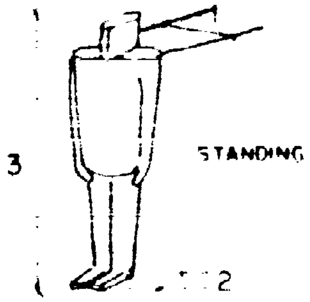
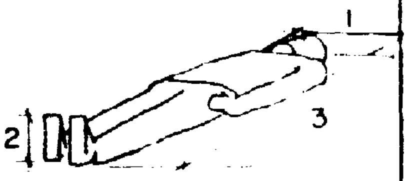
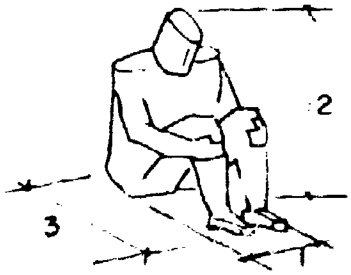
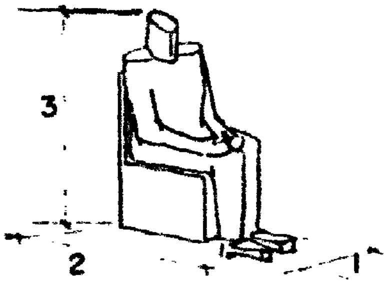
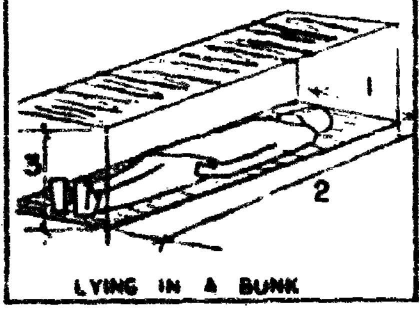
Bunks		3.42
Access Aisles		1.58
Main Aisles		0.74
Toilets and Access Aisles		0.90
Administration		0.50
Mechanical Equipment Room		0.16
Storage		0.13
Miscellaneous Space		0.07
	Total	7.5 square feet per person

This shelter is also arranged for four-high bunking. The bunks are of the dimensions shown in Figure 1, 76 inches long by 26 inches wide, 20 inches between bunks, with 8 inches between the floor and the first bunk. (Total headroom is 88 inches.) The bunking system was selected so that shelterees had the option of lying in their bunks, or sitting on the lower bunk with their feet in the narrow (24-inch) side aisles. The bunking module (8 bunks) is free-standing, demountable, and adjustable to various configurations and spacings between tiers (Figures 3 and 4).[6] Other physical features include:

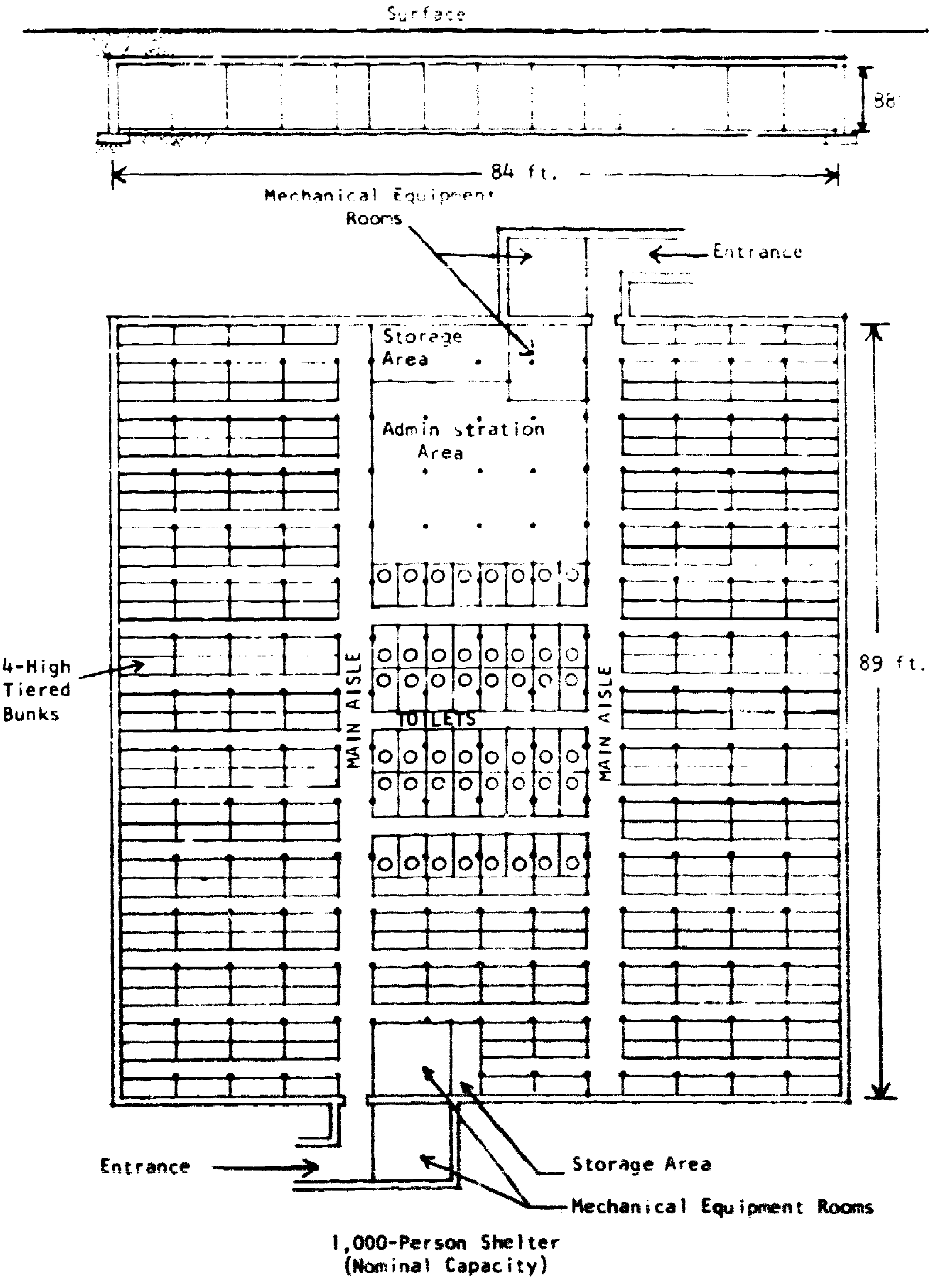
One toilet per 20 persons
Dual entries and closures
4-foot main aisles
Environmental control system
Chemicals for 24-hour closure
Water well

---

[*] These dimensions cover the 99th-plus percentile of the population. The reader is reminded that the "average" requirements for a real shelter population are significantly less than shown.

