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FINAL REPORT

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VENTILATION SURGE TECHNIQUES
VOLUME I

Prepared for:
Federal Emergency Management Agency
Washington, D.C. 20472

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Ventilation tests were made using 25 shelter configurations. Airflow patterns and temperature distributions were measured in each configuration using both natural and forced ventilation.

An evaluation of the applicability of expedient openings was made using data from the literature and personal contacts. The evaluation addressed a wide variety of construction types and cutting techniques.

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VENTILATION SURGE TECHNIQUES

Volume I

Prepared by:
M. Wright
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The objectives of this project were to investigate the effects of partitions, dense occupancy, and expedient openings on the airflow patterns in fallout shelters. Both experimental and theoretical techniques were used in the study.

The experimental program examined airflow patterns for both mechanically driven and thermally driven ventilation. Mechanical ventilation was supplied by an axial fan driven by an electric motor. The thermal ventilation was supplied by simulating the metabolic heat load of the shelter occupants. Because metabolic heat is a combination of sensible and latent heat, a theoretical analysis was made of the relative effect of each type of heat on buoyance. The result showed that latent heat has a much smaller buoyancy effect and, consequently, only the sensible heat input was simulated during the experiments using thermally driven ventilation.

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SUMMARY

I. INTRODUCTION

The use of shelters to protect the civilian population from nuclear attack has played an important role in civil defense plans for many years. In addition to protecting occupants from weapons effects, shelters must remain habitable throughout a shelter occupancy period to successfully achieve their mission of saving lives. Ventilation is important to maintaining a habitable shelter environment. Ventilation can be supplied by mechanical means such as fans, blowers, and pumps or by natural forces such as those created by wind or thermal buoyancy. The objectives of this research were to experimentally investigate the effects of partitions and dense occupancy on the airflow patterns and velocity distributions of both forced and natural ventilation in shelters and to identify and evaluate expedient means of improving the ventilation characteristics of shelters.

II. SCALE MODELS AND NATURAL VENTILATION

Prior to beginning the experimental portion of this project, Research Triangle Institute (RTI) investigated the applicability of scale models to the study of natural ventilation in shelters. Analytical expressions were developed to define maximum scaling and critical factors for similitude. Based on the results of the analysis, RTI concluded that, when thermal buoyancy is a significant driving force, scale modeling of natural ventilation will probably not be successful, although the technique could be quite useful and cost effective for studying wind-driven ventilation.

III. EXPERIMENTAL DESIGN

The full-scale model used in the experimental portion of the study was designed to represent a typical host-area shelter. It had plan dimensions of 32 feet by 48 feet. Three floor plans were used within the same exterior wall layout. The first was a single room, the second was two rooms of equal size, and the third was a large area with three small adjoining rooms. Ventilation experiments were conducted for 5 aperture configurations in the first floor plan and for 10 aperture configurations each in the second and third floor plans. For each floor plan and aperture configuration, the volume of air passing through the shelter was measured, and the distribution of air over the shelter determined, for both natural and forced ventilation by measuring the speed and direction of air movement at a series of predetermined locations within the shelter. The temperature distribution within the shelter model and outside the shelter was monitored by 24 thermistor networks tied into a 24-channel, strip-chart recorder. All velocity measurements were made using smoke and a hot-wire anenometer.

IV. EXPERIMENTAL RESULTS

By the help of computer graphics, the data from each ventilation experiment were used to develop a graphic description of the temperature and airflow patterns within the model shelter. Each graphic data presentation is accompanied by a brief narrative description of each experiment. Experimental data are also presented in tabular form. These tabular data consist of the volume of air entering the shelter and each room in the shelter, temperature data, and an "interior airflow score" for each test--a value computed to represent the relative draftiness of the shelter during each test.

V. CONCLUSIONS

Based on the study of expedient openings and on the experimental results, the following conclusions were reached:

(1) As a means of improving shelter ventilation, expedient openings are generally feasible but not always practical.

(2) Expedient openings can improve shelter air distribution if their locations are carefully planned.

(3) Thermally driven natural ventilation resulting from occupant's heating the shelter air is adequate for maintaining the chemical environment of a shelter but not adequate for temperature control, except in areas where the zonal ventilation requirement is 10 cfm or less.

(4) The physical presence of the shelter occupants does not noticeably affect the volume of air supplied by thermal forces and does not significantly affect air distribution.

(5) Partitions strongly influence shelter air distribution, but the influence can be reduced by the use of expedient openings.

PREFACE

This final report comprises two volumes. Volume I contains the main text and Appendixes A, B, and C. Volume II contains Appendix D, Test Descriptions and Data Presentations.

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I. INTRODUCTION

A. Background

Providing adequately ventilated shelter against nuclear weapons effects has long been important in civil defense planning. In particular, civil defense research has shown adequate ventilation to be imperative in any shelter occupied at a rate of 1 person per 10 square feet of floor area. Under cool weather conditions, for example, ventilation of approximately 3 cubic feet per minute (cfm) is necessary to supply oxygen and prevent carbon dioxide buildup. And, under weather conditions requiring temperature control, ventilation requirements increase dramatically, to as much as 50 cfm per person, depending on geography.

Civil defense researchers have investigated several ventilation alternatives for nuclear fallout shelters. They have developed manually powered equipment for supplying and distributing shelter air when electric power is not available, and they have conducted experimental studies to determine airflow patterns and velocity distributions in shelters ventilated by both mechanical equipment and such natural means as wind and buoyancy forces developed from metabolic heat generated by shelter occupants. The latter studies indicate that interior partition configuration and location and size of interior and exterior wall openings are factors governing air shelter supply and distribution. In many cases, existing configurations of shelter partitions and wall openings prohibit effective use of ventilating equipment to supply and distribute air. One method proposed to improve ventilation system effectiveness is to add expedient wall openings during shelter occupancy.

B. Objectives and Scope

The objectives of the research described herein were twofold: to identify and evaluate surge-period[*] activities--such as the creation of expedient openings--for improving shelter ventilation capabilities and to investigate experimentally the effects of expedient openings, partitions, and dense occupancy on airflow patterns and velocity distributions in both forced and natural ventilation of various shelter configurations.

Research Triangle Institute (RTI) undertook several activities to achieve these objectives: a literature review was conducted to ensure awareness of previous research applicable to the problem; the possibility was investigated of adding expedient openings in interior and exterior walls of shelters with various types of construction; an evaluation was made of using scale models to study shelter ventilation; theoretical analyses considering both latent and sensible heat were made to estimate shelter ventilation volume resulting from buoyancy forces developed from metabolic heat generated by shelter occupants; and an experimental program was designed and conducted to evaluate shelter ventilation rates and airflow patterns. This report describes procedures used and results obtained from these activities.

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[*] A surge period is a period of increased civil defense activity, triggered by escalating international crisis, normally considered to last anywhere from a few weeks to a year.

II. SCALE MODELS AND NATURAL VENTILATION

A. Introduction

This summary describes basic experimental-scale modeling principles, scaling criteria, and the appropriateness of scale modeling to evaluate natural ventilation.

Scale modeling has long been used as a fluid systems design and analytical tool to study and quantify natural phenomena. As a design tool, modeling is commonly used in shipbuilding and aeronautics as an inexpensive way to determine full-scale system performance characteristics without expensive, full-scale testing. As an analytical tool, modeling can represent phenomena not readily viewed in full scale--e.g., ocean flow dynamics, the atmosphere, or large river basins. In either type of application, modeling's role is clear; its utilities and limitations well documented. This section discusses potential benefits and limitations of modeling as a tool for simulating and quantifying natural ventilation expected in shelters planned for national emergency situations.

B. Brief Description of Modeling

As mentioned previously, modeling can reduce the time and cost required to solve technical design or analysis problems. If a problem can be modeled, it can sometimes be evaluated with more precise measurements, under a wider range of controlled conditions, and with more convenience than would be possible with full-scale testing. However, facilities required for testing models are often so costly they outweigh the advantage of reduced model costs.

The modeling procedure first involves determining all significant geometric lengths, L_i, of the full-scale system and all significant forces,

F_i, acting to maintain flow. Appropriate, nondimensional ratios of these factors, Pi numbers, π_j ($\pi_1, \pi_2, \ldots$), are then established to form the basis of similitude. That is, a model can be used to simulate the prototype when

$$(\pi_j)_m = (\pi_j)_p \quad , \tag{II-1}$$

for all values of $j=1,2, \ldots$. Thus, the Pi numbers are length ratios (i.e., L_1/L_2) and force ratios (i.e., F_1/F_2), whose number is determined by the Buckingham Pi theorem. The model and prototype must be geometrically similar, which, in addition to the above, requires all lengths to be scaled by the same factor, i.e.,

$$n(L_i)_m = (L_i)_p \quad , \tag{II-2}$$

where L_i represents any significant length dimension. That is,

$$L_{i_p}/L_{i_m} = n \quad , \tag{II-3}$$

where n is a constant for all dimensions specified by i. Various techniques are available for determining proper variable combinations to specify Pi numbers. The most common modern procedure is to use the governing differential equations for the phenomenon, although purely dimensional analysis can also be used effectively. Similitude, in fact, does not depend upon the method of identification of the π groupings but requires only that they be identified and maintained as dictated in the above equalities.

Modeling has many inherent limitations and requires great skill. Most cases involving complete systems require a full-scale model: an all-purpose, dissimilar model of convenient size using a convenient working fluid is of doubtful significance since data from dissimilar models can be very misleading and of great negative value. Thus, distortions will always exist in full system modeling, and their effects should be analyzed in detail as modeling procedures are validated. For example, while surface roughness--an extremely important flow systems parameter--is almost impossible to scale correctly, special techniques have evolved in aircraft and ship modeling over the years to accommodate this distortion. Turbulent mixing length is another parameter that is often distorted.

Because of these distortions, modeling is often developed piecemeal: systems may be simplified and idealized until modeling is valid, or certain controlling processes within a system may be modeled individually and an effort made to use these results to predict overall system behavior. For example, the fluid flow and heat transfer characteristics of a single-tube heat exchanger may be assessed and the results used to predict the performance of a multitube heat exchanger. Such predictions are a major undertaking.

Thus, while in theory complete systems modeling represents a simple alternative to expensive full-scale testing, its routine application as a diagnostic tool is more difficult. In fact, over the years modeling has become a complicated study focusing on techniques and theories of accommodating distortions. When the economics of a particular application, such as the aeronautics and shipbuilding industries, favor it, modeling techniques development is justified. Presently, modeling is most often used in applications involving very idealized systems to study individual phenomena. The difficulties resulting from scaling up to full size have thus become the major uncertainties associated with modeling.

C. Theory Applied to Natural Ventilation

As used in this report, natural ventilation includes ventilation induced by wind, thermal buoyancy, or some combination of the two. The geometrical ventilation flow pattern in a shelter is characteristically three dimensional and, when driven by buoyancy, directly coupled to temperature distribution within the flow field. Conversely, temperature distribution within the flow field is caused primarily by air motion, the manner and rate of heating air, and the manner and rate of heat loss from structure boundaries. Describing a naturally ventilated structure therefore involves the laws of fluid mechanics, heat transfer, and thermodynamics in a complicated, three-dimensional geometry. It is clearly not an easy problem.

The following variables are important in modeling the three-dimensional geometry of natural ventilation flow patterns:

c = specific heat of fluid.

D_e = effective diameter of cross-sectional area of exit airway (i.e., upper window, vent, etc.).

D_i = effective diameter of cross-sectional area of inlet airway (i.e., door, window, etc.).

g = gravitational acceleration.

H = effective vertical distance between inlet and exit airways (i.e., the effective stack height for the structure).

k = thermal conductivity of fluid.

Q = ventilation rate in cubic feet per minute (cfm).

$\dot{q}''$ = net heat generation rate per occupant per unit floor area of shelter (usually assumed to be the metabolic heat rate of an average person occupying approximately 1 square meter (m^2) of floor space, less losses).

ΔT = difference between entering and exiting air temperature (usually assumed to be the temperature difference driving the stack effect).

V = external air velocity (assumed normal to structure at inlet area).

β = thermal expansion coefficient of fluid.

ℓ_p^o = various characteristic dimensions of occupants (i.e., effective diameter, height, and distance between centers).

ℓ_j^s = various characteristic dimensions of shelter (i.e., plan-area dimensions ℓ_1^s and ℓ_2^s, vertical dimension ℓ_3^s, and longest plan-area perimeter from inlet to exit airway, ℓ_4^s).

ρ = fluid density.

μ = fluid viscosity.

The various length dimensions--D_i, D_e, ℓ_j^s, ℓ_p^o, and H--must be scaled by the same factor, $n = L_p/L_m$, to preserve geometric similitude. The dependent variable is the ventilation rate, Q, and the forcing factors are either ΔT or ($\dot{q}''$) and V. Fluid properties comprise the remaining variables. For all these variables, it is assumed that surface tension, thermal radiation, and compressibility effects are insignificant and that the fluid properties are constant. The need to make such a priori estimates of pertinent variables and effects is the major disadvantage of dimensional analysis. Although modern developments in analyzing differential transport equations help, some uncertainty still remains in estimating the proper variables and controlling effects and in ensuring regimes of these effects do not change during modeling.

Some of the Pi numbers, or nondimensional groupings of these variables, can be shown to be as follows:

- Reynolds number, $Re = HV\rho/\mu$
- Grashof number, $Gr = g\rho^2\beta(\Delta T)H^3/\mu^2$ if ΔT specified

  $Gr = g\rho^2\beta\,\dot{q}''(D/k)\,H^3/\mu^2$ if $\dot{q}''$ specified
- Archimedes number, $Ar = g\beta(\Delta T)\,H/V^2$ if ΔT specified

  $Ar = g\beta\dot{q}''(D/k)\,H/V^2$ if $\dot{q}''$ specified

- Prandtl number, $Pr = \mu c/k$
- Nondimensional ventilation, $Q^* = Q\rho/D_e\mu$
- Stack height, $H_e^* = H/D_e$
- Stack height, $H_i^* = H/D_i$.

Other nondimensional groupings of characteristic dimensions are less unique. Those of importance may include the following:

- Occupant height, $x_1^* = h/H$
- Shelter height, $x_2^* = \ell_3^s/H$
- Occupant spacing, $x_3^* = \ell^o/\ell_1^s$
- Occupant diameter, $x_4^* = d/\ell^o$
- Shelter perimeter, $x_5^* = \ell_4^s/\ell_2^s$
- Shelter aspect ratio, $x_6^* = \ell_1^s/\ell_2^s$
- Shelter height ratio, $x_7^* = \ell_3^s/\ell_2^s$.

There may be other variables and effects influencing natural ventilation in either the model or prototype. If a significant factor has been omitted from the formulation, the modeling is incorrect; if a factor has been legitimately omitted but may be important in the model, the modeling is incorrect; and if any π number is not maintained in the modeling, a distortion is introduced and the modeling is incorrect.

In addition to geometric similitude and dynamic similitude, complete similitude also requires compliance with two types of conditions--hydrodynamic and thermal. For a room enclosed by solid walls, hydrodynamic boundary conditions are automatically controlled and satisfied by the "no slip" condition of fluid mechanics. However, thermal boundary conditions are much more difficult to control because thermal parameters are controlled only for some surfaces involved. Temperature distributions over other surfaces depend upon the heat flow through them. To achieve complete thermal similarity, all heat flows and radiation exchanges in the prototype would have to be known for them to be reproduced in appropriate scale in the model. This is, clearly, a difficult point in thermal modeling.

If geometric and boundary-condition similitude exists, complete, natural ventilation can be represented in the function format

$$Q^* = F(\mathrm{Re}, \mathrm{Ar}, \mathrm{Pr}, H_e^*, H_i^*, x_i^* \; (i=1,\ldots,7)) \; . \qquad \text{(II-4)}$$

If the shelter and airflow are essentially isothermal and the ventilation predominantly wind driven, the Grashof number, Gr, and the Archimedes number, Ar, are unimportant. The ventilation rate is then represented as

$$Q^* = F(\mathrm{Re}, H_e^*, H_i^*, x_i^* \; (i=1,\ldots,7)) \; . \qquad \text{(II-5)}$$

If the velocity of the outside air is negligible, thermal buoyancy is the predominant, driving force, and the Reynolds number, Re, and Archimedes number, Ar, no longer enter the formulation. Under these circumstances the ventilation rate is represented as

$$Q^* = F(\mathrm{Gr}, \mathrm{Pr}, H_e^*, H_i^*, x_i^* \; (i=1,\ldots,7)) \; , \qquad \text{(II-6)}$$

where particular functional form F is to be determined in a scale model experiment.

For complete similitude, all independent model variables must be numerically equal to corresponding prototype values. Under these circumstances, the value of Q^* will then be the same for the model as for the prototype. If inequality exists between the model and the phototype for any variable, the model will determine a distorted value of Q^*. Degree of distortion will depend upon the strength of the unequal variable in the functional format, F, which is unknown at the outset. In addition, geometric and boundary-condition similitude must be maintained, or distortions will occur wherever they are not.

D. Scaling Requirements

In addition to length scaling requirements, geometric similitude, and boundary-condition similarity considerations, similitude of Re, Ar, Gr, and Pr is also important. A general feeling of modeling feasibility can be gained by examining these particular requirements in some illustrative cases.

First, assume the fluid remains unchanged. That is, air is the fluid in the model as well as the prototype. Then $(Re)_m = (Re)_p$, and since $(\mu/\rho)_m \equiv (\mu/\rho)_p$, it can be seen that $V_m H_m = V_p H_p$ or that

$$V_m = n\ V_p \ . \qquad \text{(II-7)}$$

For most gases, the ratio (μ/ρ) does not vary greatly with temperature; therefore, invariance of the ratio is reasonable for moderate (realistic) temperature differences between model and prototype. Now, since $(Ar)_m = (Ar)_p$, it can be shown that $gH_p\beta_p(\Delta T)_p/V_p^2 = gH_m\beta_m(\Delta T)_m/V_m^2$. Since $\beta \sim 1/\overline{T}$, where $\overline{T}$ is the average of the inlet and outlet temperature, it can be seen that

$$\frac{H_p(\Delta T)_p}{V_p^2\ \overline{T}_p} = \frac{H_m(\Delta T)_m}{V_m^2\ \overline{T}_m} \ . \qquad \text{(II-8)}$$

Using $V_m = n\ V_p$ and $n = H_p/H_m$, this expression becomes

$$n^3\ \frac{(\Delta T)_p}{\overline{T}_p} = \frac{(\Delta T)_m}{\overline{T}_m} \ . \qquad \text{(II-9)}$$

Rewritten in terms of actual inlet and outlet temperatures, this expression becomes

$$\frac{n^3(T_o-T_i)_p}{(T_i+T_o)_p/2} = \frac{(T_o-T_i)_m}{(T_i+T_o)_m/2} \equiv K \quad . \qquad \text{(II-10)}$$

In terms of the factor K, the conditions for the model are

$$T_{om} = \left(\frac{2+K}{2-K}\right) T_{im} \quad . \qquad \text{(II-11)}$$

Thus, if actual conditions for the prototype and the scaling, n, are such as to cause K to equal 2, the outlet model temperature must be infinite. This is clearly not realistic, yet yields the maximum possible n as

$$n_{max} = \left[\frac{T_{op} + T_{ip}}{T_{op} - T_{ip}}\right]^{1/3} \quad . \qquad \text{(II-12)}$$

For typical prototype conditions of T_i = 65F and T_o - 90F, this yields n_{max} = 1.8, which is hardly a worthwhile scale reduction from an economic viewpoint. If we recomputed this exercise with a realistic T_{om} (instead of infinity), n will come out even closer to unity, thus demonstrating the difficulty of maintaining buoyancy similitude.

For fully turbulent applications, Re is very weak in similitude requirements. Under these circumstances, if $(\mu/\rho)_m \cong (\mu/\rho)_p$, it can be argued that only the Ar number need to be simulated. Choosing the same characteristic velocities in the model and prototype yields

$$n \frac{(\Delta T)_p}{T_p} = \frac{(\Delta T)_m}{T_m} \equiv K \quad , \qquad \text{(II-13)}$$

and again in terms of actual temperatures

$$n = \frac{\frac{K}{2}(T_{op} + T_{ip})}{(T_{op} - T_{ip})} \; . \tag{II-14}$$

But since $K \leq 2$, as shown above, $n_{max} = 6.2$. When a more realistic value of T_{om} is assumed (instead of infinity), n will be reduced to a factor on the order of 2 or 3. This is probably insufficient reduction to warrant modeling.

For the case of complete, thermally driven buoyancy ventilation (wherein there is no externally imposed wind velocity) satisfying Grashof requirements is probably sufficient if $(\mu/\rho)_p \cong (\mu/\rho)_m$. Thus,

$$\beta_m(\Delta T)_m H_m^3 = \beta_p(\Delta T)_p H_p^3 \quad , \tag{II-15}$$

or

$$\frac{n^3(\Delta T)_p}{\bar{T}_p} = \frac{(\Delta T)_m}{\bar{T}_m} \equiv K \quad , \tag{II-16}$$

or

$$n = \left[\frac{K}{2}\left(\frac{T_{op} + T_{ip}}{T_{op} - T_{ip}}\right)\right]^{1/3} \quad , \tag{II-17}$$

Again, if $K \leq 2$, $n_{max} = [(T_{op} + T_{ip})/(T_{op}-T_{ip})]^{1/3}$. For the same conditions,

$$n_{max} = 1.8 \; . \tag{II-18}$$

As before, if more realistic conditions are assumed for T_{om}, n will actually be closer to unity.

To avoid the above difficulty with thermal scaling, the modeling might use a different fluid. That is, $(\mu/\rho)_m \neq (\mu/\rho)_p$. The requirements for this case are $Pr_m = Pr_p$ and either $Ar_m = Ar_p$ (with $Re_m = Re_p$) or $Gr_m = Gr_p$. In either case, the result is

$$Pr_m = Pr_p \quad , \tag{II-19}$$

and

$$n^3 \frac{\Delta T_p}{\overline{T}_p} = \beta_m (\Delta T)_m \, (\mu/\rho)_p^2/(\mu/\rho)_m^2 \equiv K \quad . \tag{II-20}$$

Or, the physical scaling must satisfy

$$n = \left[\frac{K}{2}\left(\frac{T_{op} + T_{ip}}{T_{op} - T_{ip}}\right)\right]^{1/3} \quad . \tag{II-21}$$

For a scaling of n = 10 with the same conditions for T_{op} and T_{ip}, $K \cong 0.32\, n^3 \cong 320$. Expressing $(\Delta T)_m$ as $T_{om} - T_{im}$ and solving for T_{om} yields

$$T_{om} = T_{im} + K(\mu/\rho)_m^2/\beta_m(\mu/\rho)_p^2 \quad . \tag{II-22}$$

For $(\mu/\rho)_m/(\mu/\rho)_p \cong 1/200$, $\beta_m \cong 10^{-5}\ F^{-1}$, and $Pr_m \cong 0.87$, yields $T_{om} - T_{im} \cong$ 800° F. For n = 5, $T_{om} - T_{im} \cong 100°$ F, which is more reasonable. For n = 2, $T_{om} - T_{im} \cong 6°$ F, which is very reasonable but simply not enough scaling. These are approximately the conditions that would occur if high-temperature water were used as the model fluid. Water at these conditions--500° F and 700 psia--would be difficult to handle conveniently, even if adequate scaling could be achieved. However, many other fluids have been investigated for modeling--saline solutions, benzine, etc.--but they have not proven to be even as feasible as water. It should also be noted that using liquids to model gases involves such additional problematic factors as surface tension and different turbulence characteristics that may become important in the model. In addition, maintaining thermal boundary conditions is extremely difficult with liquids used as model fluid.