	DIMENSION NUMBER 1	DIMENSION NUMBER 2	DIMENSION NUMBER 3	SQ FT	CU FT
STANDING 	1.5'	1.0'	6.0'	1.5	9.0
LYING DOWN 	1.5'	1.0'	6.0'	9.0	9.0
SITTING ON FLOOR 	1.5'	3.0'	3.0'	4.5	13.5
SITTING ON BENCH 	1.5'	2.5'	4.5'	3.75	16.875
LYING IN A BUNK 	2.2'	6.3'	1.7'	13.86	23.56

ANTHROPOMETRIC DATA


Surface
88"
84 ft.
Mechanical Equipment Rooms
Entrance
Storage Area
Admin stration Area
4-High Tiered Bunks
MAIN AISLE
TOILETS
MAIN AISLE
89 ft.
Entrance
Storage Area
Mechanical Equipment Rooms

1,000-Person Shelter
(Nominal Capacity)

7.5 sq. ft./person

Figure 2

FREE-STANDING BUNK (5-HIGH VERSION)

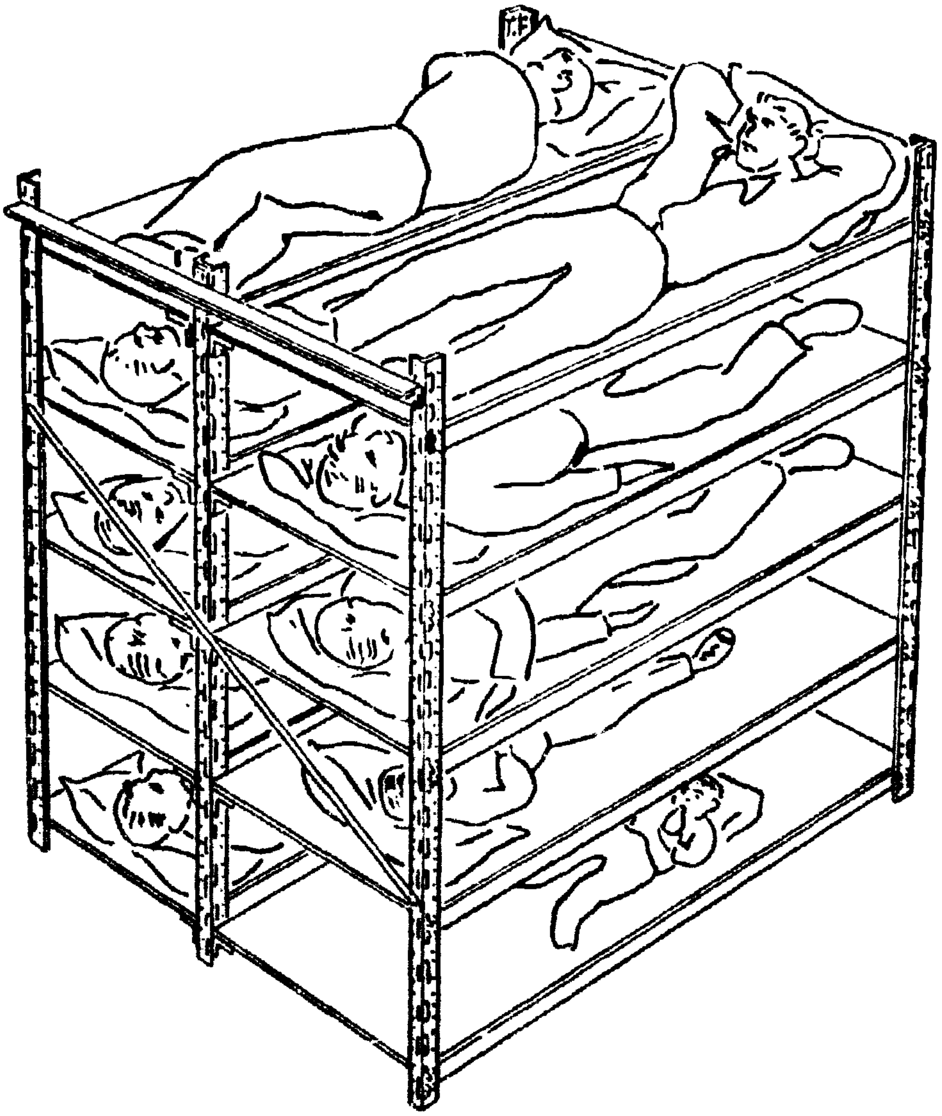
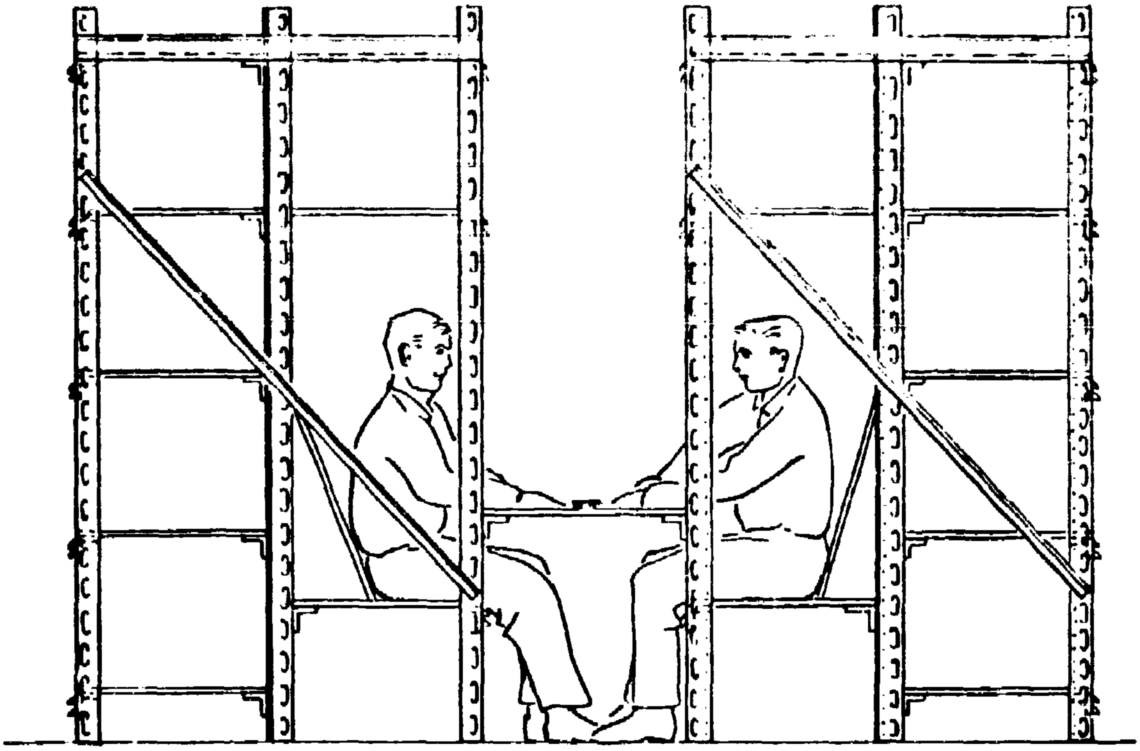
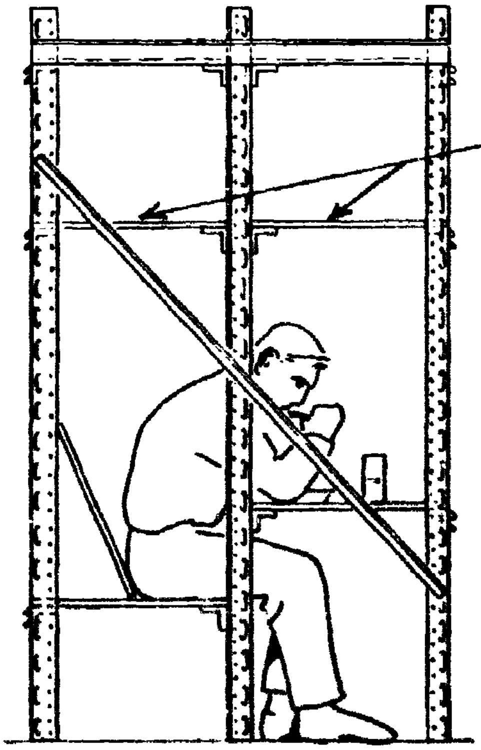


Figure 3

FREE-STANDING BUNK (5-HIGH VERSION)





NOTE: In the 4-high version these are the upper bunks and are available for reclining.

Figure 4

The cost of this unit roughly fits our cost formula of \$50 + \$20$\sqrt{p}$, where p equals the psi rating, at least up to 60 psi. Its minimum hardness (fallout shelter version) is about 5 psi. Summarizing, it has all the requirements of a good shelter and appears to perform well at 7.5 square feet per person.

Let us examine the performance possibilities of this unit at various occupancy levels (refer to Table 2). At normal occupancy, the shelterees and the shelter managers have a variety of options available to them. People may use the bunking system for sleeping or sitting. Some have the option of exercising in the main aisles or in the administration area. The managers can partition the shelter or divide the population into various groups for shift sleeping, eating, etc. The 4-high bunk or seat system does not cause large variations in space usage when hot-bunk shifting schedules are employed.* This, then, is the "normally" loaded condition, ample but not "plush" (10 square feet).

Beyond space allocations for normal occupancy there are other possibilities or overcrowding options. These are shown in Table 2 with performance measured in terms of the postures available to the shelterees. For example, in the normally loaded shelter (column 2), all of the postures shown in the left-hand column are available. As the loading increases, people lose (comfort) options.

The basis for overcrowding this shelter is two-fold. First, even at 7.5 square feet per person there is a lot of floor space available when the bunks are in use. Second, the bunking is conservative and may be used beyond its design point by putting 4 people in 3 bunks or 3 people in 2 bunks (Figure 5) or even 4 adults and children in 2 bunks. And, even for the severely overcrowded options, the individual shelteree is not required to remain in a bunk all of the time or sit all of the time or stand all of the time. He may rotate between positions.

In this example, the overcrowding options use or are made up of one or more of the following postures and related space allocations:

1. Normal bunk use consisting of 8 people reclining or sitting in one module (4 tiers of double bunks, similar to Figure 3).
2. Three people in two bunk spaces. This can be accomplished as shown on Figure 5 or by converting part of the module to seating, crowding 5 people in 4 seats and using the upper bunks (10 people seated, 2 people reclining in bunks, see Figure 4).
3. Four people in two bunk spaces. This might be done by crowding 6 people in 4 seats along the lower bunk (some parents hold their

---

*A recent analysis[5] of hot bunking on various schedules showed that for a 5-high system, area per person increased slightly as the number of bunk shifts per cycle increased. For a 3-high system, the area decreased slightly. For the 4-high system, the area remained practically constant.