Results similiar to those shown above can also be deduced if buoyancy is expressed in terms of specified heat rate, $\dot{q}'''$. This is probably the most logical format for ventilation since occupant heat rate is usually known and ΔT is usually unknown. Essentially the same conclusions apply except that model temperature T_{om} is replaced by model heat rate $\dot{q}'''_m$.

E. Conclusions

Because maintaining similitude is difficult, complete scale modeling of natural ventilation systems with significant buoyancy will probably be unsuccessful, in a quantitative sense, without enormous investment in developing the state of the art of the technique. These development costs, in addition to primary modeling facilities costs, may rapidly increase until ventilation modeling is prohibitively expensive. A comparative study should be made of typical, full-scale test costs and anticipated model study and test costs and a determination made of whether modeling should be pursued.

Maintaining similitude in natural ventilation modeling entails several specific problem areas that introduce uncertainty in model data:

- Inability to create complete similitude in both Prandtl number and Grashof number (or Archimedes number) without resorting to high-pressure (high-temperature) water.

- Inability to find convenient working fluids other than high-temperature water for models that require liquid as the working fluid.

- Difficulties involving changes of "regime" when liquids are used to simulate gases--i.e., the uncontrollability of changes in radiation exchange, temperature dependency of properties such as μ and β, surface tension, and laminar-to-turbulent transition and retransition.

- Lack of certainty in internal modeling of flow losses resulting from presence of occupants.

- Inability to model the heat losses and thermal boundary conditions, especially with liquid used to simulate air.

Some of these factors may be more important than others. For quantitative modeling, however, all these areas must be studied to assess and correct distortions.

Modeling efforts should not be abandoned completely. Indeed, some aspects of natural ventilation may be modeled at considerable savings and some aspects may be modeled that do not lend themselves to easy, full-scale study. Examples of these include the following:

- Comparative studies of model configurations, although dissimilar to full-scale models, may provide qualititative information on optimum conditions for maximum ventilation. That is, optimization on the model scale may be possible.

- The effects of using variable, in-shelter heat generation to simulate the presence of human occupants might be studied more easily in a model than in the full scale. Full-scale shelter tests using human occupants will be a difficult task because of the number of person-hours involved.

- Some specific phenomena may be more easily studied with modeling: the critical exit-to-inlet area ratio at which the exit begins acting partially as an inlet, the effect of perimeter distance from inlet to exit on the ventilation rate, and flow losses caused by the presence of occupants.

- For pure wind ventilation, it may be possible to scale properly and to better control conditions. Full-scale tests of wind ventilation might be hampered by the inability to control wind gusts and direction.

The suggestion here is that many aspects of natural ventilation might be studied by modeling, even though the results may be only model comparative and not directly subject to scaleup. Such qualitative results can be invaluable in understanding and designing full-scale systems, yet studies of the specific ways in which modeling can be applied to natural ventilation and its limitations have not been carried out. A list of specific aspects of natural ventilation should be defined and a study initiated of the role of modeling in characterizing these effects.

Finally, it is important to note that the contemporary trend is in the direction of computer modeling rather than physical modeling. Potentially, computer modeling is capable of handling many effects and ensuring proper scaling and thus represents a valid alternative to physical modeling. Natural ventilation certainly appears to be a good candidate for such numerical simulation work, especially in conjunction with full-scale and near-full-scale experimentation. Some preliminary studies should be initiated to define the possibilities of numerical modeling of natural ventilation.

III. EXPERIMENTAL DESIGN

A. Literature Review

Before designing the experimental program, Research Triangle Institute (RTI) conducted a review of pertinent literature to identify civil defense studies dealing with ventilation of fallout shelters. A limited number of computer searches were made but did not yield any significant new information sources. A library search at North Carolina State University (NCSU) yielded several studies dealing with natural ventilation of animal shelters. All of these were reviewed to determine their applicability to fallout shelters. The studies described in the literature consisted of both theoretical and experimental approaches and were valuable sources of background information. Appendix A contains a brief summary of the information reviewed and a reference list.

B. Theoretical Analyses

Although several theoretical descriptions of natural ventilation were identified in the literature, some aspects of the problem were not addressed. The most important of these is the relative effects of latent and sensible heating as driving forces for natural ventilation. To clarify this problem, RTI developed equations to describe these effects and related them to the metabolic heat rate of average shelter occupants. Appendix B contains a detailed description of these analyses, which show that latent heating produces a much lower ventilation rate than does equivalent, sensible heating.

C. Expedient Opening Analysis

One aspect of the experimental program is to investigate the usefulness of expedient openings to improve shelter ventilation. One part of this investigation was to determine effects on air supply and distribution in the experimental setup by simulating expedient openings. Another part was to determine the feasibility and practicality of making expedient openings in the walls of real buildings that might be used as shelters. RTI made these determinations by studying available literature and making personal contacts with individuals and groups having knowledge and expertise on the subject. Appendix C presents results of these analyses.

D. Program Design

The objectives of the experimental program were (1) to compare forced ventilation airflow patterns with natural ventilation airflow patterns, (2) to determine the effects of partitions and dense occupancy on airflow patterns, and (3) to determine the effects of expedient openings on airflow patterns. The following subsections describe the physical design and data collection procedures RTI used to achieve these objectives.

1. Test Facility Design

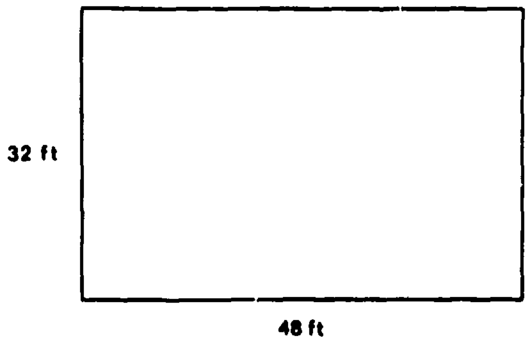
The emphasis of this project is on the ventilation of fallout shelters located in host areas. Therefore, data from the host-area shelter survey were reviewed as a basis for selecting the size and type of shelter studied in the experimental program. These data show approximately 85 percent of host-area shelters are located on the first story of single story buildings. The distribution of shelters by size shows the size category of 100 to 200 spaces to contain more shelters (about 30 percent of the total) than any other category. Based on these data, RTI elected to conduct ventilation experiments in a one-story, aboveground shelter with dimensions of 32 feet by 48 feet and a height of 8 feet. A shelter this size could contain approximately 150 shelter spaces.

The shelter was simulated by constructing a full-size structure with the above dimensions. RTI built the structure with a wood frame using 2- by 2-inch lumber. Vertical members were spaced on 8-foot centers in each direction, and horizontal members were installed with the same spacing for the ceiling. The frame was covered with 6-mil polyethylene stapled to the wood frame. Joints were taped to minimize air leakage. Exterior and interior wall openings were made by framing them and cutting away the polyethylene film.

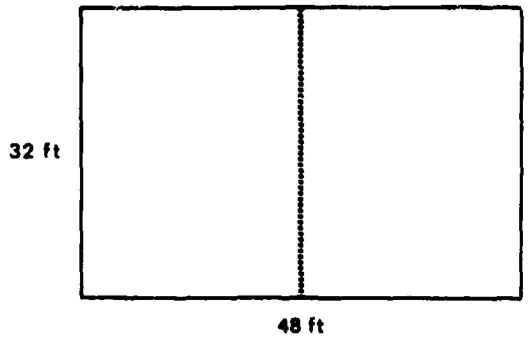
Tests were conducted with three different shelter floor plans within the same 32- by 48-foot structure. The first floor plan was a single room with dimensions of 32 feet by 48 feet. The second configuration consisted of two rooms, each having dimensions of 24 feet by 32 feet. The second configuration was obtained by constructing a single partition across the first configuration to divide it into two equal rooms. The third configuration was a large area with small adjoining rooms. This floor plan used the same exterior walls as the first two but had three small rooms along the outside walls. Two of the small rooms had dimensions of 12 feet by 16 feet and the third had dimensions of 12 feet by 12 feet. Each of the three floor plans is shown in Figure III-1.

To study the effects of aperture configuration on ventilation, RTI conducted tests with several aperture configurations in each floor plan. Specific aperture configurations were selected to represent worst and best cases, with other configurations being grouped (or ranked) between them. For the first floor plan, a single room, the following aperture configurations were studied:

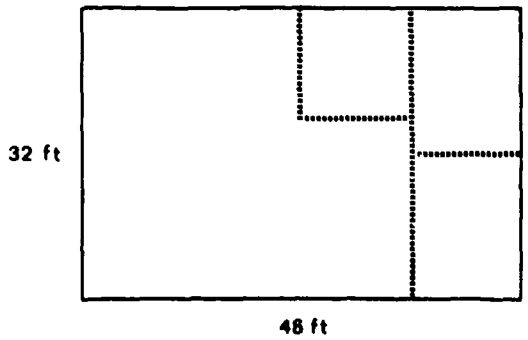
- Apertures in one wall only
- Apertures in two adjacent walls
- Apertures in two opposite walls
- Apertures in three walls
- Apertures in four walls.



a. Single Room



b. Two Rooms of Comparable Size



c. Large Area with Small Adjoining Rooms

Figure III-1. Floor Plans for Experimental Ventilation Program

For the single-room configuration, differentiating between existing openings and expedient openings may not be meaningful because apertures at any location in the exterior walls might be considered as existing openings. Testing several different aperture configurations allows identification of the most effective ventilation configuration.

Aperture configurations selected for testing in the second floor plan, two rooms of comparable size, are as follows:

- Apertures in one wall of one room
- Apertures in two walls of one room
- Apertures in both rooms in wall opposite common wall
- Apertures in both rooms but not in wall opposite common wall
- Apertures in both rooms in all walls.

As stated above, identifying exterior wall openings as existing or expedient is not very meaningful because most openings may be considered as either. Testing these five configurations for the two-room floor plan identified that giving the most effective ventilation. The two-room configuration offered an opportunity to measure effects of expedient openings in interior walls. The original construction of the interior wall had a single opening between the two rooms near the center of the wall. Additional openings were added to the interior wall in conjunction with each of the five aperture configurations listed to simulate expedient openings. These additional openings permitted evaluation of the effects of such openings on ventilating this configuration.

For the third floor plan, large area with small adjoining rooms, the following aperture configurations were studied:

- Apertures in one wall of large area
- Apertures in two walls of large area
- Apertures in all small rooms only

- Apertures in all small rooms and in large area
- Apertures in one small room and in large area.

As with the previous floor plans, exterior wall openings may be considered existing or expedient openings; therefore, no additional exterior wall apertures were tested. Expedient openings in interior walls were simulated by adding openings in partitions separating small rooms from each other and in partitions separating small rooms from the large area. One configuration of expedient openings was tested with each of the five exterior wall aperture configurations selected for the third floor plan.

The total number of floor plan and aperture configurations in which ventilation tests were conducted is 25, including 5 aperture configurations for the first floor plan and 10 aperture configurations each for the second and third floor plans.

2. Simulated Occupant Design

Simulating human occupants in a shelter involves two important parameters: heat generated by the body and the physical presence of the body. The heat generated by shelter occupants creates a temperature difference between shelter and external environments. This temperature difference creates buoyant forces that cause a stack or chimney effect, when openings exist in exterior shelter surfaces, and generate airflow through the shelter. The volume of air flowing through the shelter is a function of the temperature gradient and the number, size, and location of exterior openings. The sedentary rate of metabolic body heat generation is a function of age and sex and ranges from about 150 Btu per hour for very young children to about 400 Btu per hour for young adult males. Metabolic heat is released by the body in two forms, sensible heat and latent heat. The fraction of the total metabolic heat given off in each form depends on the dry bulb temperature of the surrounding air. For the experimental program, RTI simulated metabolic heat generation with sensible heat only, based on the analysis given in Appendix B.

Heat was generated with incandescent light bulbs. By enclosing the bulbs with a shroud, the total power input was given off as heat. The heat input used to represent each shelter occupant was selected after previous studies of the split between sensible and latent heat generated by people were analyzed. Additional effort was given to estimating steady-state shelter conditions of a crisis situation. Information developed from this effort was used to select approximately 60 watts as the sensible heat input of shelter occupants. This value is near the maximum that would be generated in the form of sensible heat. The 60-watt value was obtained by assuming that the population of each shelter represents a cross section of the total U.S. population.

The physical presence of shelter occupants obstruct airflow through a shelter and thus affects air movement patterns. To study these effects, the physical presence of the shelter occupants was simulated with Warmbody Integrated Modules, Personnel-Type (WIMPs), cylinders consisting of a wire frame approximately 68 inches tall and 15 inches in diameter covered with polyethylene plastic. The cylinder size selected was based on a recent article in Environmental Research, "Seventy-five Years of Searching for a Heat Index" [1]. In that article, a typical standing person was defined for the purpose of computing radiant heat loading. RTI concluded that a similar size could be used to measure effects of the physical presence of shelter occupants on airflow patterns. Each cylinder was positioned over a light bulb during the ventilation experiments. The composite of the light bulb and the cylinder provided a reasonable representation of shelter occupants.

E. Materials and Methods

1. Site

The experimental site chosen for the study comprised 3,000 square feet of floor space in a general commodity warehouse, C&O Warehouse No. 9, 915 Ramseur Street, Durham, North Carolina. The building, shown in Figure III-2, has dimensions of approximately 100 feet by 200 feet and is of conventional construction, with a concrete slab floor, cinder block walls, and a steel truss roof structure. Ceiling height is approximately 20 feet. Figure III-3 shows the location of the shelter and other interior details of the warehouse.

2. Shelter Construction

A full-sized model of a fallout shelter 32 feet wide, 48 feet long, and 8 feet high was built with 2- by 2-inch lumber (nominal cross section 1 and 1/2 inches square) on 8-foot centers and plywood gussets to reinforce the corners. The shelter was covered with 6-mil polyethylene film and all seams sealed with duct tape. Figure III-4 shows the completed shelter.

A three-dimensional Cartesian coordinate system was generated to help locate important features inside the shelter. The point on the floor of the northwest corner was arbitrarily chosen as the origin; the long dimension, or north-south direction, as the X-axis; the east-west direction, as the Y-axis; and height from the floor, as the Z-axis. Any point in the shelter is thus located by specifying its (X,Y,Z) coordinates in feet.

During the course of the experiments, interior walls of plastic film were added to create the second and third floor plans called for in the protocol. The second plan comprised two rooms, each 24 feet by 32 feet, and the third plan had two rooms 12 feet by 16 feet along the south end, one of which adjoined a 12-foot-square room on the east side.

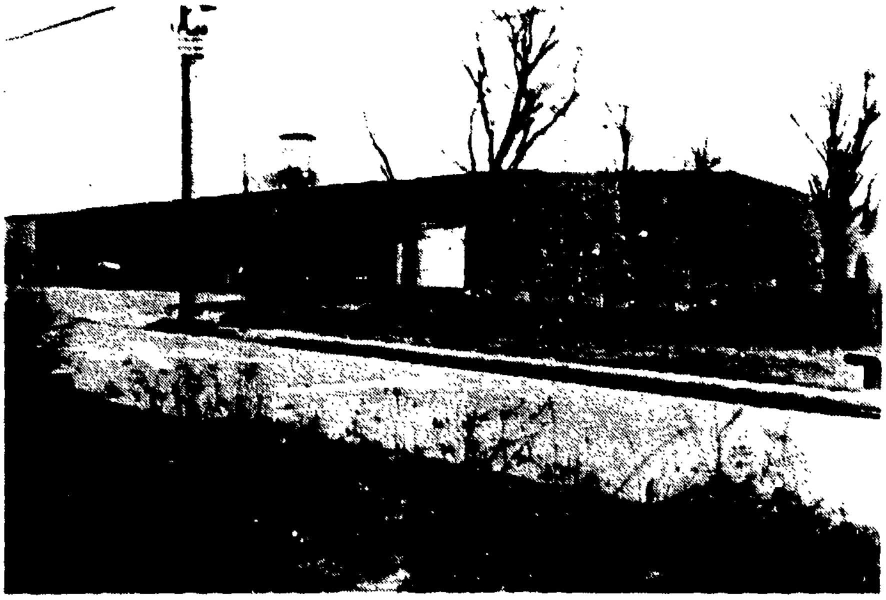


Figure III-2. C&O Warehouse No. 9, 915 Ramseur Street, Durham, North Carolina

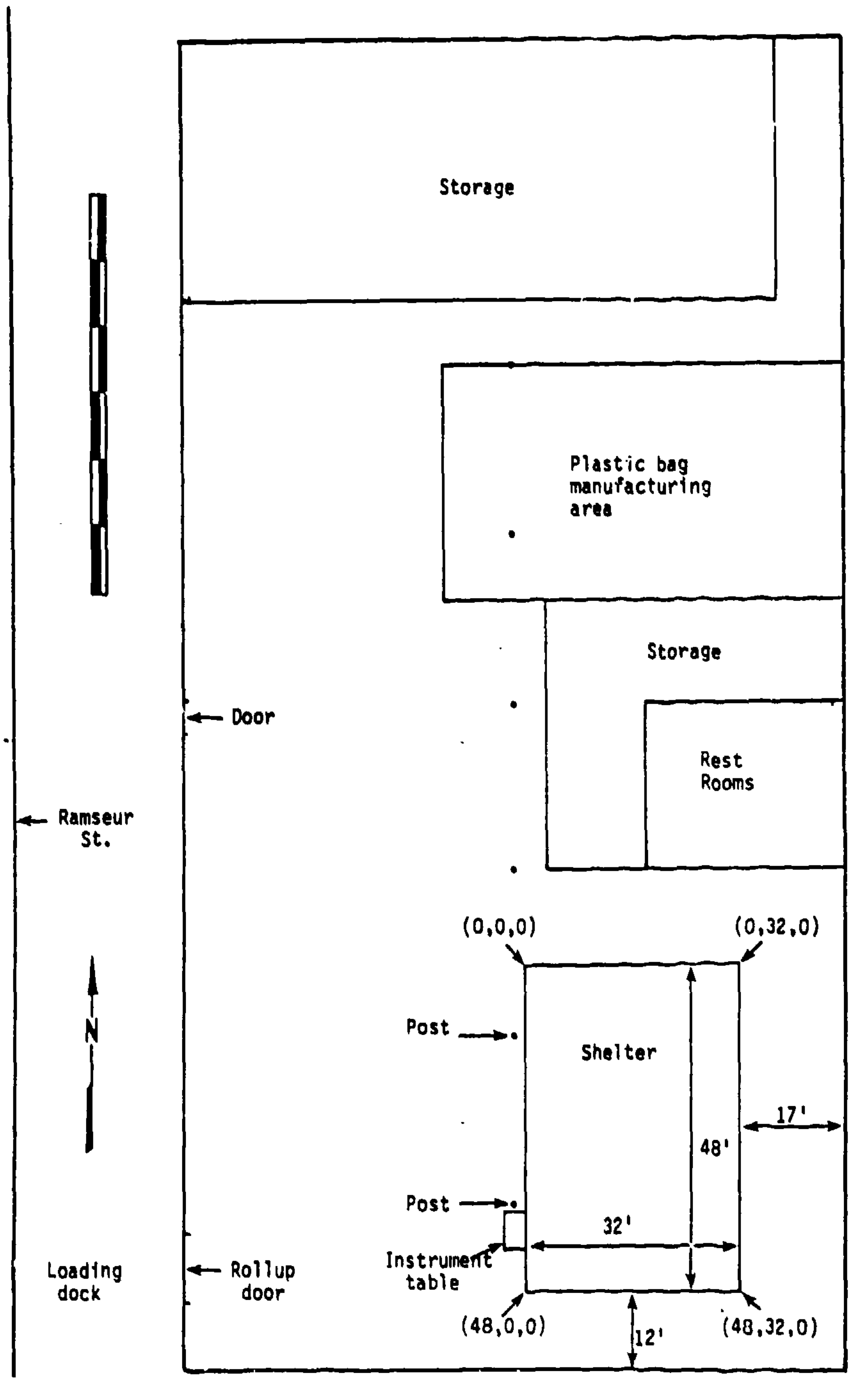


Figure III-3. Interior of C&O Warehouse No. 9

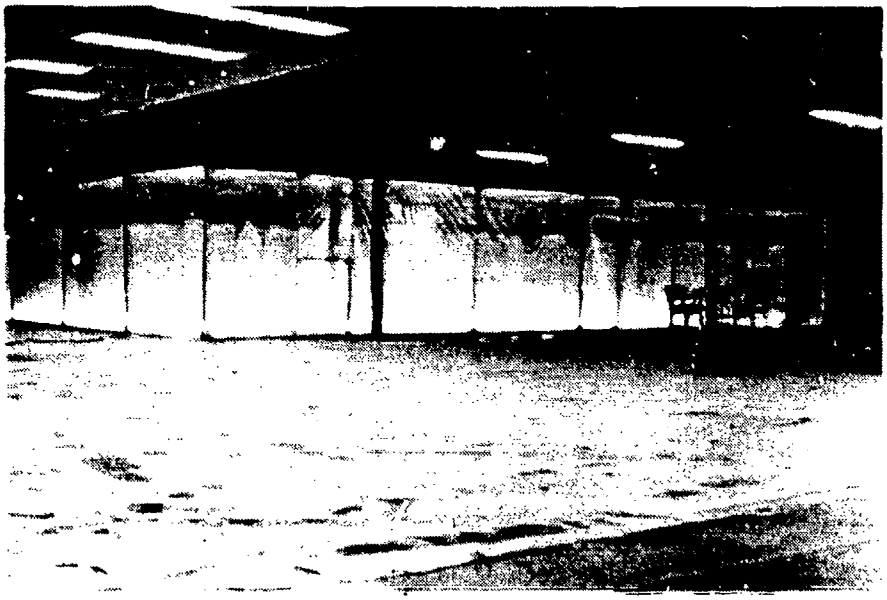


Figure III-4. View of the completed shelter in the warehouse. Shelter occupants (WIMPS) are in place inside. The nearest (left front) corner at the floor is the origin (0,0,0) of the coordinate system. The instrument table is seen at the right.

Provision was made in framing the walls for windows and doorways that could be left open or sealed shut with flaps of plastic and duct tape, depending on the aperture configuration required for each experiment. Unless otherwise specified, all "windows" were 3 feet square, and all "doorways" were 7 feet high and 3 feet wide. To ease measurements of airflows, each aperture was divided into a grid of 1-foot squares by attaching nylon strings to the framing.

The first floor plan provided two windows in each wall and one doorway in the west wall. Top edges of all these apertures were 1 foot down from the ceiling.

In the second floor plan, one doorway 7 feet high and 4 feet wide was cut in the middle of the interior wall. Later, two windows were added as expedient openings, one at the ceiling and the other at the floor to the east.

Apertures for the third floor plan consisted of one interior doorway for each room. An additional exterior window was cut in the east wall of the 12-foot-square room. Later, the following interior windows were added as expedient openings: one at the floor on the north side of the 12-foot-square room, one at the ceiling between the 12-foot-square room and the adjoining room, and one at the ceiling between the third room and the large area.

Details of all the features described above are shown in Figures III-5, III-6, III-7, and III-8.

To simulate human shelter occupants as the driving force for natural ventilation, RTI constructed 150 WIMPs from Keylite™ Reinforced Plastic, 2-inch chicken wire covered with polyethylene film. Edges were sealed with duct tape, and the top ends were closed by crimping and folding. The WIMPs were located at random inside the shelter and a 60-watt 120-volt incandescent

Figure III-5. An expedient opening. WIMPs have been removed for clarity. Notice the strings dividing the aperture into a grid of 1-foot squares, as well as the thermistor and its lead attached to the upright 2 by 2.

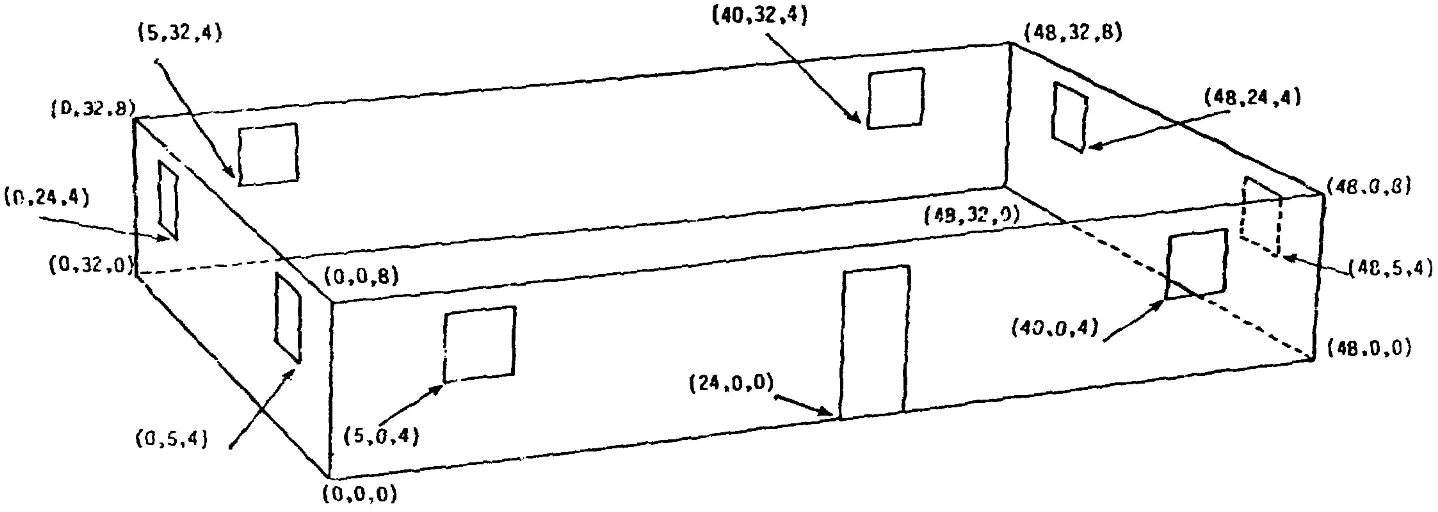


Figure III-6. Exterior Aperture Locations for Floor Plans 1, 2, and 3

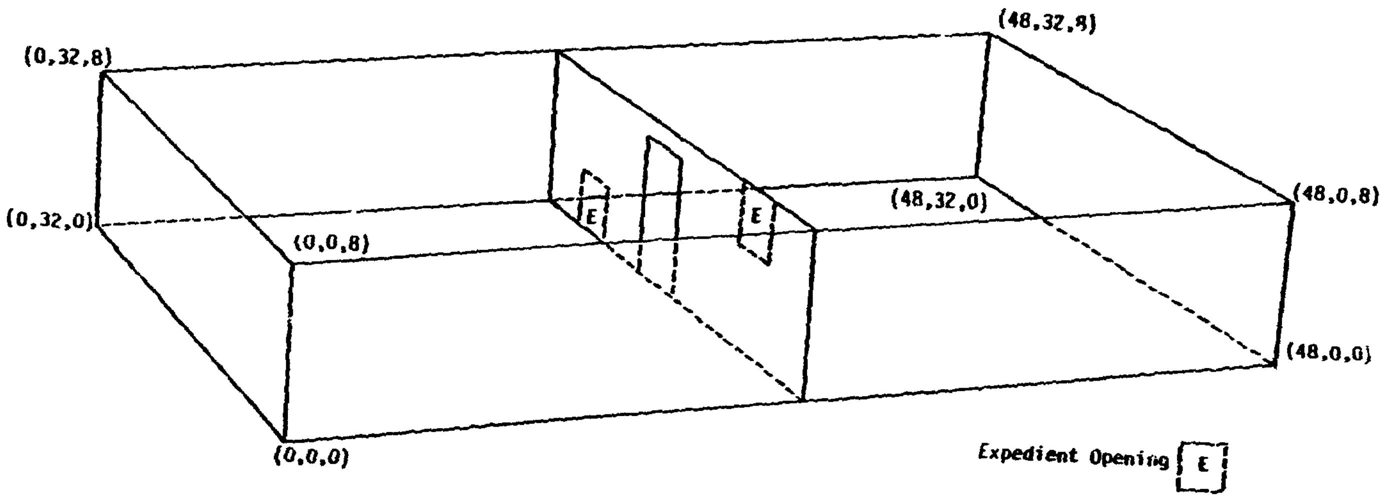


Figure III-7. Interior Aperture Locations for Floor Plan 2

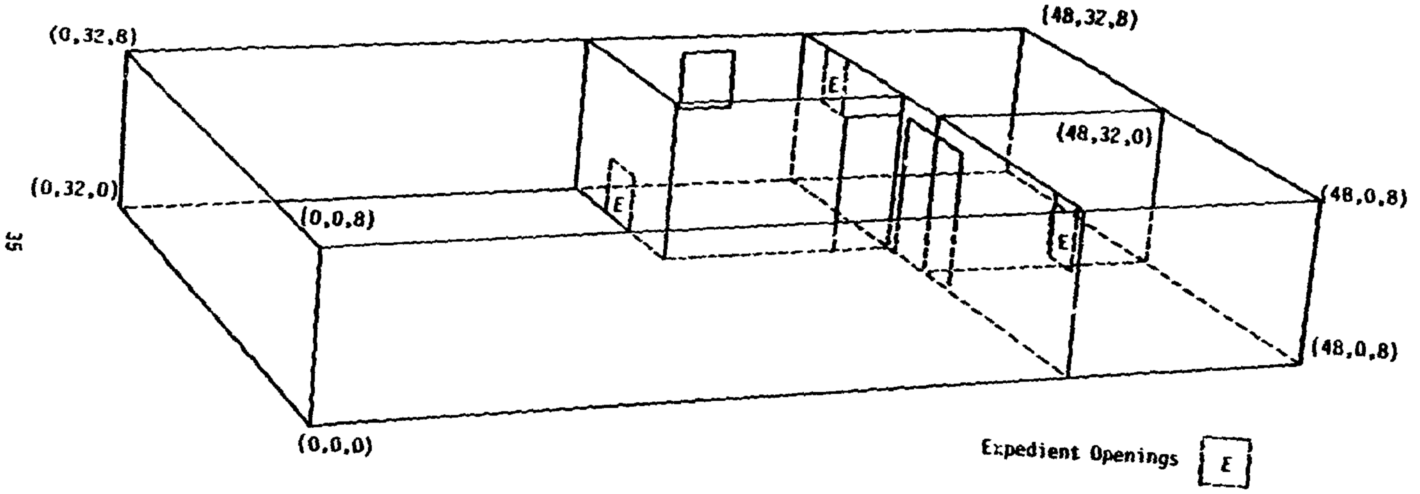


Figure III-8. Interior Aperture Locations for Floor Plan 3, With Additional Exterior Aperture lamp bulb in a porcelain, keyless receptable placed under each as a heat source. Each lamp bulb was covered with an aluminum shroud 4 inches in diameter and 12 inches high. Figures III-4, III-9, and III-10 show details of the WIMPs and the appearance of the "occupied" shelter.

Forced ventilation was provided by a 24-inch electric fan (Dayton Electric, Model 3C145, free air capacity 5,400 standard cubic feet per minute [scfm]) simulating a Packaged Ventilation Kit (PVK). The fan, shown in Figure III-11, was mounted in a wood frame on casters. In use, it was rolled up against a window and sealed to it with duct tape.

3. Instrumentation and Data Collection

Two types of data, temperature and air velocity*, were taken during each experiment. For temperature measurements, 24 thermistor networks (YSI 44202 thermilinear components plus precision resistors; see Figure III-12), referred to hereafter as "thermistors," were connected to a Brown Honeywell 24-channel strip chart recorder. Sixteen thermistors were attached to ceiling support posts at regular intervals inside the shelter, half at an elevation of 2 feet and the rest at 6 feet. Two other themistors were located at the right edge of the doorway in the west wall, one near the floor and one 6 feet high, and a third was placed outside the shelter, 6 feet from the floor. In addition, two thermistors were reserved for calibrating the system. After preliminary airflow measurements, three more thermistors were attached to the walls in places where very little air movement was observed. Figure III-13 gives locations for all thermistors. The temperature measurement circuit is shown in simplified form in Figure III-14.

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*Velocity is used here in the physical sense of a vector quantity. It comprises both airspeed and direction of flow.

Figure III-9. Warmbody Integrated Modules, Personnel Type (WIMPs). Notice the lamp bulbs and aluminum shrouds in the foreground.

Figure III-10. Interior of Shelter Showing WIMPs in Place

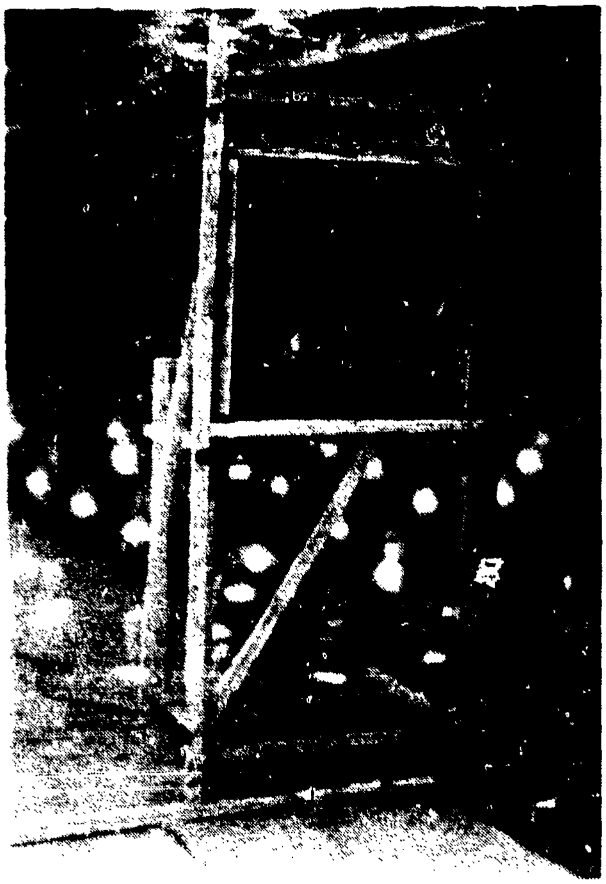
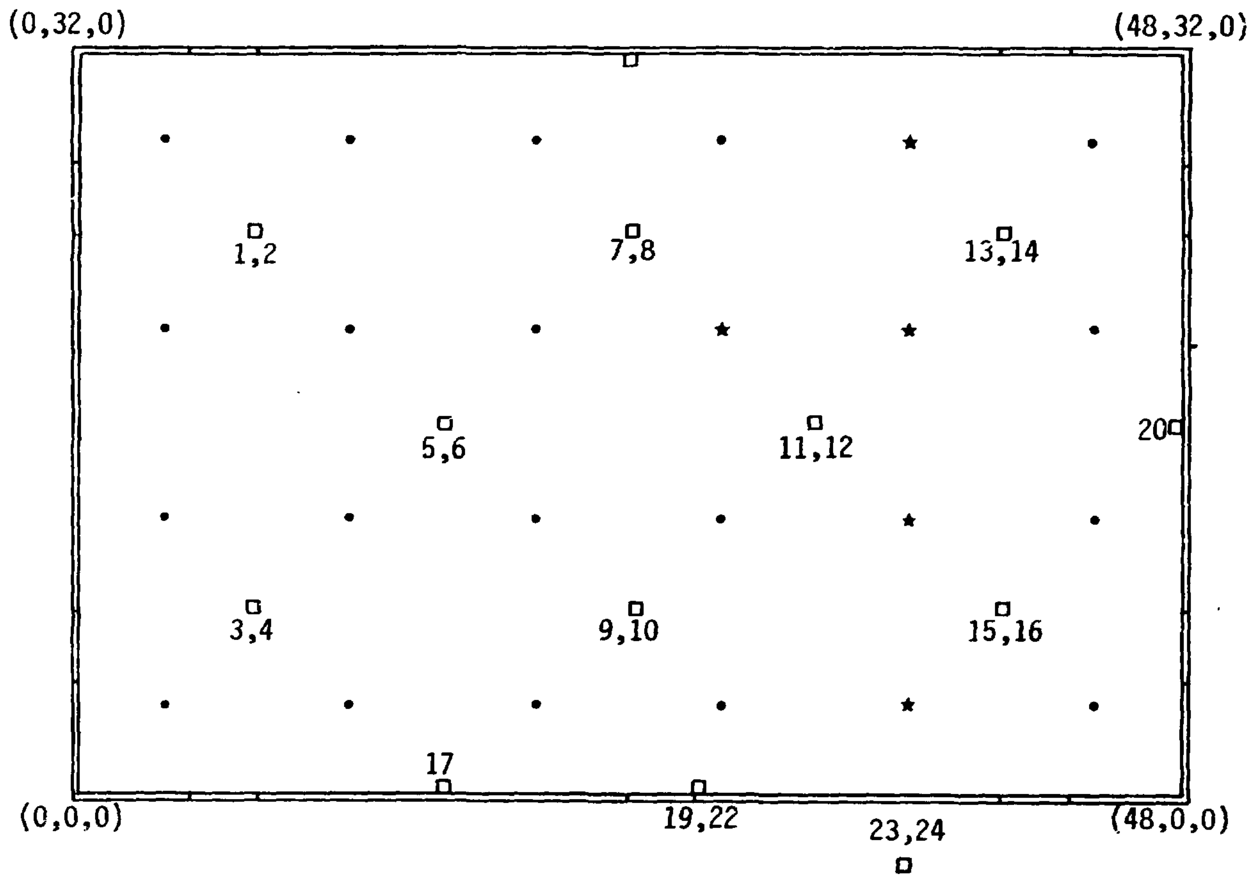


Figure III-11. Fan in Place in Window

Figure III-12. YSI thermistor network. The bead at the end of the three fine wires contains two precision thermistors. The bead is connected to a tie strip, on which its associated resistor network is also mounted.



- ● Airflow measurement point.

- ★ *Measurement points lost in configurations with three small rooms.*

- ▫ Thermistor.

Figure III-13. Interior Airflow Measurement Points and Thermistor Locations

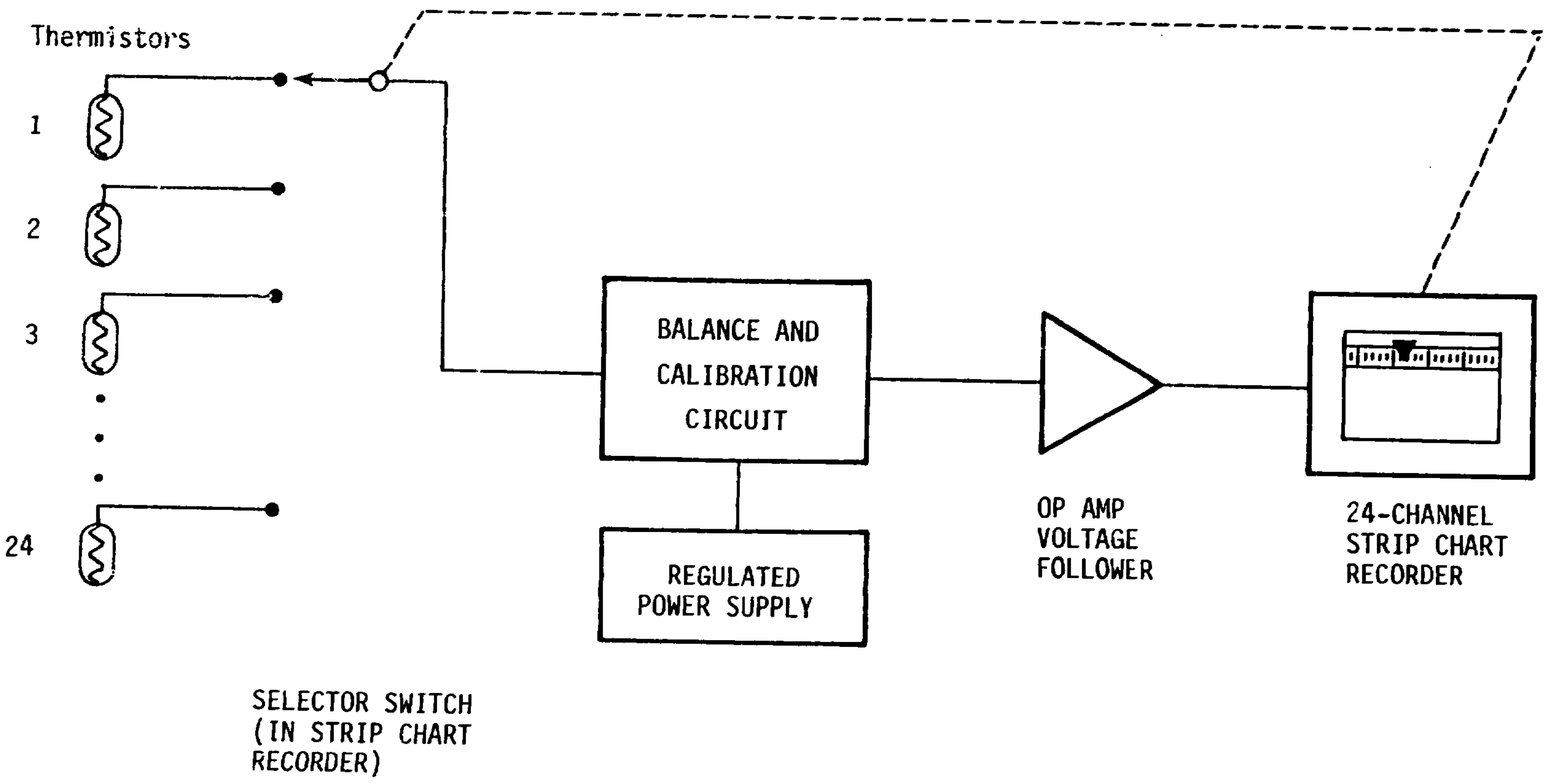


Figure III-14. Temperature Measurement Circuit

Air velocity was determined with measurements of two parameters: airflow and airspeed. Airflow was visualized by injecting streams of neutral-density smoke with a Mine Safety Appliances Smoke Generator Kit. Angles of elevation and azimuth of the direction the smoke drifted were obtained using an Edmund Scientific "Star Finder," which has two perpendicular scales marked in degrees attached to a sighting tube. Airspeed was measured in feet per minute with a Kurz Electronic Anemometer, Model 441S. All the above mentioned instruments are illustrated in Figures III-15, III-16, and III-17.

4. Experimental Protocol

The series of experiments, or runs, was conducted in order on Floor Plans 1, 2, and 3. For Floor Plans 2 and 3, runs were made for the aperture configurations in the original construction, expedient openings added, and runs repeated. The runs were made in numerical order according to the run numbering scheme given in Table III-1.

After the runs listed in Table III-1 were completed, five additional runs were conducted. Run 300 was similar to run 280 except that a stack was erected above the ceiling at Location 24,16,8. The stack, shown in Figure III-18, was composed of four cylindrical flues 6 feet high and 15 inches in diameter. Runs 310, 311, 320, and 321 were similar to runs 260, 261, 050, and 051, respectively, except that all WIMPs were removed for the former. The array of 150 60-watt lamp bulbs remained in the shelter, however.

Finally, a procedure was carried out to qualitatively determine the effect on airflow patterns of closing off the bottom of the exterior doorway. The doorway was partially closed by placing barriers 1, 2, and 3 feet high in the doorway and applying smoke with the smoke generator along the floor at varying distances from the door and at varying heights at the barrier. Smoke

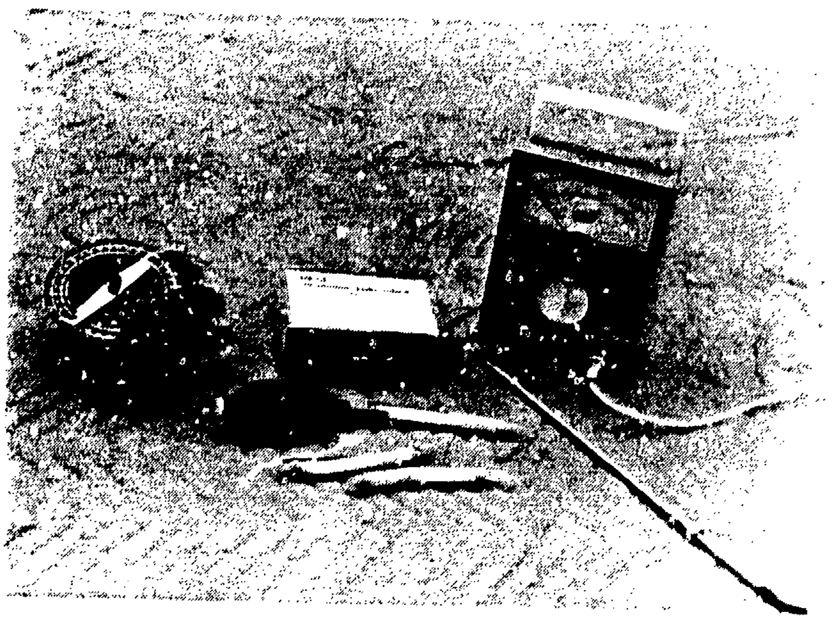


Figure III-15. Air velocity instruments. Left to right: Edmund Scientific Star Finder, MSA Smoke Tube Kit, and Kurz Electronic Anemometer.