TABLE

EXAMPLE OF OCCUPA

	Plush	Normal	
Capacity	750	1000	1
Area/Person	10.0	7.5	
Lay or Sit on Bunks	750	1000	1
3 People in 2 Bunks	---	----	
Double-up in Bunks	---	----	
Sit on Floor	---	----	
Stand	---	----	

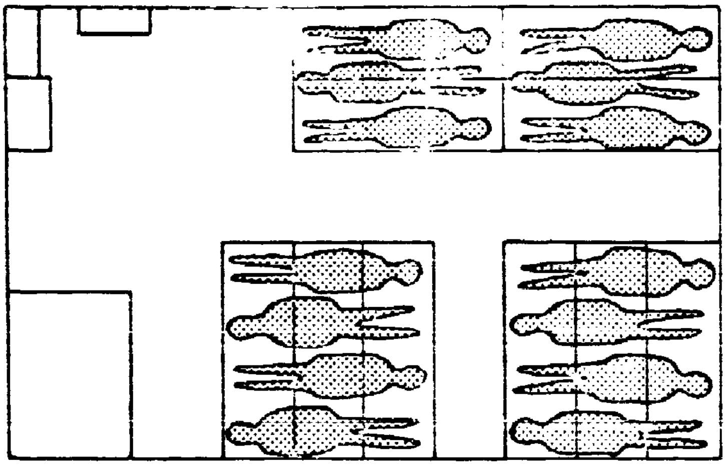
*Adding 20% more bunks by respacing tiers from 2

PERFORMANCE

	Overcrowding Options					
	2	3	4A	4B	5	6
)	2000	2500	3000	3000	3500	4000
)	3.75	3.0	2.5	2.5	2.14	1.88
)	1000	1000	1000	1250*	1000	1250*
)	----	----	----	----	----	----
·	1000	1000	1000	1250*	1000	1250*
·	----	500	~250	500	----	----
·	----	----	~750	---	1500	1500

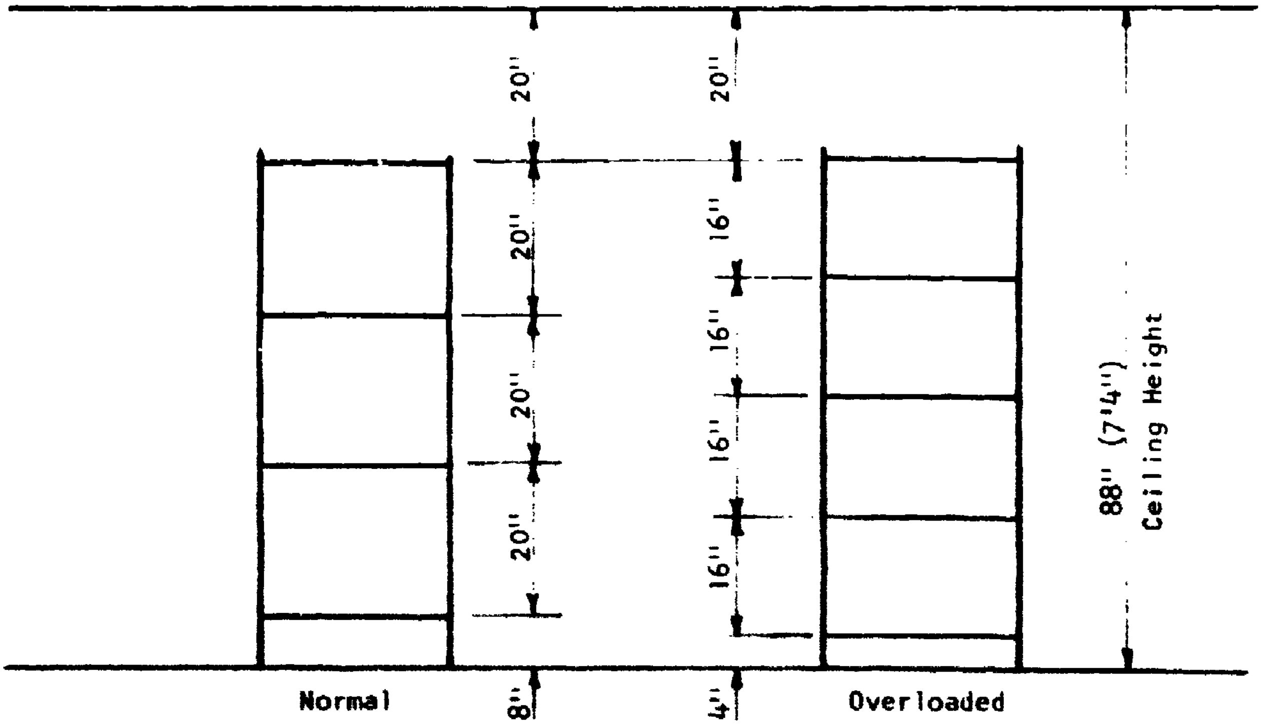
short term occupancy

nches to 16 inches.



BUNK CROWDING[3]

Figure 5


20"
20"
20"
20"
20"
8"
20"
16"
16"
16"
16"
4"
88" (7'4")
Ceiling Height
Normal
Overloaded

POSSIBLE SCHEME FOR OVERLOADING BUNK SYSTEM

Figure 6

children on their laps) and doubling-up in the remaining bunks. There is also a possibility of double-deck seating (16 seats per module).

4. Increasing the bunking module sleeping capacity 25% by respacing the tiers from 20 inches to 16 inches. This might require stocking additional sleeping surfaces and supports (see Figure 6).

5. Sitting on the floor. There is sufficient space in the aisles and administration area to accommodate 500 people at 4.5 square feet per person.

6. Standing on the floor. There is sufficient space for 1,500 people at 1.5 square feet per person.

The options in Table 2 more or less combine these various postures. However, it is difficult to describe the mechanics of using space in so simple a form. Option 2, for example, indicates overloading 100% by doubling-up in the bunks. It could also have shown 500 people next to "3 people in 2 bunks" and 500 people next to "sit on floor."

As we proceed along the options, living presumably becomes grimmer and we probably should not count on long-term occupancy. At option number 6, people are required to stand half the time and jam the bunks the other time. Although this is possible, space-wise, such overcrowding might require a reasonable stay-time of, say, not more than a day or two. And possibly the other options which require people to stand should also be considered relatively short-term occupancy solutions.

Because of this, it might be more realistic to back off from 1.88 square feet to option 3 (3.0 square feet) or option 4B (2.5 square feet) which appear to have a good chance of working, since, at least, no one is required to stand.