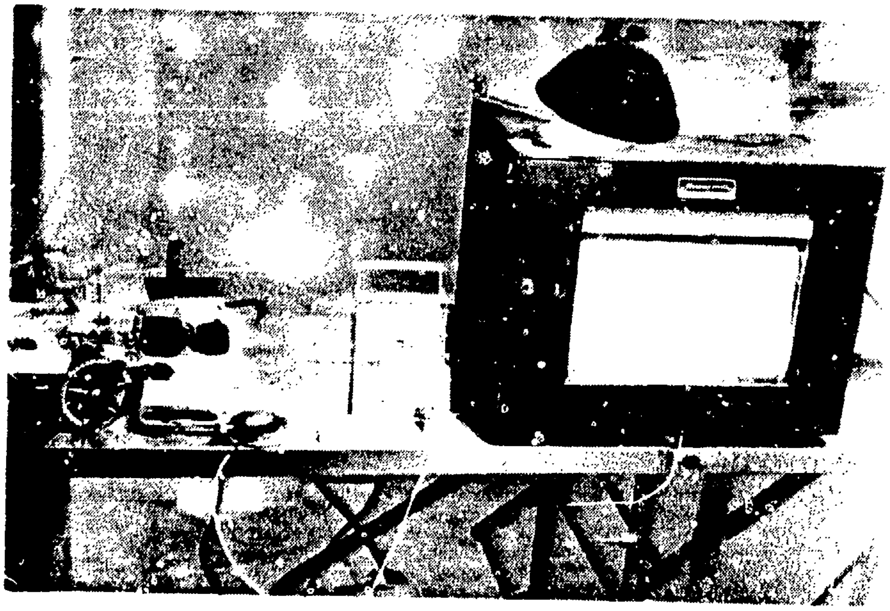


Figure III-16. Air velocity instruments with components of the temperature circuit. Left rear: Balancing Circuit and Op Amp. Right: 24-Channel Strip Chart Recorder.

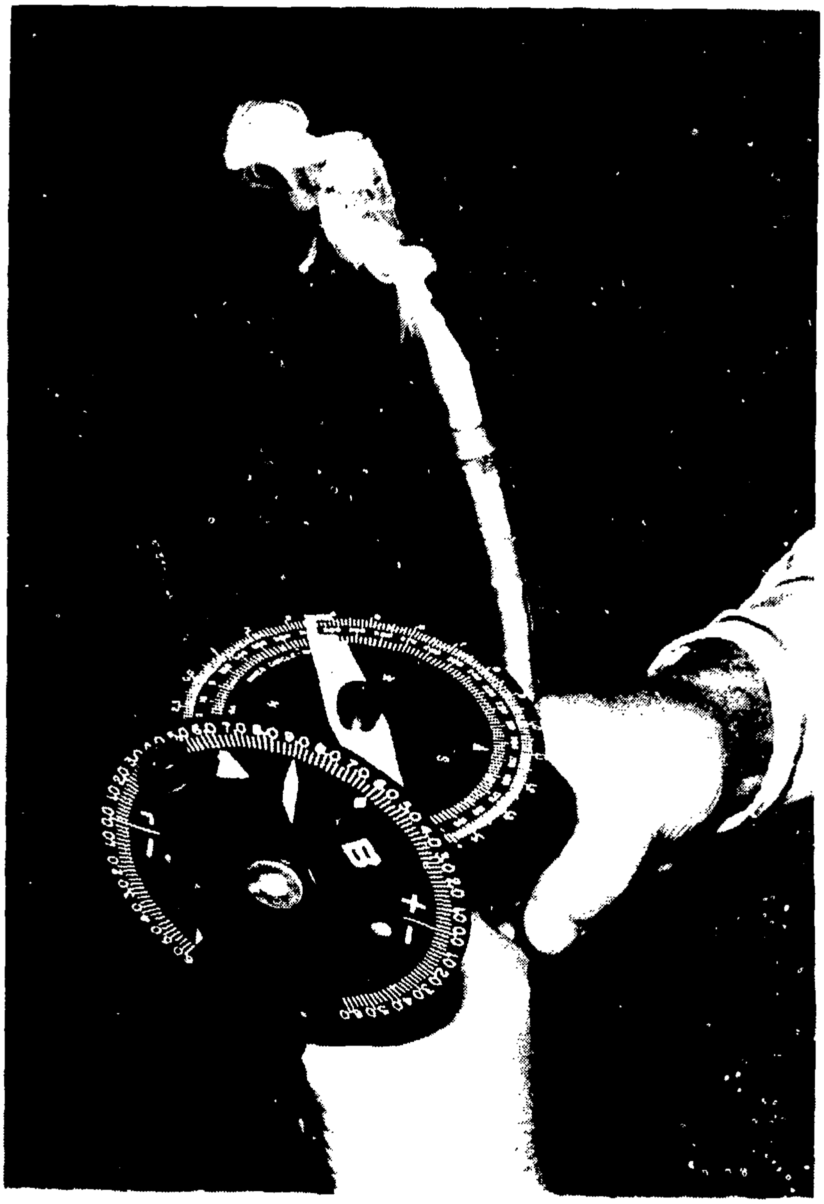


Figure III-17. Smoke Generator and Star Finder

Figure III-18. Six-Foot, 4-Flue Stack Erected in Center of Ceiling

TABLE III-1. EXPERIMENTAL RUN NUMBERING SCHEME

Aperture Configuration	Run Numbers			
	Original Construction		Expedient Openings Added	
	Natural Ventilation	Forced Ventilation	Natural Ventilation	Forced Ventilation
Floor Plan 1: Single room				
Apertures				
One wall only	010	011	---	---
Two adjacent walls	020	021	---	---
Two opposite walls	030	031	---	---
Three walls	040	041	---	---
Four walls	050	051	---	---
Floor Plan 2: Two rooms of comparable size				
Apertures				
One wall of one room	100	101	150	151
Two walls of one room	110	111	160	161
Both rooms in end walls	120	121	170	171
Both rooms not in end walls	130	131	180	181
Both rooms in all salls	140	141	190	191
Floor Plan 3: Large area with small adjoining rooms				
Apertures				
One wall of large area	200	201	250	251
Two walls of large area	210	211	260	261
All small rooms only	220	221	270	271
All small rooms and large area	230	231	280	281
One small room and large area	240	241	290	291

was also applied along the wall below the windows. Tests were made with and without the fan.

5. Experimental Procedure

The experimental procedure followed was uniform for all runs. The lamps under the WIMPs were first turned on and about 20 minutes allowed for thermal equilibrium to be established in the shelter.

For natural ventilation runs, the fan was pushed away from the window but kept inside the shelter. The temperature measuring circuit was then turned on and allowed to warm up. It was calibrated with glass thermometers in oil baths with Thermistors 23 and 24. The strip chart recorder was then turned on and allowed to cycle through all 24 thermistors at least three times.

Air velocity measurements were first made at all the apertures, including any expedient openings. The smoke generator was used at each 1-foot square indicated by the grid of strings in the apertures, mainly to determine only whether air was flowing into or out of the square. Occasionally--for example, when there was an appreciable flow parallel to a wall--the angle of air movement through the aperture was measured with the Star Finder. Airspeed measurements at each 1-foot square were then made with the Kurz Anemometer.

Interior air velocity measurements were made at each of the 24 airflow measurement stations shown in Figure III-13. Separate readings were taken at heights of 8 feet, 6 feet, 2 feet, and 0 feet, after which another set of temperature recordings was made.

The forced ventilation runs were conducted in the same manner, with the following differences. The fan was rolled up to the appropriate window, sealed to the edge with duct tape, and turned on. The WIMP lamps remained on. Temperature recordings and air velocity readings were made at all apertures except that with the fan. Interior air velocity measurements were made only at the 6- and 2-foot heights. The forced ventilation runs were completed with another temperature recording.

IV. EXPERIMENTAL RESULTS

Data collected from the ventilation experiments were analyzed and presented in two formats. First, the data from each test were used to develop a graphic description of the temperatures and airflow patterns within the test facility. Second, pertinent parameters from each ventilation test were summarized and presented in tabular form.

A. Graphic Data Presentation

The data collected from the ventilation experiments were three-dimensional in nature. The presentation of such data in two dimensions always involves some data loss. To minimize this loss, and to maintain as much clarity as possible, Research Triangle Institute (RTI) selected and investigated three alternative means of representing the behavior of airflows in and out of the shelter. The first alternative, a two- or three-point perspective drawing, would be the most accurate representation of the magnitude and direction of the airflows. A major shortcoming of this approach, however, is the shortening of more distant vectors because of their increasing distance from viewpoint. The second alternative approach to graphical representation is contour plotting. The major drawback with this method is that it cannot indicate flow direction. The third alternative selected is horizontal vector mapping, which plots vectors at each point on a grid to indicate magnitude and direction of a flow phenomenon.

A search was made to find examples of computer graphic software to perform the three different alternative graphical representations identified above. This search led to a library of plotting routines maintained by the National Center for Atmospheric Research (NCAR). After reviewing NCAR routines adaptable to RTI's inhouse Tektronix 4051 computer graphics system, RTI concluded that the vector mapping routine had the highest probability of success. This routine was used to plot airflow vectors on a rectangular grid at specific altitudes for which data were available.

The flow vector routine was adapted into a program that takes as input the results of airflow measurements within the shelter at any height specified in the experimental design. While the experimental measurements recorded the azimuth, elevation, and speed attributes of each airflow vector, the plots produced by the program show only the azimuth and the scalar magnitude of the airspeed. RTI decided to exclude the elevation parameter, which would have required projection of the flow vector onto the horizontal plane, and simply to plot the scalar value of the velocity instead. This decision ensured that significant flows with a large vertical component were not reduced to much shorter vectors by being projected onto the horizontal plane. The alternative would have presented a false picture of the magnitude of the flows given the horizontal basis of the plots.

The program (illustrated in block form in Figure IV-1) begins by setting all appropriate input array values to zero and setting key constants to their working values. Next, a prompt for "Run Number and Title Header" is printed, asking for the current run number and shelter configuration. This is followed by prompts for data input at the beginning of each of the four independent input modules:

- Input wall configuration data
- Input interior velocity data
- Input temperature data
- Input aperture velocity data.

Once the data have been input into the arrays of the different modules, plot subroutines corresponding to each of the four modules can be run in any order

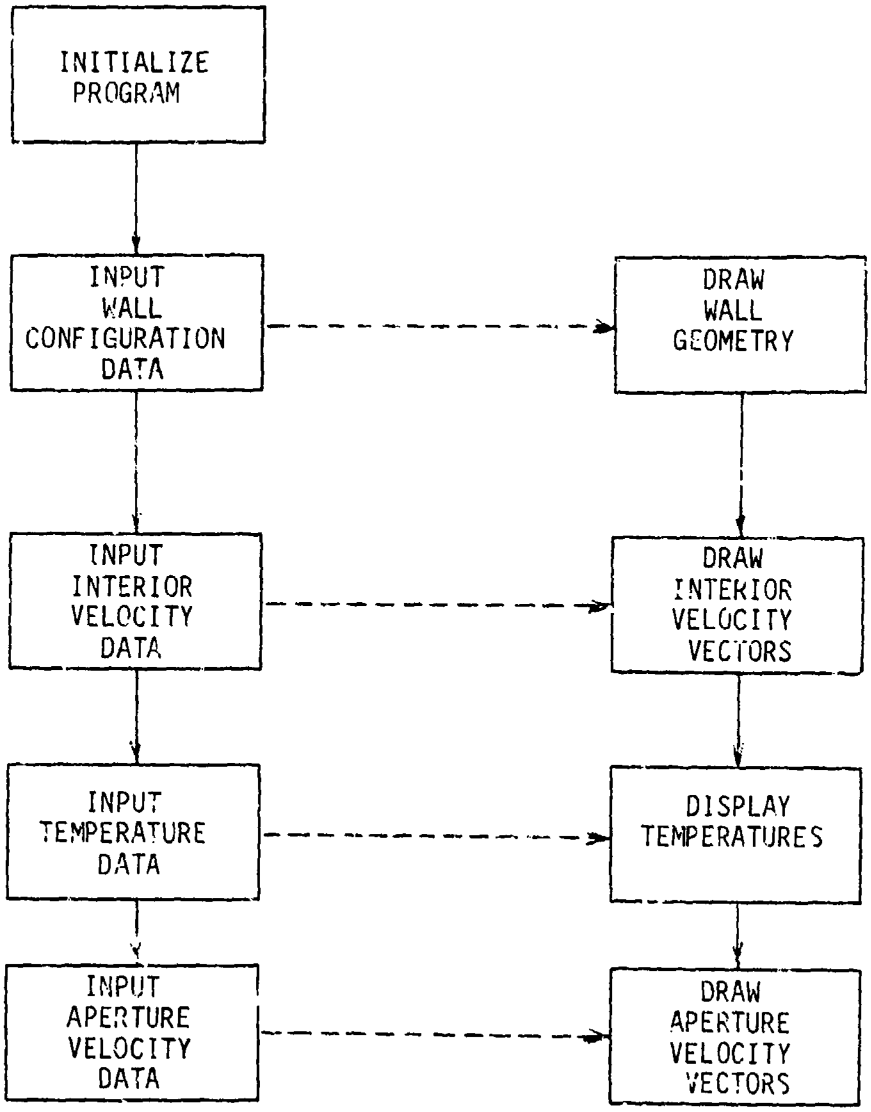


Figure IV-1. Modular Structure of the Plotting Program to produce visual data plots on a viewing screen. Hard copies of these plots can then be produced on the Tektronix 4631 hard copy unit.

One major consequence of adapting the flow vector approach was that many vectors cross each other in the vicinity of aperture openings. This resulted from the venturi phenomenon experienced by airflows as they passed through the apertures. Although it could be construed from the plots that the flow paths cross each other, they never did. The vectors plotted at the apertures simply exhibited directions based on the convergence of airflows as they neared the openings. Another contributing factor was the placement of the nylon string grids on the exterior faces of all the apertures. Had the grids been placed on the inside face of the aperture openings, the flow vectors would have been either parallel or divergent in their directions. It must be emphasized therefore that the vectors plotted do not represent airflows that actually cross; rather, they represent the magnitude and direction of airflows at a discrete point in three-dimensional space.

Another consequence of the flow vector approach was the problem of plotting the wide range of airflow velocities. Most runs exhibited conditions ranging from stagnant in some locations to flows of several hundred feet per minute through apertures and along the floor. This wide variation necessitated application of a scaling factor during vector plot generation to keep the largest vectors from extending completely off the page. Maintaining the same scaling factor within runs assured an accurate picture of the interlevel differences in flow rates. In a number of cases, however, a smaller scaling factor had to be applied to forced ventilation runs to obtain reasonable vector lengths. This difference in scaling factors must be kept in mind when comparisons are made between natural and forced ventilation runs.

To accompany each of the graphic descriptions, RTI prepared brief narrative descriptions of airflow patterns and temperature distribution within the test structure. All of these narrative and graphic data are presented in Appendix D, which is a separately bound volume of this report. Eight examples of the narrative and graphic data are presented below.

1. Run No. 020

In Run No. 020, one door opening and three window openings were made in the exterior wall of a single 32- by 48-foot shelter area. The door opening dimensions were 3 feet by 7 feet, and the window openings were 3 feet by 3 feet at a height of 4 feet above the floor. Airflow measurements were made at the 24 grid points on each of the 0-foot (floor), 2-, 6-, and 8-foot (ceiling) levels of the shelter. Additional measurements were made at all of the aperture openings.

At the floor level, airflows in and around the exterior doorway fanned out into the shelter as shown by the diverging vectors in Figure IV-2. Flow rates at points in the airstream passing through the doorway were measured at 70 to 80 feet per minute (fpm). As the airflow fanned out from the doorway, speeds dropped as shown by the steady decrease in the magnitude of the vectors. A common phenomenon due to the presence of the WIMPS was a shadowing effect on measurement points downstream from the direction of the doorway. This effect resulted in smaller velocities at some measurement points located only inches from strong streams of air flowing between the bases of the WIMPS.

At the 2-foot level, flow vectors quickly dropped to less than 5 fpm, except in the vicinity of the exterior doorway, where flows of 60 to 65 fpm were present. At the 6-foot level, virtually all interior flows were less

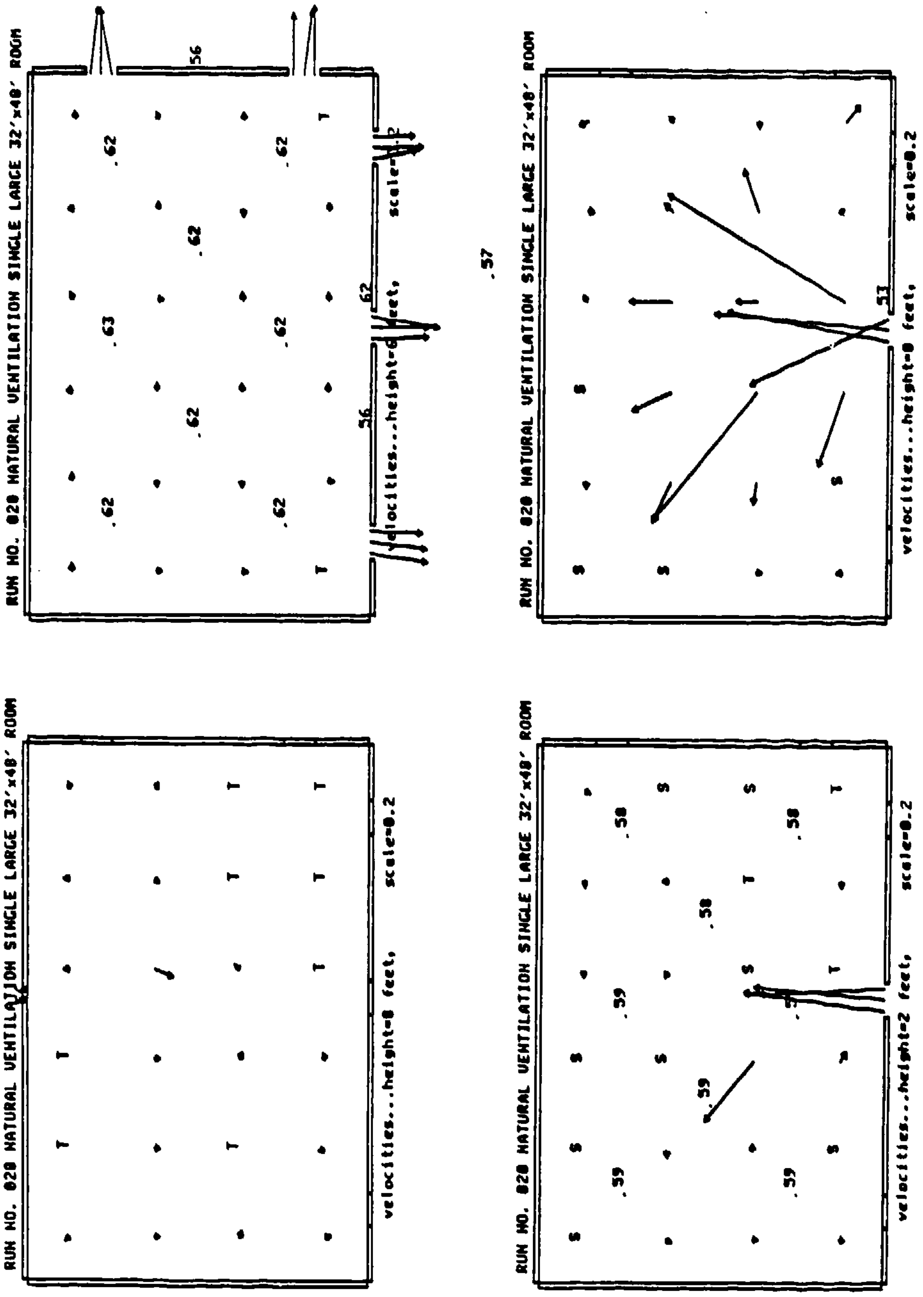


Figure IV-2. Airflow Vectors for Run No. 020

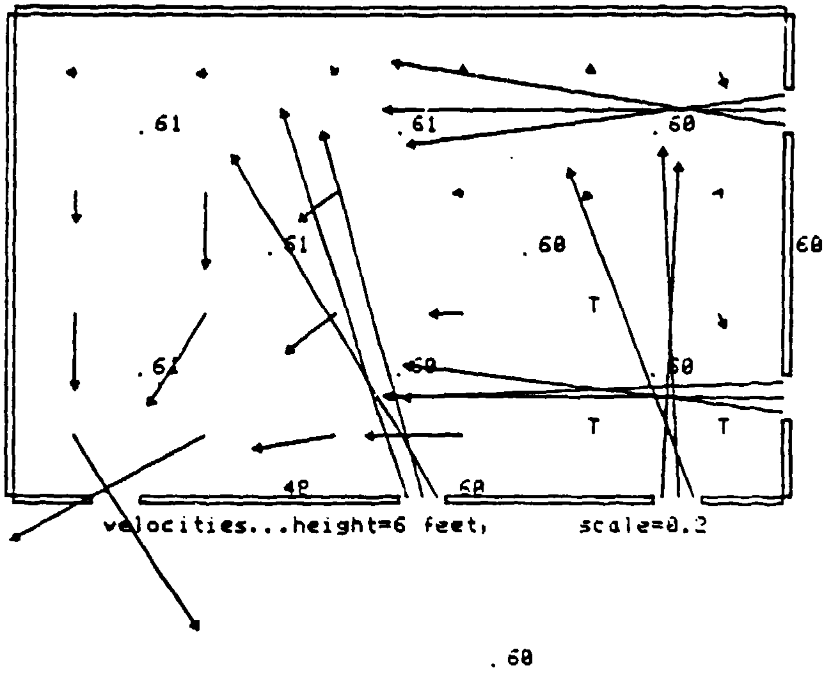
than 5 fpm and in random directions. At the 6-foot level of the window and door openings, the majority of flows were straight out of the shelter at 30 to 35 fpm. At the 8-foot level, airflows were either turbulent or at very low speed.

The air temperatures at the different heights within the shelter should be noted. At the floor level of the exterior doorway, a thermistor measured the temperature of the incoming air at 53° F. At the 2-foot level throughout much of the shelter, the air temperature was 5 to 6 degrees higher (58° to 59° F) while, at the 6-foot level, the temperatures were 62° to 63° F. This is a maximum temperature gradient of 10 degrees between the floor level at the doorway and the 6-foot height of the central portion of the east side of the shelter. The thermistor located in the middle of the east wall at the ceiling level measured a temperature of 56° F, indicating a boundary layer of cold air at the ceiling and wall of the shelter.

2. Run No. 021

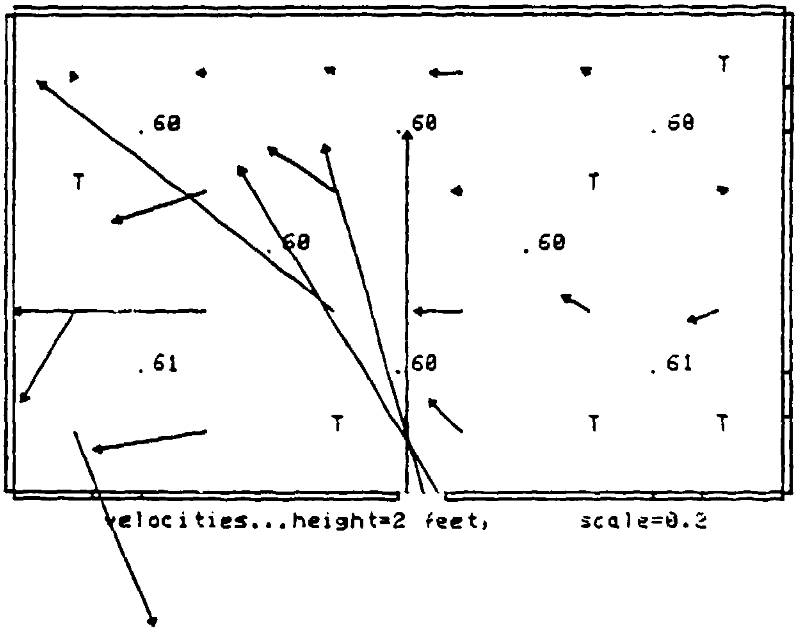
In the forced-flow version of Run No. 021, an exhaust fan of 5,400 cubic feet per minute (cfm) capacity was placed in the north window aperture of the shelter's west wall. Airflow vectors were measured at the 2- and 6-foot levels, as shown in Figure IV-3. Many vectors had magnitudes twice those seen during natural ventilation with speeds of 110 to 130 fpm at the 2-foot level of the doorway. The presence of the fan created a counterclockwise flow, which entered through the doorway and passed around and out through the fan. At both the 2- and 6-foot levels, flows in through the window and doorway apertures seem to cross, but they do not. The directions of the flow vectors at the plane of the aperture measurement grid are still convergent as the outside air experiences a venturi effect while

RUN NO.021 FORCED FLOW, APERTURES IN TWO ADJACENT WALLS



velocities...height=6 feet, scale=0.2

RUN NO.021 FORCED FLOW, APERTURES IN TWO ADJACENT WALLS



velocities...height=2 feet, scale=0.2

Figure IV-3. Airflow Vectors for Run No. 021

being drawn into the shelter interior. Flows in through the doorway and the windows at the 6-foot level were at 120 to 130 fpm.

Due to the large inward flows through the apertures and the large number of points exhibiting turbulence, the temperatures at the 2- and 6-foot levels varied by only a degree or less. Both levels were recorded at 60° to 61° F. There was some question about the performance of the thermistor mounted at 6 feet on the west wall just north of the exterior doorway. The reading taken from this thermistor was 48° F, but no conclusive determination was made about its accuracy during this run. Aside from the boundary layer of cold air within which the thermistor was located, it appeared to be functioning properly in this and all subsequent runs.

3. Runs No. 170 and 171

In the shelter configuration with two rooms of approximately equal size, an east-west wall was added along the short axis of the single room. This wall contained a 4- by 7-foot doorway and two 3- by 3-foot window apertures. The two windows were designated as expedient openings since one was located on the floor on the east side of the doorway and the other was located at the ceiling on the west side of the doorway. The only major flows at the floor level of the natural ventilation run (see Figure IV-4) occurred at the corners of the shelter close to the four exterior window apertures. Flow rates at these points were 25, 50, 50, and 65 fpm clockwise from the southwest corner of the shelter. At the 2-foot level, all flows were either stagnant, turbulent, and/or less than 5 fpm. At the 6- and 8-foot levels, similar flows were present. Temperatures in the shelter ranged between 69° F at the floor level in the south room to 76° to 77° F at the 6-foot level.

In Run No. 171 (see Figure IV-5) the fan was placed in the west window of the north wall. The presence of the fan had a major effect on the intake of

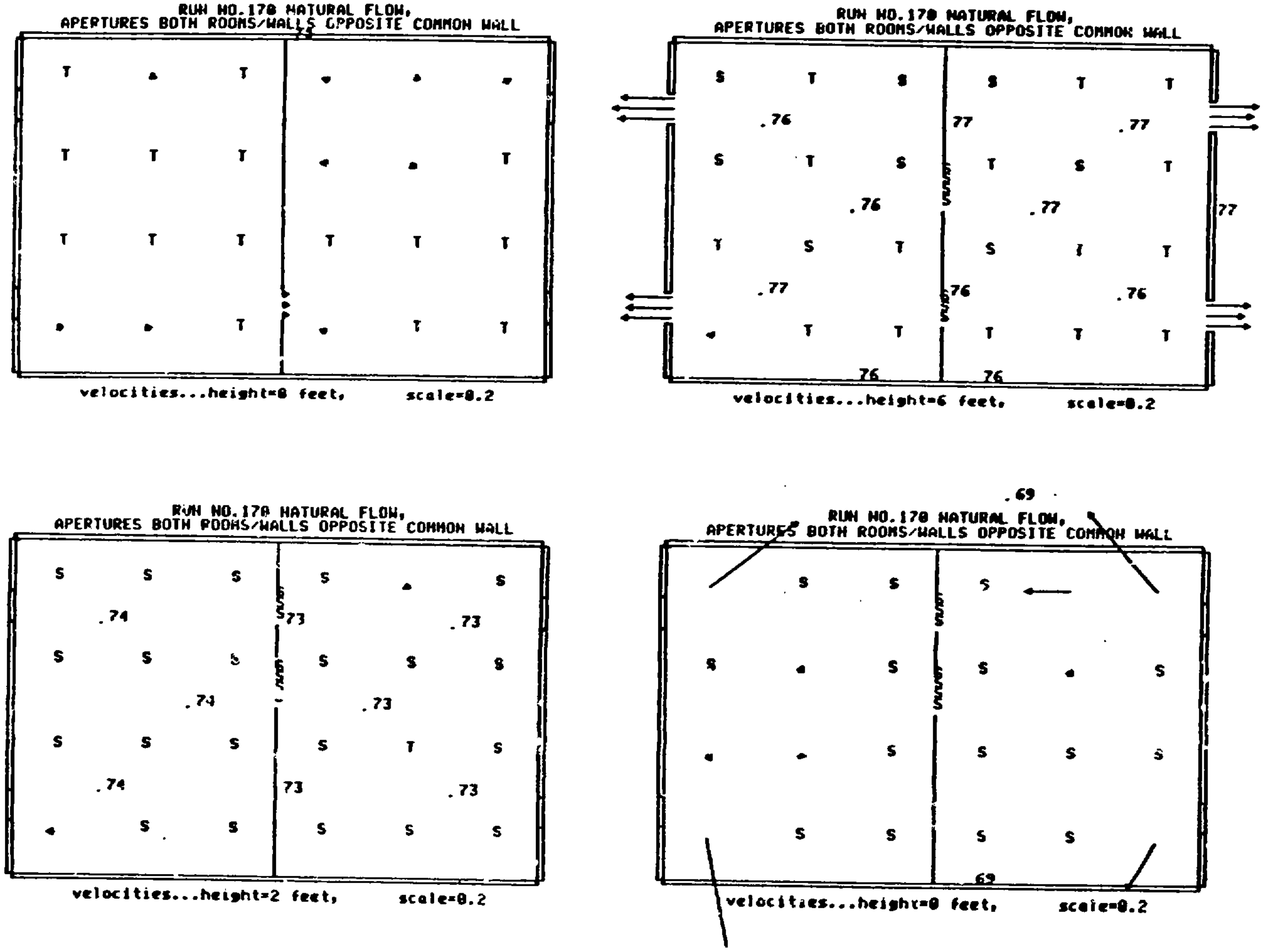
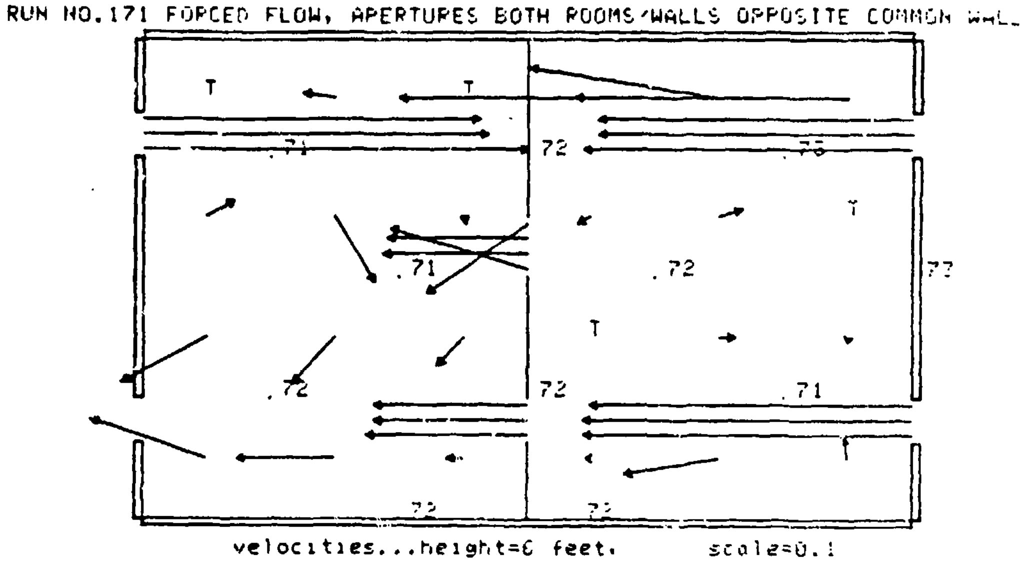


Figure IV-4. Airflow Vectors for Run No. 170



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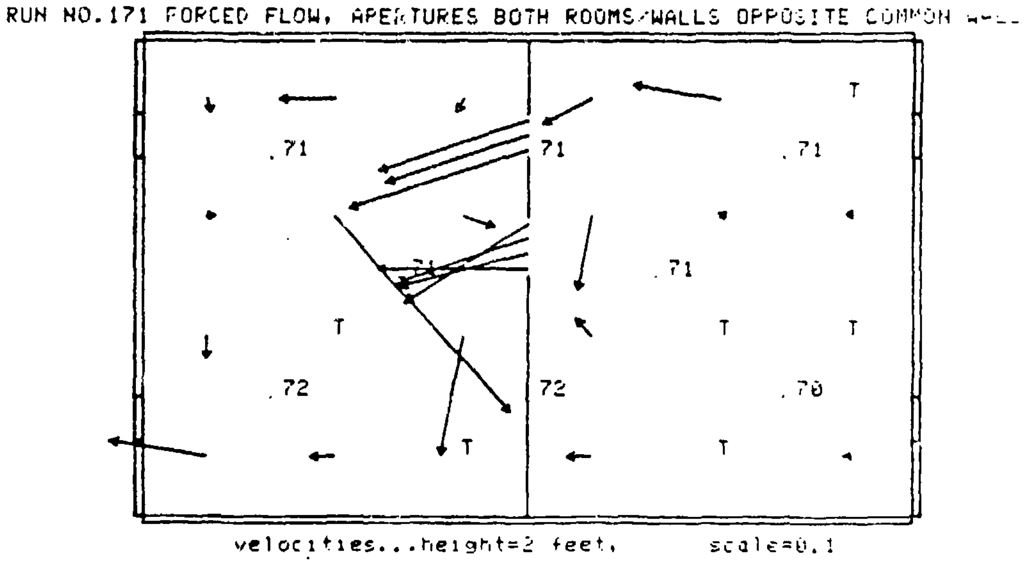


Figure IV-5. Airflow Vectors for Run No. 171

air into the shelter. Flows through the east-west wall from the south room were 85 to 120 fpm at the 2-foot level. One flow vector in the north room, which traveled clockwise from the east window in the north wall around to the exhaust fan, was measured at 170 fpm.

At the 6-foot level, flows in through the windows in the south wall were 195 to 205 fpm. Large flow was seen again in through the east window in the north wall, where one flow vector was measured at 240 fpm. Flow through the interior doorway and the high window aperture in the east-west wall was 80 to 100 fpm at the 6-foot level. As was the case with most forced-flow ventilation runs, the temperature differences between the 2- and 6-foot levels were only one or two degrees.

4. Runs No. 260 and 261

In Run No. 260 (see Figure IV-6) three windows and one door were located in the walls of the large open area opposite three smaller interior rooms. Each of these interior rooms had extra 3- by 3-foot windows in addition to a single doorway.

As was the case with all natural-flow runs with the doorway in the west wall of the shelter, most major flows were at the floor level at speeds between 40 and 140 fpm. Flow vectors at the doorways of the two south rooms had magnitudes between 30 and 45 fpm and created counterclockwise, circular flow in the southeast room and clockwise, circular flow in the southwest room. At the 2-foot level, most interior flows had decreased to less than 5 fpm, except at the sites of the different apertures. Flow through the exterior doorway at the 2-foot level remained between 57 and 63 fpm. At the 6-foot level, most flows dropped to less than 5 fpm, although flows out of the southeast room and the small central room were between 5 and 15 fpm. The flows exhausting the large open area through the windows and the exterior

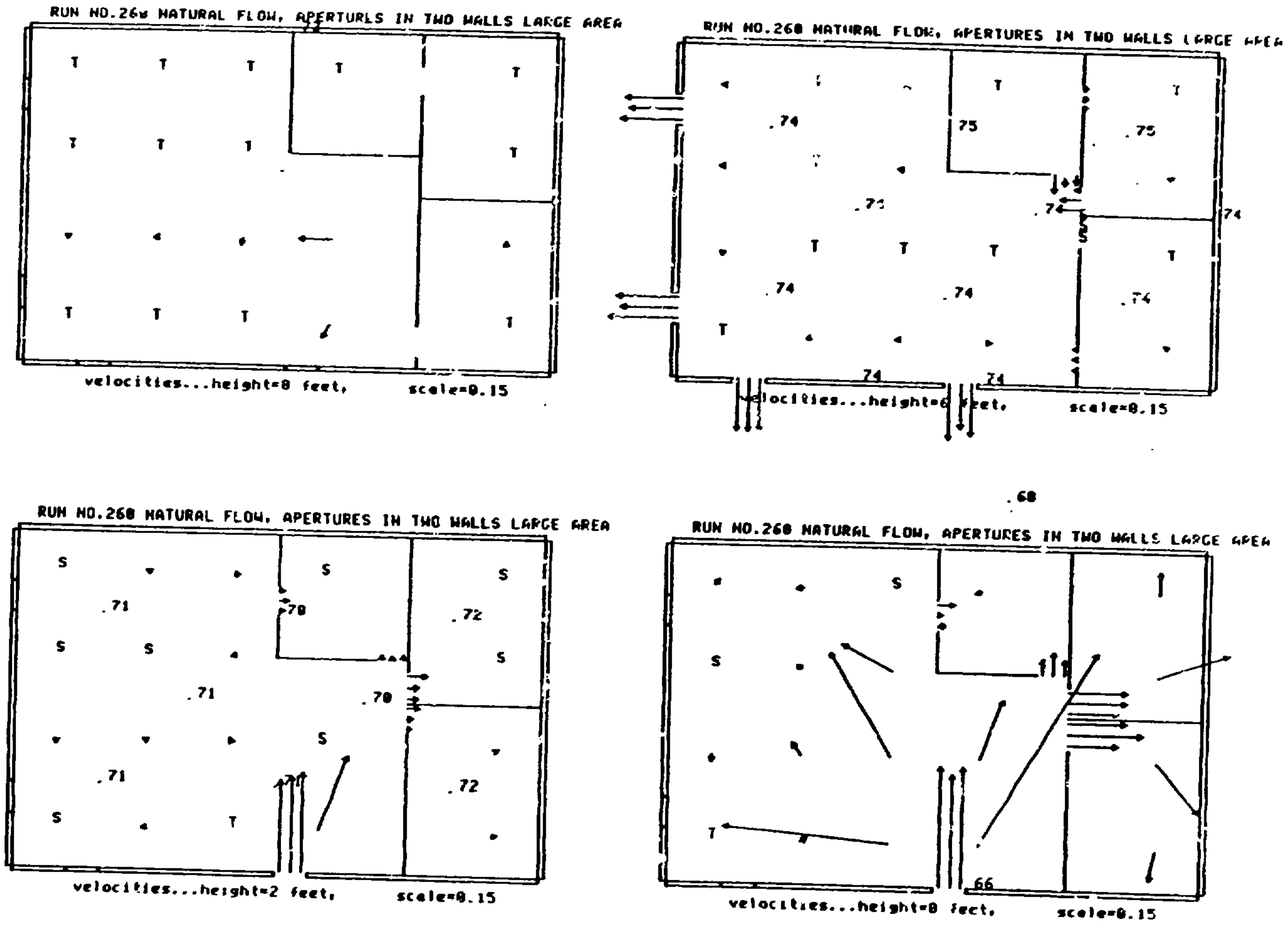


Figure IV-6. Airflow Vectors for Run No. 260

doorway ranged between 30 and 40 fpm. At the 8-foot level, almost all flows were turbulent or less than 5 fpm with only a few exceptions.

The differences in air temperatures inside and outside the shelter were significant. The temperature of the air entering at the floor level was 66° F but increased to 70° to 72° F by the time it ascended to the 2-foot level. At the 6-foot level, temperatures were 74° to 75° F.

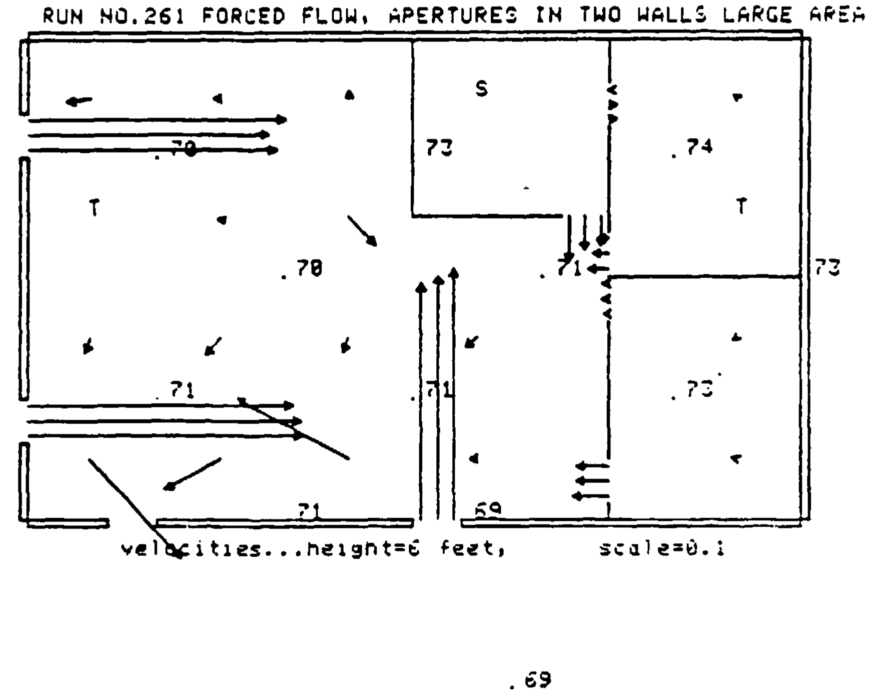
In Run No. 261 (see Figure IV-7) the fan was placed in the north window of the west wall of the shelter. Several interesting effects resulted from this configuration. While creating the clockwise and counterclockwise flows that arise at the various openings on each side of the exhaust fan, it also caused floor level flow into the small central room on the east wall.

Airflows in through the exterior doorway at the 2-foot level were 145 to 150 fpm, and one interior flow vector near the doorway pointing toward the northwest corner of the large open area was measured at 230 fpm. Once again the clockwise and counterclockwise circulation patterns were set up in the small southeast and southwest rooms, respectively. Another consequence of this configuration was an eddy flow in the northeast corner of the large open area. The temperature range within each level and between levels was only 3° to 4° F.

5. Runs No. 320 and 321

Runs No. 320 and 321 were made in the single-room configuration with the shelter occupants removed. The aperture configuration for Run No. 320 involved two 3- by 3-foot window openings in each of the four walls of the large single room, along with a single 3- by 7-foot doorway in the middle of the west wall.