Ventilation and Heat Dissipation

Much of the research work concerned with overcrowding possibilities has been directed at establishing shelter tolerance limits in terms of oxygen and carbon dioxide concentrations and the thermal environment. This is done because it appears that physiological stress rather than psychological stress is more important in determining performance during the shelter period. And these environmental parameters largely determine the level of physiological stress.

A. Ventilation and Closure Capability

Several physiological studies have indicated that concentrations of oxygen and carbon dioxide in shelter environments should be limited to not less than about 17% and not more than about 3% by volume respectively. These studies also indicate that the O_2 limit is not as critical as the

CO_2 limit in terms of damaging pathological changes. Dunlap[7] suggests that 11-12% O_2 and 3-5% CO_2 are critical limits for prolonged exposure beyond which "widespread crisis" would be likely to occur.

The minimum ventilating rate required to maintain 3% CO_2 is about half a cubic foot of outside air per minute per person. Current OCD design practice calls for a minimum of 3 cfm/person, which corresponds to a terminal concentration of about 0.5% CO_2. Oxygen concentration is not critical at these rates. Thus, normally designed ventilating systems have an overload capacity of up to 6 times the nominal shelter population.

High-quality shelter designs may also include a "button-up" capability* by providing a source of oxygen and chemicals to remove carbon dioxide. The cost of these materials and the appurtenant items for their use varies almost directly with the shelter population and the closure time. Current systems are usually designed for 24 hours and cost between $10 and $15 per person.[8]

Although one can provide chemicals for any length of time for any number of shelterees, the limitation in closure time is usually determined by the shelter's heat-dissipating capacity. For underground structures, the mechanism for heat transfer is, in a sense, passive** and is a function of a variety of parameters such as shelter shape, wall area, initial soil (and shelter) temperature, soil diffusivity and conductivity (type of soil), and the film coefficient of heat transfer at the inside walls. And, given these parameters and the shelter loading, closure performance depends upon the metabolic heat rate and the maximum allowable air temperature.

Heat calculations involving the human body usually assume about 400 BTU/hour*** given off by a body at rest. For very little or "moderate" activity this might be 500 BTU/hour. On the low side, it has been shown that for very inactive groups the metabolic rate might be as low as 300-320 BTU/hour.[9]

The temperature criterion in shelter environmental calculations is normally measured in terms of effective temperature which is an empirical sensory index involving dry-bulb temperature, humidity, and air velocity.

---

*As a countermeasure against firestorms or gross contamination of the ventilating system.

**It may be possible, even for the firestorm case, to design electrically powered well-water cooled systems for this purpose. Although severe fires may increase outside air temperatures as high as 2100°F, sufficient oxygen may remain to allow engine-generators to function, albeit at reduced power (like derating for high altitudes). Temperatures may be reduced by installing cooling coils upstream of engine air intake.

***1 BTU/hour is roughly equivalent to 1/4 Kg Calorie/hour.

An effective temperature of 85°F is a currently used threshold value above which deep body temperature would be expected to rise (and therefore irrecoverable pathological changes to occur).[10] In the button-up situation, effective temperature is probably equal to dry-bulb (air temperature, since the shelter air is likely to become saturated with water vapor (100% humidity). In recent tests,[9] the Navy considers effective temperature to be a valid measure of human physiological response to heat except in predicting water needs.*

Without going into all of the mathematics involved and the test data accumulated over the past two or three years, it seems that if soil conditions are ideal (wet, sandy, compact soils), and the soil is maintained at about 55°F, an effective temperature of 85°F will not be exceeded in 24 hours if the shelter provides about 35 square feet of wall surface per occupant. This also assumes a metabolic rate of 500 BTU/hour/person.

The shelter configuration providing this much surface area per occupant will necessarily be minimum in cross-section, unlike the rectangular structure used as an example herein. That structure allows only 18-19 square feet of surface area; and, since the time-temperature rise relationship is not proportional** to surface area, the time to reach 85°F effective temperature is much less than 18/35 times 24 hours. It is likely to be less than 4 hours. Although we include the cost of the O_2-CO_2 chemicals for 24 hours, it is apparent that additional means for heat dissipation are necessary and/or the design criteria must change. However, assuming that heat transfer to the soil is the only means available for heat dissipation and the physiological limitations are fixed, we may be willing to pay for a small cross-section (if additional cost is, in fact incurred) to have the capability.

Now let us examine other possibilities. First, there is the matter of allowable temperature. Although 85°F effective temperature may be a good limit for long time periods, there is evidence that 90° E.T. or slightly higher may be acceptable for short periods. Dunlap[7] suggests that 90-94°F represents a range of critical limits beyond which a "widespread crisis"*** is likely to occur.

Second, let us consider metabolic rate. The Navy tests show that for extremely inactive people (and in hot, crowded shelters they are likely to be), the heat output drops to 320-300 BTU/hour.

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*Water needs are discussed further in following sections.

**Time-temperature histories (calculated and tested) show rapid rise during the first few hours of closure and gradual tapering off thereafter. Typically, for shelters starting at 55°F and designed for a maximum of 85°F at 24 hours, roughly 3/4 of the allowable temperature rise occurs within 4 hours or less.

***Not defined.

Third, there are possibilities of precooling the shelter by running the environmental control system either periodically or perhaps continuously during the prewar period. We might also consider freezing the soil within a few feet of the shelter walls.

Fourth, it may be economically feasible to condition the soil during construction to obtain better heat transfer characteristics.

Fifth, 24-hour closure is apt to be two to four times greater than necessary in nearly all shelters. Therefore, the closure time requirement may be reduced to, say, 8-12 hours. While not resulting in significantly lower end temperatures, shorter closure times may allow exposure to higher temperatures.

Sixth, we might furnish the shelter with some manually operated devices for stirring the air* to reduce effective temperature, eliminate CO_2 pockets, and increase heat transfer by increasing the surface film conductance. Of course, this would be done at the expense of increasing the metabolic rate but might produce some net benefits.

With all of these working favorably, then, we might have an allowable E.T. of 90°F, a soil temperature of, say, 40°F, and a metabolic rate of 320 BTU/hour/person. Roughly speaking, these parameters vary in the following way for a given closure time: the change in the difference between soil and air temperature is proportional to the rate at which heat is liberated. The variation in this temperature difference versus surface area is non-linear and can be described by the curve shown on Figure 7. With this information it is now possible to approximate performance under overcrowded conditions for a minimum cross-section configuration and for the large rectangular shape. Consider the following:

1. With a soil temperature of 55°F, and using a metabolic rate of 320 BTU/hour/person, what is the maximum 24-hour temperature for the small cross-section loaded to 2 times capacity? From Figure 7 the ΔT at 35/2 = 17.5 sq. ft. is about 54°F for 500 BTU/hour. At 320 BTU/hour, $\Delta T = 320/500 \times 54 = 35$°F and the final temperature = 55 + 35 = 90°F.

2. The same situation except with a soil temperature of 40°F and a rate of 500 BTU/hour. Then $T_f = 40 + 54 = 94$°F.

3. Using the same shelter, but loaded to 3 times capacity (if this is possible for the configuration), assuming 40°F soil temperature and 320 BTU/hour. For 35/3 = 11.7 sq. ft., $\Delta T_{500} \cong 80$°F. At 320 BTU/hour, $\Delta T = 80 \times 320/500 = 51$°F and $T_f = 40 + 51 = 91$°F.

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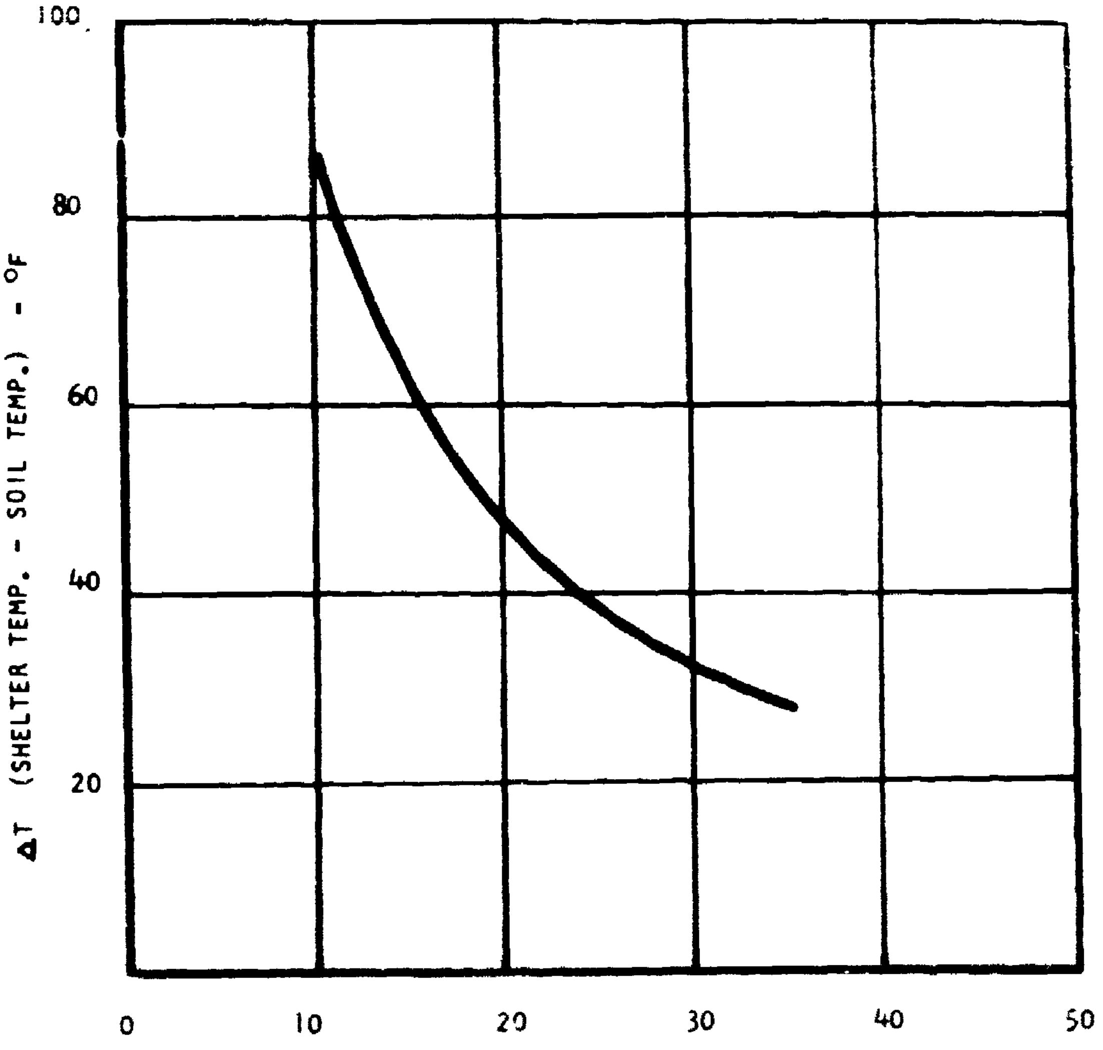
*Hand fans or something like an Indian punkah.



SURFACE AREA PER PERSON SQ. FT.

24 - Hour Closure Performance
500 BTU/Hr/Occupant
Excellent Soil Conditions

Figure 7

4. For the large, rectangular structure, normally loaded (7.5 sq. ft. per person floor area, 15.3 sq. ft. per person wall area), what is the final temperature for $T_{soil} = 55^{\circ}F$, and 320 BTU/hour? For 15.3 sq. ft., $\Delta T \cong 61^{\circ}F$ at 500 BTU/hour. ΔT_{320}, then, equals $320/500 \times 60 = 39^{\circ}F$ and $T_f = 55 + 39 = 94^{\circ}F$.

5. Similarly, for this structure what is the maximum loading if $T_{soil} = 40^{\circ}F$, $Q_{met.} = 320$ BTU/hour, and the E.T. is allowed to reach $94^{\circ}F$? $\Delta T_{500} = 500/320 \times 54 = 84^{\circ}F$.

   From Figure 7, 84°F corresponds to about 11 sq. ft. surface area/person. The maximum overload for 24 hours is, then, 15.3/11 or about 40%.