While the airflows for Run No. 320 (see Figure IV-8) repeated the common fan-out phenomenon seen in earlier runs, there were no concentrated airstreams



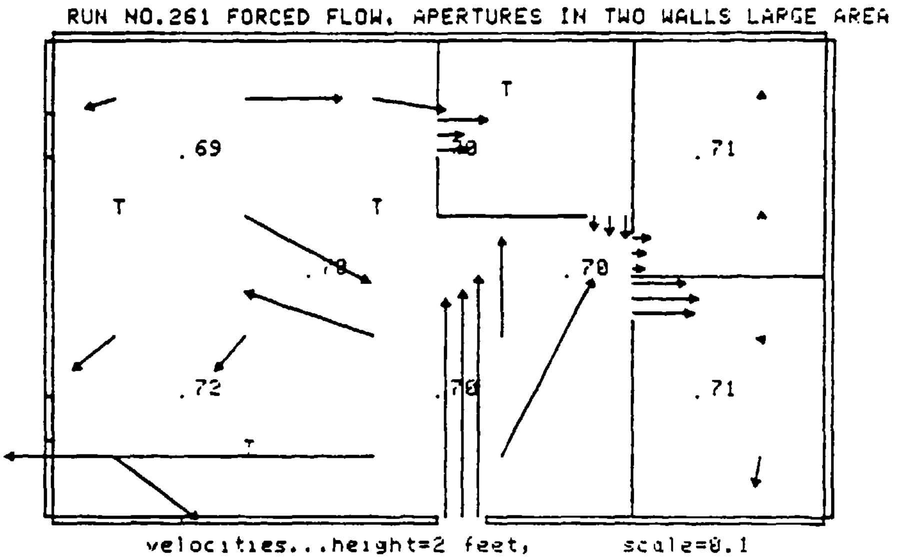


Figure IV-7. Airflow Vectors for Run No. 261

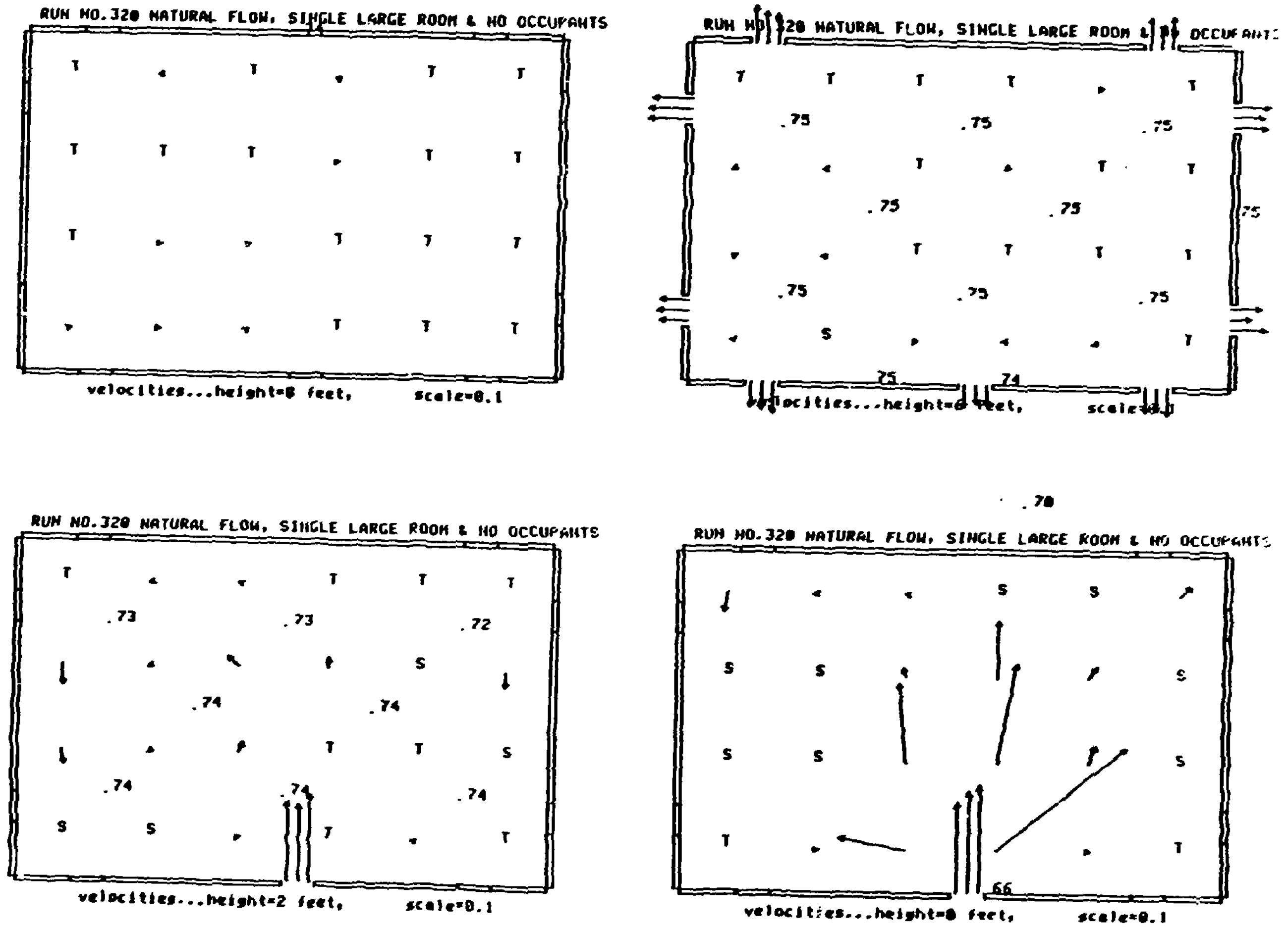
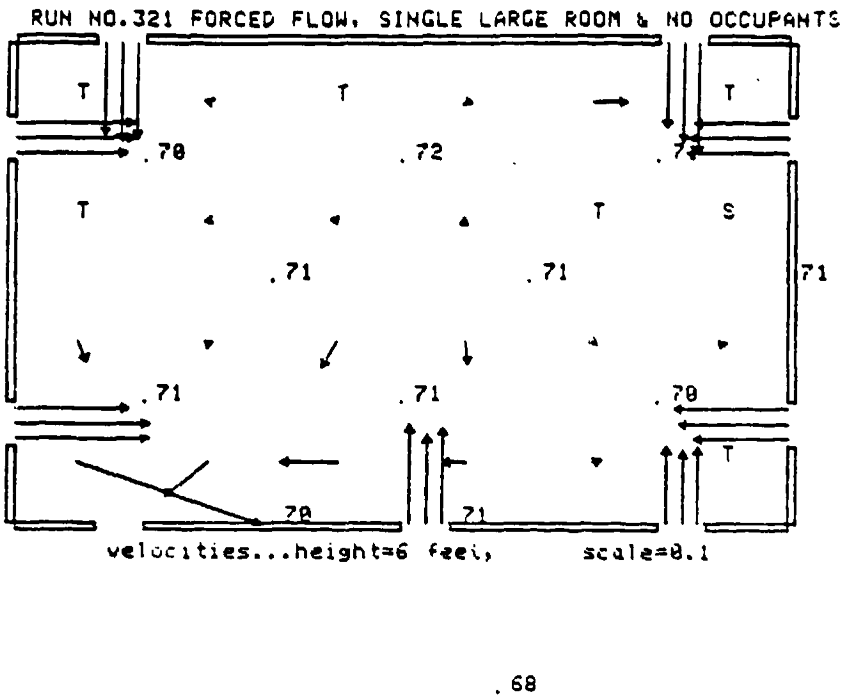


Figure IV-8. Airflow Vectors for Run No. 320

as occurred in the presence of the cylindrical WIMPS. Airflow at the floor level through the exterior doorway was between 85 and 100 fpm, and the fan-out flow vectors were between 60 and 150 fpm. With the absence of streaming, all of these flows quickly fell to less than 5 fpm before they reached the far walls of the shelter. Two exceptions to this rapid decline in airspeed occurred in the northeast and southeast corners, farthest from the doorway, where the window openings supplied additional cool air.

At the 2-foot level, flow in through the doorway was between 72 and 82 fpm, while most interior flows were less than 5 fpm. A few 10 and 20 fpm flows remained in the north portion of the shelter. At the 6-foot level, almost all interior flows were turbulent, while flows of warm air out through the exterior openings were between 20 and 40 fpm. At the 8-foot level, all flows were less than 5 fpm. The temperature gradient between the floor level of the doorway and the 6-foot level in the interior of the shelter was 9° F or between 66° F and 75° F.

In Run No. 321 (see Figure IV-9) the fan was placed in the north window of the west wall. At the 2-foot level, interior flows were primarily in the direction of the exhaust fan and were largest in the central portions of the shelter. A significant number of points along the outside walls of the shelter registered minimal airspeeds of 5 fpm or less. The flow into the shelter through the exterior doorway was between 70 and 80 fpm. At the 6-foot level, flows in through the 3- by 3-foot windows ranged between 50 and 85 fpm, while flow in through the doorway was between 55 and 65 fpm. Interior temperatures at the 2-foot level varied between 69° and 71° F, while at the 6-foot level the variation was between 70° and 72° F.



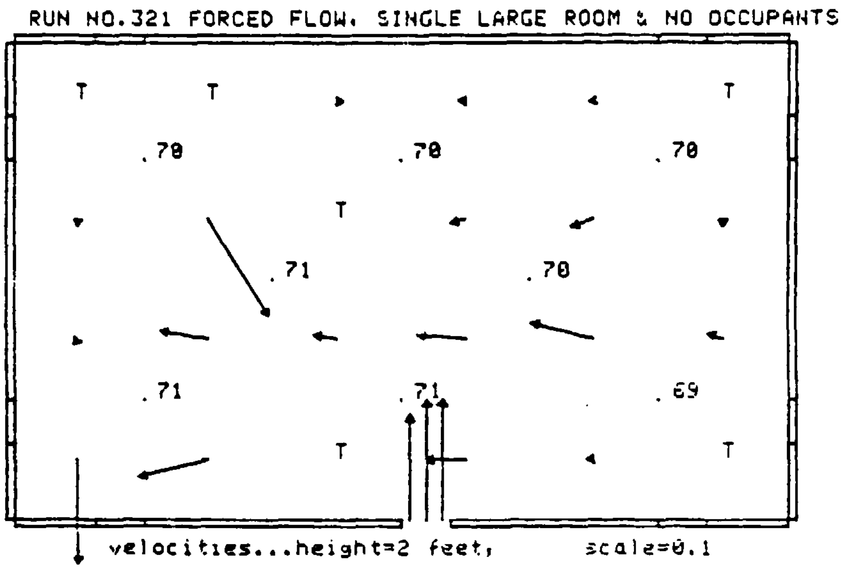


Figure IV-9. Airflow Vectors for Run No. 321

B. Tabular Data Presentations

Airflow and temperature data collected in the experimental phase of the project, 55 individual runs, are summarized in Tables IV-1, IV-2, and IV-3. Interpretations of these data are discussed below.

1. Airflow

Columns labeled "Ventilation rates" in Tables IV-1 through IV-3 give the air volumes (in cubic feet per minute [cfm]) that circulated through each room, as well as the entire shelter, for each run. These numbers were derived from measurements of air flowing through each aperture according to the following equation:

$$Q = \sum_{i=1}^{n} A_i V_i \quad ,$$

where

Q = volume flow in cfm

A = cross-section area in square feet

V = airspeed in feet per minute (fpm)

n = number of measurement points.

In this case, A = 1, since each aperture was divided into 1-foot squares by nylon strings stretched across the plane of the opening. Measurements were made in the middle of each square--9 for a 3- by 3-foot window, 21 for a 3- by 7-foot doorway, etc.

For Floor Plans 2 and 3, ventilation rates are given for individual rooms. The sums of these rates do not necessarily equal rates for the entire shelter because flow values of air shared by adjacent rooms through common apertures are counted for both rooms.

A quantitative basis for comparing the runs with respect to air movement within the shelter is furnished by numbers in the "Interior Air Flow Score"

TABLE IV-1. AIRFLOWS AND TEMPERATURES

Floor Plan 1: Single Room

Run		Ventilation rates, cubic feet per minute		Interior airflow score	Temperatures, °F				
Natural	Forced	Entire shelter	Per person		Ambient	Entering	Minimum	Maximum	ΔT
010		780	5.2	0	60	56	56	68	12
020		975	6.5	1	57	53	53	63	10
030		918	6.1	0	59	57	57	65	8
040		1,290	8.6	9	49	49	49	59	10
050		1,373	9.2	6	48	49	48	57	9
	011	5,270	35.1	69	63	63	60	67	7
	021	5,750	38.3	80	60	59	59	61	2
	031	5,840	38.9	94	59	58	58	62	4
	041	5,345	35.6	70	56	55	54	58	4
	051	5,460	36.4	54	51	51	51	55	4

TABLE IV-2. AIRFLOWS AND TEMPERATURES.

Floor Plan 2: Two rooms of comparable size

Run		Ventilation rates, cubic feet per minute				Interior airflow score	Temperatures, °F				
Original construction											
Natural	Forced	North room	South room	Entire shelter	Per person		Ambient	Entering	Minimum	Maximum	ΔT
100		263	603	603	4.0	2	58	55	55	66	11
110		348	835	835	5.6	1	59	55	55	67	12
120		275	260	535	3.6	0	52	--	51	61	10
130		320	735	695	4.6	0	63	60	59	71	12
140		545	896	1,212	8.0	8	59	58	58	66	8
	101	230	5,630	5,630	37.6	75	56	56	54	60	6
	111	260	5,610	5,610	37.4	38	64	63	63	70	7
	121	6,000	3,625	5,750	38.3	114	57	--	57	62	5
	131	6,200	5,670	5,935	39.6	179	65	64	64	67	3
	141	5,395	2,395	5,375	35.8	63	63	62	61	67	6

(Continued)

TABLE IV-2. AIRFLOWS AND TEMPERATURES (Continued)

Floor Plan 2: Two rooms of comparable size

Run		Ventilation rates, cubic feet per minute				Interior airflow score	Temperatures, °F				
With expedient openings											
Natural	Forced	North room	South room	Entire shelter	Per person		Ambient	Entering	Minimum	Maximum	ΔT
150		172	540	540	3.6	0	70	64	63	77	14
160		412	811	811	5.4	0	64	61	61	71	10
170		267	240	489	3.3	0	64	--	63	77	14
180		356	776	720	4.8	7	61	60	59	71	12
190		561	943	1,202	8.0	10	69	63	63	76	13
	151	330	5,690	5,690	37.9	94	62	61	61	67	6
	161	334	5,550	5,550	37.0	60	66	64	63	72	9
	171	6,140	3,900	5,640	37.6	118	69	--	69	73	4
	181	5,586	5,618	5,650	37.7	129	68	67	65	71	6
	191	5,295	2,833	5,140	34.3	64	73	70	69	75	6

TABLE IV-3. AIRFLOWS AND TEMPERATURES

Floor Plan 3: Large area with small adjoining rooms

Run: With expedient openings: Natural	Run: With expedient openings: Forced	Ventilation rates, cubic feet per minute: Southwest room	Southeast room	East room	Large area	Entire shelter	Per person	Interior airflow score	Temperatures, °F: Ambient	Entering	Minimum	Maximum	ΔT
280		275	267	168	909	1,368	9.1	8	71	67	66	77	11
290		274	134	75	1,168	1,098	7.3	0	69	65	65	75	10
	251	280	171	185	5,850	5,850	39.0	143	67	66	65	73	8
	261	332	96	310	6,070	6,070	40.5	116	69	68	68	74	6
	271	5,595	2,440	1,640	3,793	5,030	33.5	60	69	--	68	74	6
	281	1,068	1,140	868	2,848	5,425	36.2	81	69	68	67	73	6
	291	1,470	62	210	3,360	6,040	40.3	60	66	66	65	73	8
Special Runs													
300 (280)		273	278	140	1,083	1,519	10.1	6	69	65	65	75	10
310 (260)		168	184	180	1,023	1,023	6.8	8	66	64	63	76	13
320 (050)		--	--	--	--	1,602	10.7	7	69	65	65	75	10
	311 (261)	330	247	283	283	6,170	41.1	101	67	66	66	74	8
	321 (051)	--	--	--	--	--	38.9	62	69	68	67	73	6

TABLE IV-3. AIRFLOWS AND TEMPERATURES (Continued)

Floor Plan 3: Large area with small adjoining rooms													
Run		Ventilation rates, cubic feet per minute						Interior airflow score	Temperatures, °F				
Original construction													
Natural	Forced	Southwest room	Southeast room	East room	Large area	Entire shelter	Per person		Ambient	Entering	Minimum	Maximum	ΔT
200		83	80	56	594	594	4.0	0	63	61	60	72	12
210		122	115	125	908	908	6.1	2	66	62	61	74	13
220		446	406	110	412	550	3.7	0	63	--	63	70	7
230		257	246	148	694	1,046	7.0	3	64	63	61	74	13
240		242	100	85	1,118	1,074	7.2	1	65	60	60	72	12
	201	136	174	162	5,970	5,970	39.7	110	63	62	61	68	7
	211	145	90	159	5,130	5,130	34.2	56	69	68	68	73	5
	221	5,800	1,658	1,090	3,345	5,515	36.8	39	64	--	64	70	6
	231	1,243	1,115	779	5,437	5,305	35.4	74	65	64	64	67	3
	241	1,275	62	155	5,050	5,050	37.7	58	64	63	62	71	9
250		26	95	65	561	561	3.7	0	64	64	64	73	9
260		92	124	92	925	925	6.2	4	68	66	66	75	9
270		371	360	144	232	503	3.4	3	72	--	72	79	7

(Continued)

columns in Tables IV-1 through IV-3. These numbers are "coefficients of draftiness." The score for each run was obtained by adding up the airspeed values at the 2- and 6-foot levels for 19 of the 24 interior measurement points, dividing by 10, rounding to the nearest integer, and subtracting 8.* The minimum score is therefore 0. The average score for natural ventilation runs is 3, with a range of 0 to 10; that for forced ventilation runs is 84, with a range of 38 to 179. Scores seem to be skewed slightly in favor of the forced runs, however, due to differences in airflow patterns between the two modes of ventilation. In natural ventilation, the fastest airspeeds observed were along the floor, with mostly stationary or gently rising air noted at the 2- and 6-foot levels. In the forced ventilation runs, however, a significant horizontal component was present in airflows at these levels. On the average, the ventilation rate for forced runs was 6 times that for natural runs. However, the average interior airflow scores imply that forced runs were 28 times as drafty as natural runs, at least at heights of 2 and 6 feet.

Figure IV-10 shows a diagram of the paths taken by streams of air moving into and out of a doorway in an external wall, as visualized with the help of the smoke generator. A tilted imaginary plane with its low end inside seemed to form a boundary between the air streams entering and leaving the shelter. Very little mixing occurred along this boundary plane, which shifted up and down a few inches in the aperture. In the external doorway, this boundary plane was probably responsible for funneling air downward toward the floor, causing the high-speed streaming observed just inside the doorway.

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*Of the 24 points, 5 were eliminated in Floor Plan 3, and measurements were not made at the floor and ceiling in forced-ventilation runs. The remaining values were thus present for all runs. Readings of less than 5 fpm (the threshold) were given an arbitrary value of 2; thus, the minimum total for all 19 points is 76, which, when divided by 10 and rounded, equals 8.

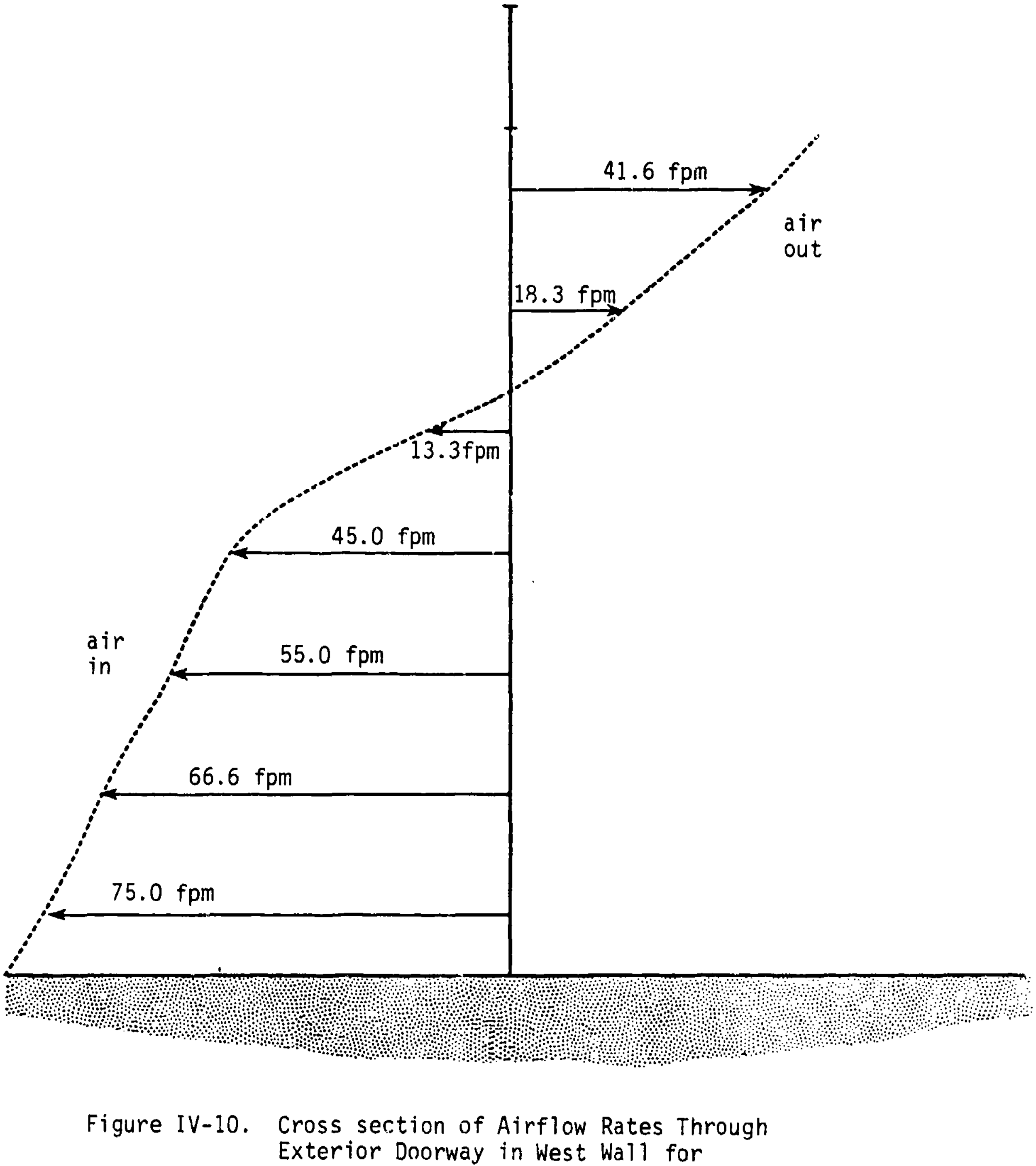

Figure IV-10. Cross section of Airflow Rates Through Exterior Doorway in West Wall for Natural Ventilation Run No. 020

A considerable degree of uncertainty ("noise") was introduced into the airspeed readings by turbulence, which was almost always present around openings, especially in natural ventilation runs. Air moved both into and out of some of the 1-foot squares and occasionally changed direction. In addition, low-speed measurements with the Kurz anemometer were less accurate than high-speed measurements, and considerable "eyeball integration" was necessary when the meter was read.

2. Temperature

In the last five columns of Tables IV-1 through IV-3, the following temperatures are presented for each run: (1) ambient or outside air (Thermistor 18), (2) air entering the shelter through the exterior doorway near the floor (Thermistor 22),* (3) minimum temperature observed, usually the same as entering air temperature, (4) maximum temperature, usually found at 6 feet or near the ceiling, and (5) ΔT, or the difference between maximum and minimum temperatures.

During the experimental period, ambient temperatures (outside the shelter) ranged from 48° to 73° F, averaging 63.5° F. Extremes of minima and maxima were 48° and 79° F; the average temperature inside the shelter was 65.5° F. As expected, values for ΔT were higher for natural ventilation runs than for those in which the fan was used. They ranged from 7° to 14° F, with an average of 10.8° F; the range in forced-ventilation runs was 2° to 9° F, and the average was 5.8° F. Although theory states that natural ventilation is driven by ΔT, there is no consistent correlation in these experiments between ventilation rates and ΔT's because the parameters being manipulated, aperture and room configurations, influenced ventilation rate along with ΔT,

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*Temperatures of entering air are not given for runs 120, 121, 170, 171, 220, 221, 270, and 271 because the exterior doorway was closed for these runs.

and because no experiments were performed where heat input was varied and aperture and room configuration held constant.