Although these computations are really too coarse for planning purposes, the order-of-magnitude comparisons are fairly good indications of benefits obtainable from planning (i.e., engineering-wise, to have the precooling capability; and management-wise, to keep people quiet, lowering the number of BTU's produced). This idea applies to all shelter configurations. For a minimum cross-section, good planning may allow for severe overcrowding. For a conventional structure, it may afford a substantial closure capability where, in fact, little appeared to exist. Or from another viewpoint, planning increases the performance/cost ratio.

B. Heat Dissipation for Extended Occupancy

Although an adequate supply of ventilating air (or chemicals) constitutes a basic requirement for shelter habitability, providing for heat dissipation over an extended time period is the overriding cost and performance factor. For a period of several days shelter time, it appears impractical to design an underground building to eliminate all the heat through the walls. The reasons for this are, first, that the cost of additional surface area is more than the cost of cooling equipment. Second, it may not work in a large part of the country.* Third, without additional means of converting latent (moisture) heat into sensible heat, the shelter will become dripping wet and this may cause physiological problems (if it persists for days). And fourth, it is difficult to predict the psychrometric conditions of an uncontrolled shelter environment over extended time periods.

Normally, shelter designers ignore the effects of the walls and soil when selecting the mechanical equipment. System design is usually based on a minimum of 3 cfm per person ventilating air plus additional ventilation or cooling to maintain 85°F effective temperature.

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*Assuming no precooling, which, at any rate, would require equipment purchase that might as well be a bona fide environmental control system.

The amount of extra air or cooling required depends on the temperature and humidity of the outside air. The exact value of these depends on location and the severity of summertime conditions. Engineers, generally, do not pick the worst recorded values. Rather, they select conditions which have a high probability of not being exceeded during the June through September period. For new shelter designs this is taken at the 5% level, which means that the chosen values have a long history of not being exceeded for more than about 150 hours during the summer* and, practically, this also means 150 hours out of the year. Very few of these hours run consecutively because of weather changes and normal day-night variations. Typical conditions at this level are shown in the following table.

TABLE 3

Location	Dry-Bulb Temp. (°F)	Rel. Hum. (%)
Denver, Hot-Dry	91	20
Austin, Hot-Humid	95	45
Los Angeles, "Mild"	86	45
Average+	90	50

+Roughly countrywide and typical of Chicago and New York 5% design conditions. This would meet the design requirements of about 3/4 of the population.

Cooling techniques can be loosely categorized by the way a system rejects heat. The categories are: (1) by transfer of sensible and latent (water vapor) heat to the outside air; (2) by transfer of sensible heat to water; (3) by the evaporation of water; and (4) combinations of these. The actual system used will vary depending on weather, availability and temperatures of ground or surface water, filtering requirements, cost, and a variety of performance factors. Generally, for high-quality shelters an adequate source of well water appears to be an important shelter asset.

However, for the purposes of determining overcrowding capability, let us examine the performance of a system designed to reject heat to the outside air only. For outside conditions of 90°F dry-bulb and 50% relative humidity and a metabolic rate of about 500 BTU/hour, the system is required to supply about 30 cubic feet per minute of air per person. As mentioned previously, this air quantity is sufficient to maintain 85°F effective temperature for all but 150 hours per year.

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*In a recent study[11] to determine the feasibility of using packaged ventilation units to upgrade identified fallout shelter spaces, a 10% probability level, or 300 hours per year, was used.

To determine the performance of the system for various amounts of overloading, it is useful to have the probability of occurrence of environmental conditions other than at the 5% level (90°F dry-bulb, 75°F wet-bulb). Based upon recent weather bureau data, probabilities for Atlanta, Georgia* are given in the following table.

TABLE 4

Atlanta, Georgia (1960 Data)

Probability of Exceeding Temperatures during the Summer (%)	Number of Hours	Temperatures (°F) D.B.	Temperatures (°F) W.B.	Rel. Hum. (%)
5	150	90.0	75.0	50
10	300	87.5	74.5	55
15	450	85.5	74.0	59
20	600	83.5	73.5	63
25	750	82.5	73.0	64
30	900	81.0	72.5	66
35	1,050	79.5	72.5	68
40	1,200	78.5	72.0	73
45	1,350	77.0	71.5	77
50	1,500	76.0	71.0	79

For the 1,000-person nominally loaded shelter, the maximum outside conditions possible to maintain 85°F effective temperature within the shelter at various overloading options can be computed and matched to Table 4 by trial and error. The results of the computations are shown in Table 5.

TABLE 5

	Normal	Option 1	Option 2	Option 3
Capacity	1000	1500	2000	2500
Sq.Ft./Person	7.5	5.0	3.75	3.0
CFM/Person	30	20	15	12
Maximum Outside Conditions	90 FDB 75 FWB	85 FDB 74 FWB	83 FDB 73 FWB	78 FDB 72 FWB
Hours Exceeded	150	450	750	~1,200
% Hours per Summer Exceeded	5	15	25	40
% Hours per Year Exceeded	1.7	5.1	8.5	13.7

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*Atlanta was selected not only because the 5% design condition is 90, 75, but also because the summertime variations are not as great for many other places. In addition, the combinations of air temperature and humidity shown in Table 4 are the worst possible at any probability level, since the dry-bulb and wet-bulb temperatures do not necessarily coincide, in fact.

Although these computations are rather crude, they give an approximation of the magnitude of performance of contemporary shelter environmental control systems. If it is considered that an enemy's option is not influenced by weather conditions (even in countervalue wars), then the highly overloaded shelter system has a good chance of maintaining survivable environmental conditions--that is, 85% or more of the time.

Even for the remaining 15% or so of the year where survivability may be marginal, we have other "plus" values going for us. It is possible to reduce metabolic rate by keeping people quiet. There may be a little extra "built-in" by dissipating through the walls. We have the possibility of rotating people between the hot and cool shelter areas. In addition, people might become acclimated to short periods of high effective temperatures (90-94 E.T.), especially with sufficient water for drinking and sponging or showering. And lastly, it might prove to be relatively inexpensive during the initial phases of a shelter-building program to provide a little "extra" cooling capacity to handle the possibilities of severe overcrowding.

C. Water

If one were to ask an experienced shelter systems engineer to name one item he would rather have above all others, he would probably say, "A water well." He might qualify his answer in terms of quantity, quality, temperature, and pumping power, but even if all (or any) of these were not optimum for his purposes, he still might vote for the well simply because water is very useful. Beyond supplying needs for consumption, water can be used for heat dissipation, fire protection, decontamination and sanitary purposes; and it need not be potable for such usage. In addition, adequate water, especially well water:

1. fulfills the need for protected sources for blast shelters;
2. is less likely to become contaminated than other large sources, due to natural filtering;
3. can augment or replace other supplies in the postattack period;
4. results in environmental control systems which are least dependent on outside air conditions (i.e., the well water essentially eliminates the problem of selecting design percentile levels);
5. allows use of off-the-shelf equipment (e.g., flush toilets, standard cooling coils, water-cooled engine-generators, water-cooled refrigerant condensers, piping, etc.);
6. may result in significant cost savings for shelter support systems, particularly for environmental control systems which include high-quality filters;
7. permits substantial increases in overcrowding capability.

Current civil defense planning calls for water storage amounting to 3-1/2 gallons per person. Recent studies have recognized the importance of hedging against serious dehydration due to severe shelter environments and have suggested that this be changed to 4 or 5 quarts per day. One study[7] indicates that 6 quarts per day would be required at 90°F E.T. for persons at rest and as much as 12 quarts per day for light activity. Add to this an uncertainty about shelter stay-time and an overcrowding potential, storing water becomes unwieldy and costly. Besides being a poor performer, this system requires checking to make sure the water is there and probably has zero legacy value in the postattack period.

Alternatively, a water well system has more potential at comparable cost. Consider the 1,000-person shelter with stored water in sufficient quantity to allow 1 gallon per day per occupant for 2 weeks or, say, 15,000 gallons total. This would cost roughly $2,000 to $3,000. An equivalent water well would need to produce less than 1 gallon per minute. At 2.5 times the nominal shelter occupancy (2,500 persons) this would be less than 2 gallons per minute. A 1-2 gpm well is a fairly small well, and according to a leading hydrologist* there is better than a 95% chance of getting 1 or 2 gpm anywhere in the country. In most places individual wells produce much more.

Minimum per capita use of ground water is currently about 30 gallons per day. Based on a state-by-state survey,[12] consumption is approximately as shown in the following table:

TABLE 6

% Total Population	Well Water Use (gal/day/person)
29	30-50
32	50-100
18	100-500
19	500-1,000
2	over 1,000

(median 70 gal/day/person)

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*J.J. Geraghty, Water Information Center, Port Washington, L.I., N.Y., personal correspondence. An interesting difference of opinion about finding water has developed during our investigation. We have had occasion to query hydrologists about water wells and hard-rock miners concerning shaft-sinking. Hydrologists are notoriously pessimistic about finding large quantities of water at any given location. The miners, on the other hand, almost unanimously agree that water flow into their "diggings" is their biggest headache. "No matter where we punch a hole in the ground," says R. Budd of the Walsh Construction Company, "we find a couple hundred gallons a minute."

Deleuw, Cather and Company also state in a recent report[13] on deep excavation techniques for shelters: "For the open cut excavation envisioned herein there will be only a limited number of sites where ground water will be located at levels 150 feet or more below the surface of the ground. It will be vitally important...to give priority attention to the matter of water control."

The cost of obtaining sufficient ground water will vary according to depth, and to geological and other local factors. In some places ground water is available under pressure (artesian wells) or at moderate depth which would allow hand pumping. At other sites it might be necessary to drill several hundred feet and install powered pumping equipment.

However, assuming that underground constructors are correct in their statements concerning ground water (see footnote on page 22) at least small flows should be expected at most sites at depths no more than 100 to 200 feet. Completed wells to these depths including casing and pump are normally available for less than $3,000.* Of course, such wells require electric power and this cost should be added before making a comparison between stored and pumped water. However, one could argue that high-quality shelters normally require power for ventilation purposes and that the additional capacity needed for the pump would be negligible.

Assuming the availability of water, the cost of cooling a 30-psi, 1,000-person shelter, overcrowded to 2.5 times nominal capacity for extended operation would be 5-10% over the regular or normal costs.

Conclusions

Although this study is limited in terms of its depth of coverage of habitability performance of shelters, we believe the following general observations are in order:

1. Crowding shelters beyond their nominal capacities should be given serious consideration in the development of shelter programs, since it may permit designers to:

   a. reduce over-all costs,
   b. purchase harder structures,
   c. plan for good early capabilities,
   d. obtain higher legacy values,
   e. do a better job in phasing,
   f. or, use combinations of these.

2. Aside from the obvious benefits available, some overcrowding might necessarily occur because of short warning times, variations in shelter and population distribution, errors in the system, or because of other uncertainties.

3. Given adequate ventilation and heat dissipation equipment, it appears possible to overcrowd normally designed shelters 150% (5 people in 2 spaces) for extended periods (many days). More severe options seem available for shorter periods.

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*An "average" well in upper New York State cost $6-10 per foot to drill including steel casing, and at 200 feet will include a submersible pump delivering 5-10 gallons per minute at 40 pounds per square inch pressure. The pump is rated at 1 horsepower and costs about $300-400 installed.

4. There appear to be ways of designing around the major physiological problems (heat dissipation, water and sanitation needs) by furnishing shelters with water wells. Systems using well water and designed for overloading incur small cost increases over normal shelter costs.

5. Since overcrowding may produce significant increases in system performance if it can be counted on to work, we would recommend that additional work be undertaken to establish some limits for planning purposes. This work might be directed in two ways--first, the undertaking of some paper studies aimed at developing optimum overcrowded shelter configurations; second, the undertaking of large simulated occupancy studies to determine space utilization limitations. Such tests should not confuse the space utilization problem with the heat dissipation and water problems* and should be designed, in part, to determine the usefulness of tiered bunking systems.

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*For an example of properly run tests, refer to reports in Ref. 4.

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