After the main series of 50 experimental runs, 5 additional runs were made to determine (1) the effect of a stack and (2) changes caused by removing the WIMP bodies but leaving the 60-watt lamp bulbs in place. Run 300 (Floor Plan 3), with apertures in all small rooms and large areas plus expedient openings, was similar to run 280, except that a stack made of four cylindrical flues 15 inches in diameter and 6 feet long was installed in the center of the ceiling. Although the stack exhausted 428 cfm, or 28 percent of the ventilation for the entire shelter, the overall ventilation rate was only 11 percent greater than that for run 280. Interior air movement was more diffuse, as indicated by a lower interior airflow score.

Runs 310 and 311 were similar to runs 260 and 261 (Floor Plan 3, apertures in two walls of large area plus interior expedient openings), and runs 320 and 321 resembled runs 050 and 051 (Floor Plan 1, apertures in all four walls). Overall ventilation rates were from 2 percent to 17 percent greater; however, the only difference in interior air movement was that flows were more uniform with no channeling.

Finally, a qualitative procedure was performed to determine the effect of a low barrier in the exterior doorway on air movement into the shelter. The smoke generator was used for visualization. As long as the air outside the shelter remained absolutely still, a barrier up to 3 feet high did not prevent air at floor level as far as 3 feet away from climbing over the barrier and entering the shelter. Air from directly beneath a window was seen entering the shelter after surmounting the sill 4 feet from the floor. However, with a slight breeze blowing, low-level air tended to move parallel to the shelter walls and was prevented from entering by a barrier as low as 1 foot high.

V. CONCLUSIONS

Fallout shelter ventilation requirements range from 3 to 50 cubic feet per minute (cfm) per occupant. These requirements depend on the activity and metabolic rates of the occupants, as well as the ambient temperature and humidity (and therefore the location of shelters in the country). Ventilation rates obtained in the shelter configurations tested under natural ventilation in this study were on the low end of these requirements, averaging 6.0 cfm, with a range of 3.3 to 10.1 cfm. Most of these shelter configurations are therefore usable, with minimal occupant distress, only in the cooler and drier sections of the country.

Suitable modifications for improving shelter ventilation include (1) enhancing the stack effect, i.e., providing as much vertical distance as possible between inlets and outlets, (2) using packaged ventilation kits (PVKs) or other mechanical fans to provide forced ventilation, (3) planning to take advantage of wind, and (4) lowering occupant density.

In addition to ventilation requirements of the entire shelter, consideration must be given to the adequacy of ventilation of rooms or sections within a shelter.

In Floor Plan 3, stagnant air was encountered frequently, especially in configurations with few exterior windows. The 12-foot-square "east" room was especially sensitive to aperture changes because of its size and the fact that, after expedient openings were added, it was the only room with openings in all four walls.

Expedient openings can improve the ventilation of rooms in a shelter, but only if their locations are carefully planned. In Floor Plan 3, two of the three rooms and the large area experienced improved ventilation after the expedient openings were added. Ventilation in the other room was impaired, however.

Throughout this study, fast-moving drafts were observed along the floor of the structure. In a real situation, such drafts could be detrimental to occupants, especially young children and the elderly, unless efforts are made to block or disperse air streams or to channel them into ill-ventilated rooms.

Thermally driven natural ventilation that results from occupant heating of the shelter air is not generally adequate for temperature control except in areas where the zonal ventilation requirement is 10 cfm per occupant or less. Such ventilation is adequate to maintain the proper chemical balance in the shelter atmosphere and could prove to be a valuable ventilation technique if a shelter situation arises during a season when temperature control is not needed.

Expedient openings can be very useful in improving both the volume of air supplied and the distribution of air within a shelter. Proper positioning of expedient openings is important, and, in many cases, sophisticated equipment and skilled labor are required to create them.

The presence of the shelter occupants does not noticeably affect the volume of air supplied by thermal forces and does not hinder the distribution of air within the shelter. Occupants do cause some degree of channeling of the air among individual occupants and groups of occupants. This channeling creates localized areas of stagnant air, but such areas are quite limited in size and would not be detrimental to the overall air distribution.

Partitions have a strong influence on the distribution of air within a shelter by blocking the flow of air. Expedient openings in interior partitions could be extremely valuable in improving the air distribution in shelters that have partitions and limited exterior wall openings.

Increasing the vertical distance between ventilation openings by adding stacks can significantly increase the volume of air supplied by thermal forces. The practicality of using this technique in a real shelter situation has not been adequately determined.

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APPENDIX A

LITERATURE REVIEW, NATURAL VENTILATION

APPENDIX A

LITERATURE REVIEW, NATURAL VENTILATION

1. Introduction

In a survey of previous research on natural ventilation in buildings, 22 sources were selected as representative of the state of the art. Although all had some applicability to the ventilation of fallout shelters, only 5 were directly concerned with shelters per se. Five more were of general interest, and the remaining 12 dealt with agricultural buildings.

Most of the sources contained detailed discussions of theory based on mathematical analyses and all but five described experiments using models of structures (mathematical, physical, or both) to predict airflow.

2. General Theory

"Air movement into, through, or out of a building may be caused by wind or thermal forces, acting alone or together. Arrangement, location, and control of ventilating openings should be to combine rather than oppose the two forces"[1].

"For buildings which depend totally on wind effects and temperature differences to provide sufficient ventilation for the housed animals, the primary design concern should be the amount of natural ventilation which occurs when wind speeds approach zero. That is, when a noticeable wind is present most structures will ventilate sufficiently when the side and/or end walls are opened. However, when the wind ceases, the geometry of the structural design should still provide or allow a satisfactory ventilation rate by the stack effect, i.e., flow caused by temperature differences between the inside and outside of the structure"[2].

Airflow due to wind alone can be approximated by the relationship:

$$Q = EAV$$

where

Q = airflow, cubic feet per minute

A = free area of inlet openings, square feet

V = wind velocity, feet per minute

E = effectiveness of openings (E should be taken as 0.50 to 0.60 for perpendicular winds, and 0.25 to 0.35 for diagonal winds).[2a]

However, airflow due to the combination of wind and thermal forces is not the simple algebraic sum of both forces. If both flows are equal, the total is about 30 percent greater than either flow [2]. ASHRAE gives a graph [3] for estimating total flow where wind and thermal effects are unequal. The GATX study [4] addresses the issue of wind forces at angles other than perpendicular to an exterior wall.

Flow due to the thermal (or stack) effect alone depends on the presence of at least two openings in an enclosed structure: an inlet, and an outlet that is higher than the inlet. Also required is a source of heat inside the structure. Without both these requirements there is no thermal flow.

"If there is no significant building internal resistance, and assuming indoor and outdoor temperatures are close to 80° F, the flow due to stack effect is:

$$Q = 9.4\, Ah(t_i - t_o)$$

where

Q = airflow, cubic feet per minute

A = free area of inlets or outlets (assumed equal), square feet

h = height from inlets to outlets, feet

t_i = average temperature of indoor air in height h, degrees Fahrenheit

t_o = temperature of outdoor air, degrees Fahrenheit.

9.4 = constant of proportionality, including a value of 65 percent for effectiveness of openings. This should be reduced to 50 percent (constant = 7.2) if conditions are not favorable.

"Greatest flow per unit area of openings is obtained when inlets and outlets are equal. . . .Increasing the outlet area over inlet area, or vice versa, will increase airflow, but not in proportion to the added area"[3].

J. M. Bruce [5,6,7,8] gives very thorough discussions of the theory of the stack effect. Equations for air velocity [5]

$$V = 2gH\Delta T/T_1$$

and for temperature difference

$$\Delta T = 0.0074T_1 \ (Q/A_2)^{2/3} \ /H^{1/3}$$

are useful in design calculations for shelter ventilation.

(In these equations,

V = velocity in meters per second

g = gravitational acceleration, 9.8 meters per second squared

H = height, vertical distance between inlet and outlet in meters

ΔT = temperature difference between interior and exterior in degrees C

T_1 = interior temperature in degrees K

Q = sensible heat output of occupants in kilowatts

A_2 = outlet area in square meters.)

Bruce disagrees with ASHRAE with regard to the inlet-outlet area ratio.

"When operating under stack effect with inlets (the low level ventilation openings) too restricted, the upper openings become part inlet and part outlet due to the unstable stratification of cold and warm air. The net result is flow in and out of the upper opening and therefore a decrease in the planned outlet area with a corresponding ventilation rate much less than the designer's intention. A commonly used rule-of-thumb is that inlets should have twice the area of outlets. It is not known if this is a real limit, or whether indeed the ratio two is satisfactory in all situations. . . increasing the inlet-outlet ratio has little effect on the outlet area derived"[6].

Another important result of Bruce's derivation is "that the ventilation rate and the temperature difference are virtually independent of the external temperature, i.e., the stack effect is the same winter and summer for the same outlet area, height, and heat load"[5].

The importance of turbulence is emphasized by several authors [9,7,10,11,12,2,1]. One frequently used indicator of turbulent flow is the Reynolds Number, defined as flow divided by viscosity [3,2]. It is usually specified for inlets in the case of forced ventilation [12] or for outlets for natural thermal ventilation [2] and is dependent on the geometry of the opening and the velocity. Turbulent flow appears for Reynolds Numbers in the range of 2,000 to 4,000 and above [3]. Timmons stated the claim, referring to work by others, that "complete kinematic similarity (exists) between model and prototype when flows are dynamically similar, e.g., when similar Reynolds Numbers exist in model and prototype"[12]. This implies a simple quantitative method of verifying the validity of a model.

3. Experimental Methods

Experimental studies in ventilation present a number of specific requirements where "real" or physical modelling is done (as opposed to mathematical modelling, usually done with a computer [13,10,11,1]). These include a structure, either full-size or scaled down; a working fluid; a means of making the fluid flow through and/or around the structure; and a means of visualizing, measuring, and recording the velocity of the flow.

In the literature reviewed, structures were modeled using existing buildings [14,15], full-size models of polyethylene sheeting on wood framing [16,17], full-size models made of insulated hardboard panels on wood framing with transparent Perspex (plexiglas) sections [18,19,20], a scale model of rigid polyurethane sheets held together by tape [7], small two-dimensional plastic models on a water table [21,22], and plastic and wood scale models in wind tunnels [4,12].

In the studies of forced and wind ventilation, airflow was induced by fans, blowers, Packaged Ventilation Kits (PVKs), Kearny pumps [14,18,15,20,9], water flowing across a table [9,21,22], and wind tunnels [4,12]. The thermal ventilation studies used electric heat sources to simulate building occupants. They included butyl bags through which warm water was pumped, thermostatically controlled to release 80 watts, to represent 45 kg pigs [20]; 100 watt incandescent light bulbs surrounded by aluminum foil cylinders, to simulate people [16,17]; and 125 watt butyl bag heaters, to simulate 90 kg pigs [18]. Other studies used an array of 25 10-ohm resistors connected to a variable voltage supply [7], a 186-watt heating pad in conjunction with a 250-watt radiant heating lamp [19], and seven resistance heaters totaling 10 kW. In a theoretical paper, an estimate of 445 watts per beast [5] was given for the sensible heat output of growing cattle of 364 kg (800 lb).

Some studies used small neutral-buoyancy liquid-film bubbles injected into the air stream to visualize and measure flows [18,20,9,4,1]. The bubbles were photographed using a movie or stop-motion camera and flows were measured by tracing the progress of individual bubbles over several frames of film. A disadvantage of this method, where low flow rates are involved, is that the life of a bubble is limited to a few seconds.

Another measurement method involves the use of smoke [19,9], which can be produced by igniting a special pellet, or by the use of an enclosed generator that delivers a thin smoke stream through a long wand. Flow patterns are traced by filaments of smoke that can be seen and photographed. The disadvantage of smoke, aside from irritation of the respiratory mucosa of the experimenters, is that it diffuses into a homogeneous haze.

Other methods of visualization include the use of Fourth of July sparklers and streams of small cork particles [9]. These, however, would be of very little value with low-speed flows. In the water table studies [9,21,22], colored ink was injected into the flowing water with a hypodermic syringe and the flow patterns traced by hand. Hot-wire and laser-Doppler anemometers have been used to measure airflow speeds but not direction [9,11,12]. Laser-Doppler anemometry is valuable in situations where it is important not to interfere with the flow being measured.

4. Conclusions

There are several limitations to be considered in the use of some of the literature reviewed in the present study. Some instrument problems have been mentioned above. Another matter is the difference in ventilation requirements between livestock and people. Randall [20] gives a recommended ventilation range of 0.19 to 1.9m^3/hr•kg of livestock housed and Wright et al. [16] cite the Defense Civil Preparedness Agency (DCPA) shelter requirement of 3 to 50 cubic feet per minute per occupant, which, at an average of 70 kg per person, corresponds to 0.073 to 1.214 m^3/hr•kg, roughly half the requirements of livestock. This seems to imply that modern, well-ventilated housing for farm animals would make poor fallout shelters, and that such design features as open ridges and large wall openings may be inappropriate for shelters, particularly in winter. Conversely, if the thermal ventilation systems discussed in the literature are adequate for cattle and pigs, scaling them down to human requirements should present no insurmountable problems.

Finally, odor may have an important part in shelter ventilation. The sense of smell and the common chemical sense, operating in conjunction as a single perceptual system, plays a complex, emotional, and sometimes subtle role in the human evaluation of well being [3]. Adequate ventilation can minimize the problem of objectionable odors generated during shelter occupancy.

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APPENDIX B

METABOLIC HEATING AND SHELTER VENTILATION

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METABOLIC HEATING AND SHELTER VENTILATION

An investigation of the relative effects of sensible and latent heating on thermally driven ventilation was made to establish a basis for simulating the metabolic heat load of shelter occupants in a shelter environment. A review was also made of past research on metabolic heating. The following sections present the results of the investigation.

1. Effects of Latent Heating on Buoyancy

Thermally driven natural ventilation in a shelter occurs at a rate determined by the square root of the buoyancy of the air within the shelter. Buoyancy, in turn, is generated by the release of metabolic heat into the air by the occupants, a release which is divided into sensible and latent components. In modeling thermal ventilation, therefore, it is important to ascertain the relative effectiveness of these heat releases in generating buoyancy. Such data are plotted in Figure B-1. In this figure the ratio of latent-to-sensible heat release is designated as L/S, and the fraction of the total heat release that is sensible is designated as S/(L + S). These quantities are zero and unity, respectively, for cases in which no latent heat is involved. Specific heat release is computed as N.H/60 ($Q_s \cdot \rho_s$), where

N = number of occupants

H = average metabolic heat rate per occupants, = S + L

Q_s = shelter ventilation rate for a prescribed aperture configuration, cfm

ρ_s = ambient density of air, at typical laboratory conditions of 65° F dry bulb and 50 percent relative humidity, = 0.0754 lb $_{air}/ft^3$

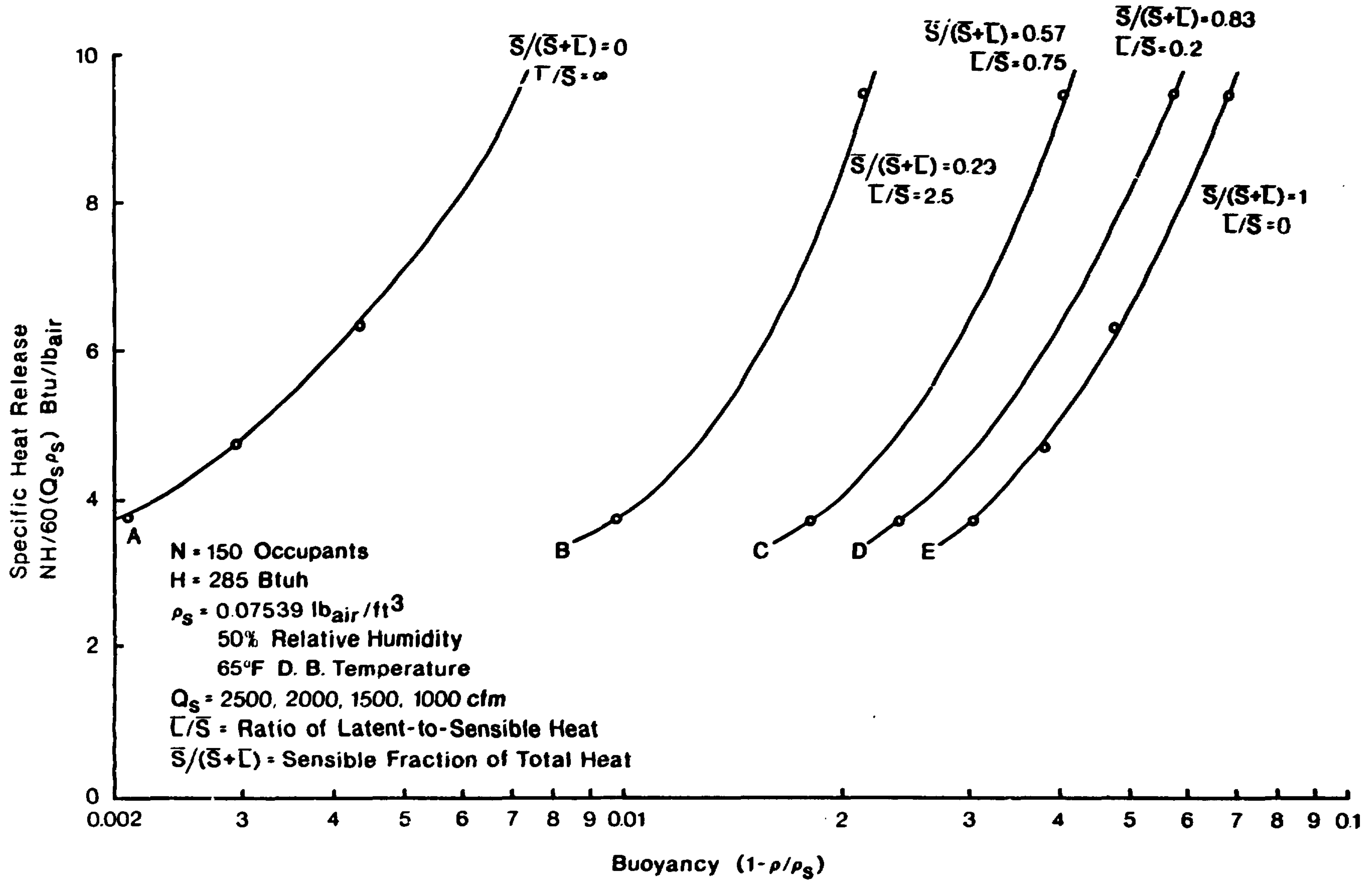
Specific Heat Release
NH/60($Q_s \rho_s$) Btu/lb_{air}
10
8
6
4
2
0
0.002
3
4
5
6
7
8
9
0.01
2
3
4
5
6
7
8
9
0.1
Buoyancy ($1-\rho/\rho_s$)
$\overline{S}/(\overline{S}+\overline{L})=0$
$\overline{T}/\overline{S}=\infty$
$\overline{S}/(\overline{S}+\overline{L})=0.23$
$\overline{L}/\overline{S}=2.5$
$\overline{S}/(\overline{S}+\overline{L})=0.57$
$\overline{L}/\overline{S}=0.75$
$\overline{S}/(\overline{S}+\overline{L})=0.83$
$\overline{L}/\overline{S}=0.2$
$\overline{S}/(\overline{S}+\overline{L})=1$
$\overline{L}/\overline{S}=0$
A
B
C
D
E
N = 150 Occupants
H = 285 Btuh
ρ_s = 0.07539 lb_{air}/ft^3
50% Relative Humidity
65°F D. B. Temperature
Q_s = 2500, 2000, 1500, 1000 cfm
$\overline{L}/\overline{S}$ = Ratio of Latent-to-Sensible Heat
$\overline{S}/(\overline{S}+\overline{L})$ = Sensible Fraction of Total Heat

Figure B-1.

ρ = density of heated air, lb/ft^3

S = proportion of H released sensibly, = $(\rho_s Q_s)\ \bar{S}$

L = proportion of H released as evaporative latent heat, = $(\rho_s Q_s)\bar{L}$.

The specific heat release represents the total heat, Btu, released into each pound of airflow that traverses the shelter. It can be seen that this heat release is directly proportional to the number of occupants and inversely proportional to the rate of ventilation. The rate of ventilation is in turn dependent upon the shelter configuration and buoyancy, $(1 - \rho/\rho_s)$, a complicated dependency involving momentum principles. Here, various typical ventilation rates, as shown in the figure, were assumed and used to determine the range of variation of the specific heat release that might be typically encountered. This range was approximately 3.5 to 9.5 Btu/lb$_{air}$, with N and H chosen as 150 and 285 Btuh, respectively.

The maximum buoyancy that can be produced in a shelter would occur if the entire normal metabolic heat were to be released sensibly, i.e., $\bar{L} = 0$ $(\bar{L}/\bar{S} = 0)$. Under these conditions shelter temperatures become extremely elevated. Such a heat release is depicted as curve E in Figure B-1. It is clearly seen that the buoyancy is approximately proportional to the heat release under these conditions, although not exactly, and that buoyancies in the range of 0.03 to 0.07 should be typical for the specified ventilation rates and other conditions. The dry bulb temperatures that occur for this case range from 81° F to 104° F.

If the same amount of heat is released into the air entirely as latent heat, i.e., $\bar{S} = 0$ $(\bar{L}/\bar{S} = \infty)$, then the buoyancy would be as depicted by curve A. Here it can be seen that the range of buoyancy would be from 0.002 to

0.007, or approximately 7 to 10 percent of the sensible buoyancy. With the expected square root relationship between ventilation rate and the square root of buoyancy, it is clear that latent heating (evaporative moisture addition) does not have a significant direct influence on ventilation rate when compared to an equivalent amount of sensible heating.

When the figure, curve A, is viewed it is also clear that latent heating does produce buoyancy, which in turn will produce ventilation. When this is the only mode of heat addition, it is clear that it cannot be neglected by comparison to an equivalent amount of sensible heating that does not exist. That is, in an actual situation where a large portion of the heat addition is latent, then a significant fraction of the total buoyancy produced will be caused by this latent heating. This effect can be formulated by defining B_L and B_S as the buoyancy produced by the latent and sensible heating, corresponding to $\bar{L}/\bar{S}$ equal to ∞ and 0, respectively, and noting that the total buoyancy B would be

$$\begin{aligned} B &= B_L \;(L/(L + S)) + B_S \;(S/(L + S)) \\ &= [B_L \;(L/S) + B_S][L/S + 1]^{-1} \end{aligned} \qquad (1)$$

Thus, curves B, C, and D in the figure follow directly from such a computation for various specified values of L/S. The curves in the figure were actually computed from an ASHRAE psychrometric chart and necessarily reflect some approximation due to charting. Thus, the above expression and the curves should agree only approximately.

For actual shelters where $\bar{S}/(\bar{S} + \bar{L})$ is expected to be in the range of 0.8 to 0.95, curve D is thought to be representative. Thus, if the specific heat release is 6.0 $\mathrm{Btu/lb_{air}}$, then 17 percent of this is due to latent heat and 83 percent due to sensible heat. The total buoyancy under these conditions would be approximately 0.038. If the heat release into the air is simulated only by its sensible component and N.H/60 ($Q_s \cdot \rho_s$) reduced accordingly by a factor of 0.83, the buoyancy from curve E would be 0.0395. Thus, under conditions that are thought to be representative of both actual and experimental conditions, latent heating can be ignored in determining buoyancy within a very small error. The error in the ventilation rate will obviously be much less.

Under conditions wherein a very large fraction of the total heat release is latent, then error can occur when buoyancy is simulated using only the sensible component. For example, with a $\bar{S}/(\bar{S} + \bar{L}) = 0.29$, curve B, and a total heat release of 8.0, the sensible component will be approximately 2.4 Btu/lb$_{air}$ and the buoyancy approximately 0.019. Extrapolating curve E and reading $(1 - \rho/\rho_s)$ for 2.4 Btu/lb$_{air}$ heat release will yield a buoyancy that is somewhat in error but not greatly so. The very rapid asymptotic nature of these curves, however, makes it clear that if $\bar{S}/(\bar{S} + \bar{L})$ were significantly less than 30 percent, significant error would begin to occur in representing the total buoyancy by the sensible component of the heat release. It is not, however, believed that these cases are of pertinence to shelter ventilation.

A mathematical expression for the curves of this figure was developed by noting that from a simple heat balance on a shelter

$$\frac{NH}{60(\rho_s Q_s)} = \bar{S} + \bar{L} = \bar{S}\,(1 + \bar{L}/\bar{S}) \qquad (2)$$

Also, a property relationship can be developed in the format

$$(\rho_s - \rho)/\rho_s = \frac{\bar{S}}{C_p T_s} + \frac{\bar{L}}{1.64\, h_{fg}} \approx S\left(\frac{1}{126} + \frac{\bar{L}/\bar{S}}{1810}\right) \qquad (3)$$

Eliminating $\overline{S}$ in these expressions yields

$$\frac{NH}{60(\rho_S Q_S)} = \frac{126\ (1 + \overline{L}/\overline{S})}{1 + 0.07\ (L/S)} - \left(\frac{\rho_S - \rho}{\rho_S}\right) \qquad (4)$$

which accurately represents the $NH/60(\rho_S Q_S)$ versus $(1 - \rho/\rho_S)$ curves with $\overline{L}/\overline{S}$ as a parameter. It should be noted that Figure 1 was originally constructed assuming $T_S = 65°F$. However, the curves are approximately independent of T_S as shown in the above equation and should be applicable for all ambient temperatures within an accuracy of about 1 percent.

In conclusion, it can be seen that although both latent and sensible heating causes buoyancy, for many practical applications latent heating is important only insofar as it represents a value that must be determined so that the resulting sensible component can be calculated and used to determine ventilation. The latent heating oftentimes does not directly influence ventilation but does so indirectly by reducing the available sensible heating. Then, if the ratio of the latent to sensible heating is known for a given shelter, the ventilation is determined from the momentum considerations that relate the ventilation rate, Q, to the buoyancy, $(1 - \rho/\rho_S)$. Such a relationship is described below.

2. Effects of Buoyancy on Ventilation Rate

The rate of ventilation that occurs in a given structure is related through momentum principles to the buoyancy driving force and, as described above, the buoyancy can be caused by either sensible or latent heating, or both. The basic relationship is

$$Q_S = C(D,\ A_e/A_i,\ A_e,\ X_i) \cdot \sqrt{H^*} \cdot A_e \cdot (1 - \rho/\rho_S)^{1/2} \qquad (5)$$

where Q_s is the rate of flow of ambient air into the shelter, cfm, H^* is an effective height of the exit area above the inlet area, ft, and A_e is the exit area, ft^2. The loss coefficient C is dependent upon the effective length of the flow path, D, the areas A_e and A_i, and other undefined factors such as occupant density and average occupant size. A typical value for this coefficient will be approximately 200 $cfm/ft^{5/2}$.

In terms of the variables plotted in Figure B-1, this expression is

$$\frac{NH}{60(\rho_s Q_s)} = \frac{NH}{60\rho_s \, C \, A_e \sqrt{H^*}} \left(1 - \rho/\rho_s\right)^{-1/2} \qquad (6)$$

By plotting this expression as a family of operating lines on Figure B-1, the actual ventilation that can be expected for a shelter with a given C and a prescribed value for L/S can be determined at the appropriate cross-over point. Such a plot is shown in Figure B-2 for selected values of C. If all of the heat input to a shelter is sensible heat, then the value of $NH/60(\rho_s Q_s)$ is reached at the cross-over points along the line corresponding to L/S = 0. Q_s is then calculated. If L/S is known to be 0.2, for example, then values are taken at the cross-over points along the line L/S = 0.2 and Q_s values then determined.

In summary, Figure B-2 indicates clearly that if C can be determined or in some way estimated for a given shelter configuration, then the ventilation rate for N occupants releasing a total of H Btu/hr of heat can be predicted relatively easily if the partitioning of the heat between sensible and latent components can be estimated and specified.

3. Latent Versus Sensible Heating in an Actual Shelter

It is now clear that if the ratio $\overline{L/S}$ can be specified for a given shelter, the rate of ventilation can then be predicted. However, estimating $\overline{L/S}$ for an actual shelter is not straightforward. A technique is presented

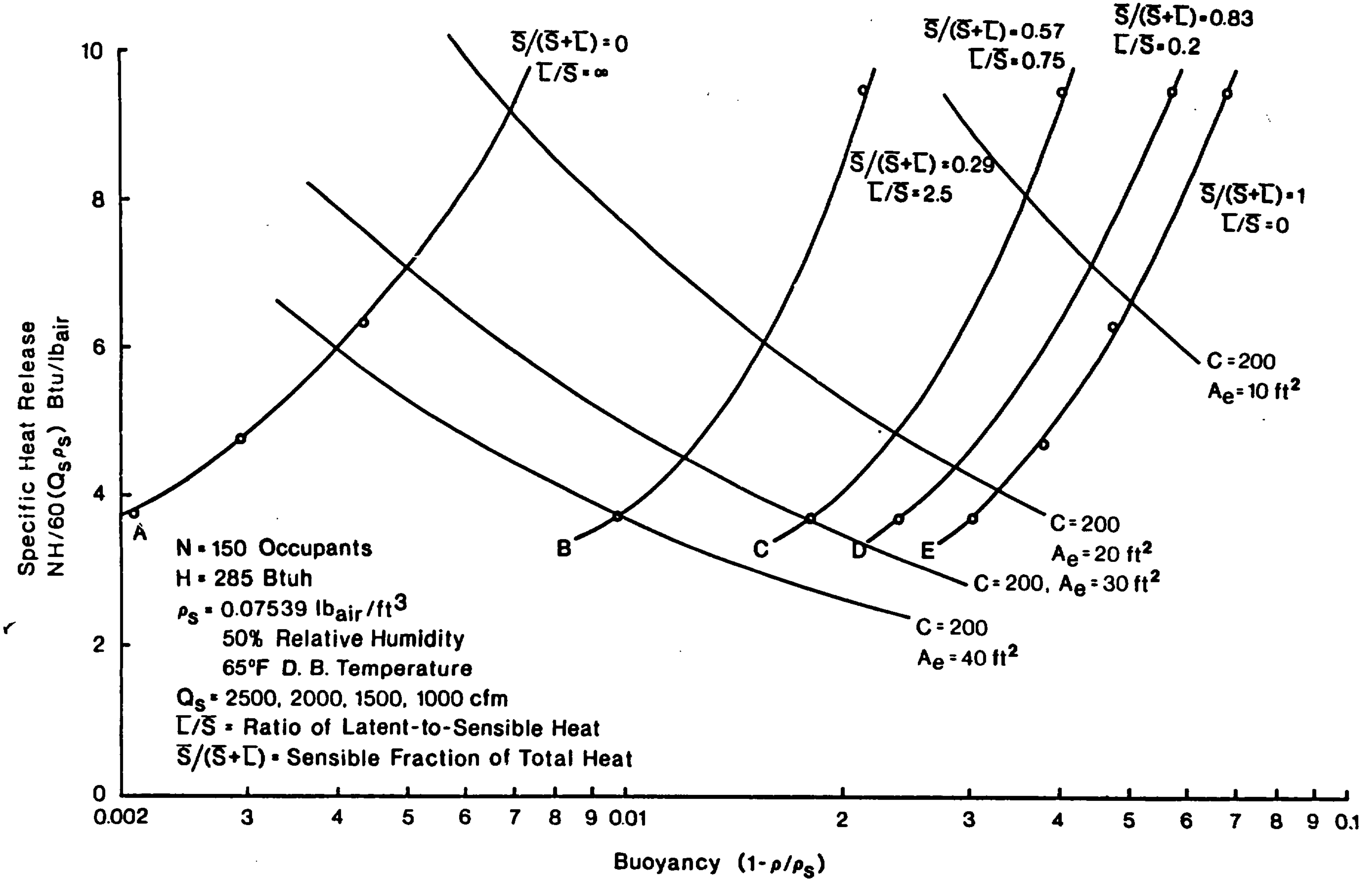Specific Heat Release
NH/60($Q_s\rho_s$) Btu/lbair
0
2
4
6
8
10
0.002
3
4
5
6
7
8
9
0.01
2
3
4
5
6
7
8
9
0.1
Buoyancy ($1-\rho/\rho_s$)
A
B
C
D
E
$\overline{S}/(\overline{S}+\overline{L}) = 0$
$\overline{L}/\overline{S} = \infty$
$\overline{S}/(\overline{S}+\overline{L}) = 0.29$
$\overline{L}/\overline{S} = 2.5$
$\overline{S}/(\overline{S}+\overline{L}) = 0.57$
$\overline{L}/\overline{S} = 0.75$
$\overline{S}/(\overline{S}+\overline{L}) = 0.83$
$\overline{L}/\overline{S} = 0.2$
$\overline{S}/(\overline{S}+\overline{L}) = 1$
$\overline{L}/\overline{S} = 0$
C = 200
$A_e = 10\ ft^2$
C = 200
$A_e = 20\ ft^2$
C = 200, $A_e = 30\ ft^2$
C = 200
$A_e = 40\ ft^2$
N = 150 Occupants
H = 285 Btuh
$\rho_s = 0.07539\ lb_{air}/ft^3$
50% Relative Humidity
65°F D. B. Temperature
Q_s = 2500, 2000, 1500, 1000 cfm
$\overline{L}/\overline{S}$ = Ratio of Latent-to-Sensible Heat
$\overline{S}/(\overline{S}+\overline{L})$ = Sensible Fraction of Total Heat

Figure B-2.

here that is based on the data of the Monoman Calorimeter Project [1], along with a few basic assumptions. First, it is assumed that the data developed in the Monoman study are applicable also to an average person. Second, it is assumed that the moisture release (latent heating) is dependent only upon the dry-bulb temperature in the immediate vicinity of each occupant and relatively independent of humidity and air motion. Third, for the purposes of the present study it is assumed that the ambient temperatures of the air entering the shelter are always in the range of 65° F to 96° F.

A tabulation of some of the data from the Monoman study is shown in Table 1 where $\overline{S}$ represents the rate of sensible heat removal and $\overline{L}$ represents the rate of latent heat removal from an average occupant.

A plot of these data is presented in Figure B-3. Here it can be seen that below 55° F dry-bulb temperature the average occupant will release approximately 285 Btu/hr total heat and that approximately 87 percent of this heat release is as sensible heat. At 65° F this percentage has dropped slightly to 83 percent, but above this temperature the fraction of the total heat that is sensible drops rapidly. At approximately 97° F, the body is unable to cool itself sensibly. Thus, the maximum temperature expected within an actual shelter is approximately 97° F. The maximum relative humidity in a shelter is 100 percent, and when these two conditions occur simultaneously, the human body is unable to maintain its temperature.

To determine a relationship between $\overline{S}/(\overline{L}+\overline{S})$ and T_{db}, a semi-log plot was made and is shown in Figure B-4. For temperatures above 65° F, a relatively accurate exponential curve-fit was obtained in the form

$$\overline{S}/(\overline{S} + \overline{L}) = 1 - [-A(B - T_{db})] \tag{7}$$

where $A = 0.0640$ and $B = 96.5°$ F, for the range $65° \text{ F} < T_{db} < 96.5° \text{ F}$. Since

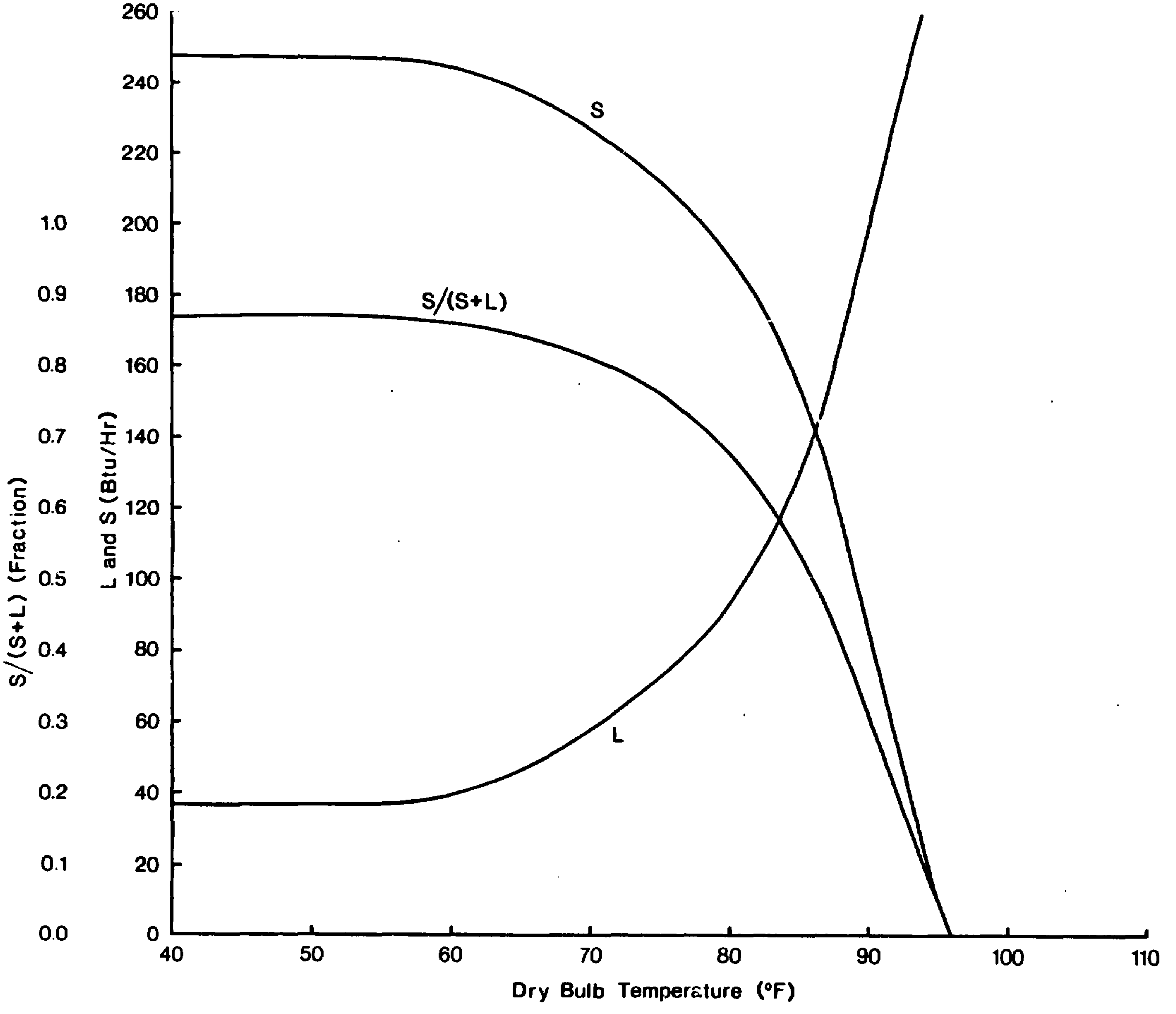
260
240
220
200
180
160
140
120
100
80
60
40
20
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
S/(S+L) (Fraction)
L and S (Btu/Hr)
S
S/(S+L)
L
40
50
60
70
80
90
100
110
Dry Bulb Temperature (°F)

Figure B-3.

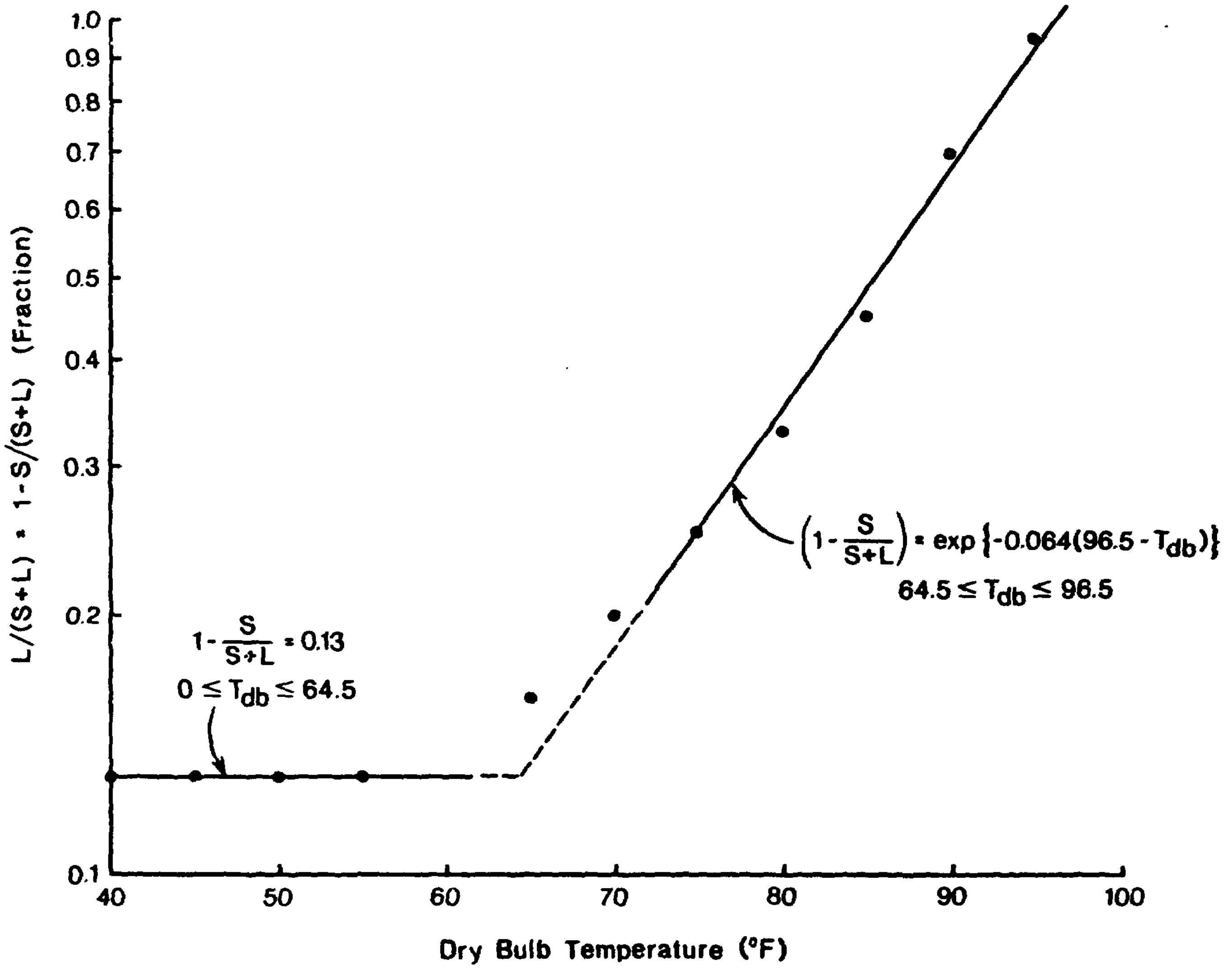
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
L/(S+L) = 1-S/(S+L) (Fraction)
40
50
60
70
80
90
100
Dry Bulb Temperature (°F)
$1-\frac{S}{S+L} = 0.13$
$0 \le T_{db} \le 64.5$
$\left(1-\frac{S}{S+L}\right) = \exp\{-0.064(96.5-T_{db})\}$
$64.5 \le T_{db} \le 96.5$

Figure B-4.

the air within a shelter will be in excess of 65° F in most applications, the behavior of the data below 65° F was not thought to be important. Since the sensible heat can be calculated as $\overline{S} = C_p\ (T_{db} - T_s)$, eliminating T_{db} yields

$$\overline{S} = \frac{C_p}{A}\ \ell n \left(\frac{\overline{L}/\overline{S}}{1 + L/S} \right) - C_p\ (T_s - B) \tag{8}$$

This expression should be applicable to a single occupant, as in the Monoman experiment, as long as the air surrounding the occupant is at T_{db} and the air leaving that occupant is approximately T_{db}. That is, the air in the immediate vicinity of the occupant is well mixed. As far as an entire shelter is concerned, the presumption here would be that the equation would be applicable on an average basis or, equivalently, the air within the enclosure is well mixed and all occupants experience the same environment. For an entire enclosure, therefore, it would be expected that the total $\overline{S}$ for all occupants is related to the ratio of the total $\overline{L}$ to the total $\overline{S}$ by this expression. The expression in no way implies the outlet air temperature will be equal to all the temperatures within the enclosure. In fact, due to the "hot spots" in the internal flow pattern, it is expected that some temperatures within an enclosure will exceed the exit temperature considerably.

Combining equations (2) and (8) yields an expression that defines the partitioning of heat between sensible and latent components for an actual enclosure. This expression is

$$\frac{NH}{60(\rho_s Q_s)} = (1 + \overline{L}/\overline{S}) \left[\frac{C_p}{A}\ \ell n \left(\frac{\overline{L}/\overline{S}}{1 + L/S} \right) + C_p\ (B - T_s) \right] \tag{9}$$

Thus, the value of $NH/60(\rho_s Q_s)$ for an actual shelter can be computed if the $\overline{L}/\overline{S}$ value for that shelter is known. A family of such lines is shown superimposed

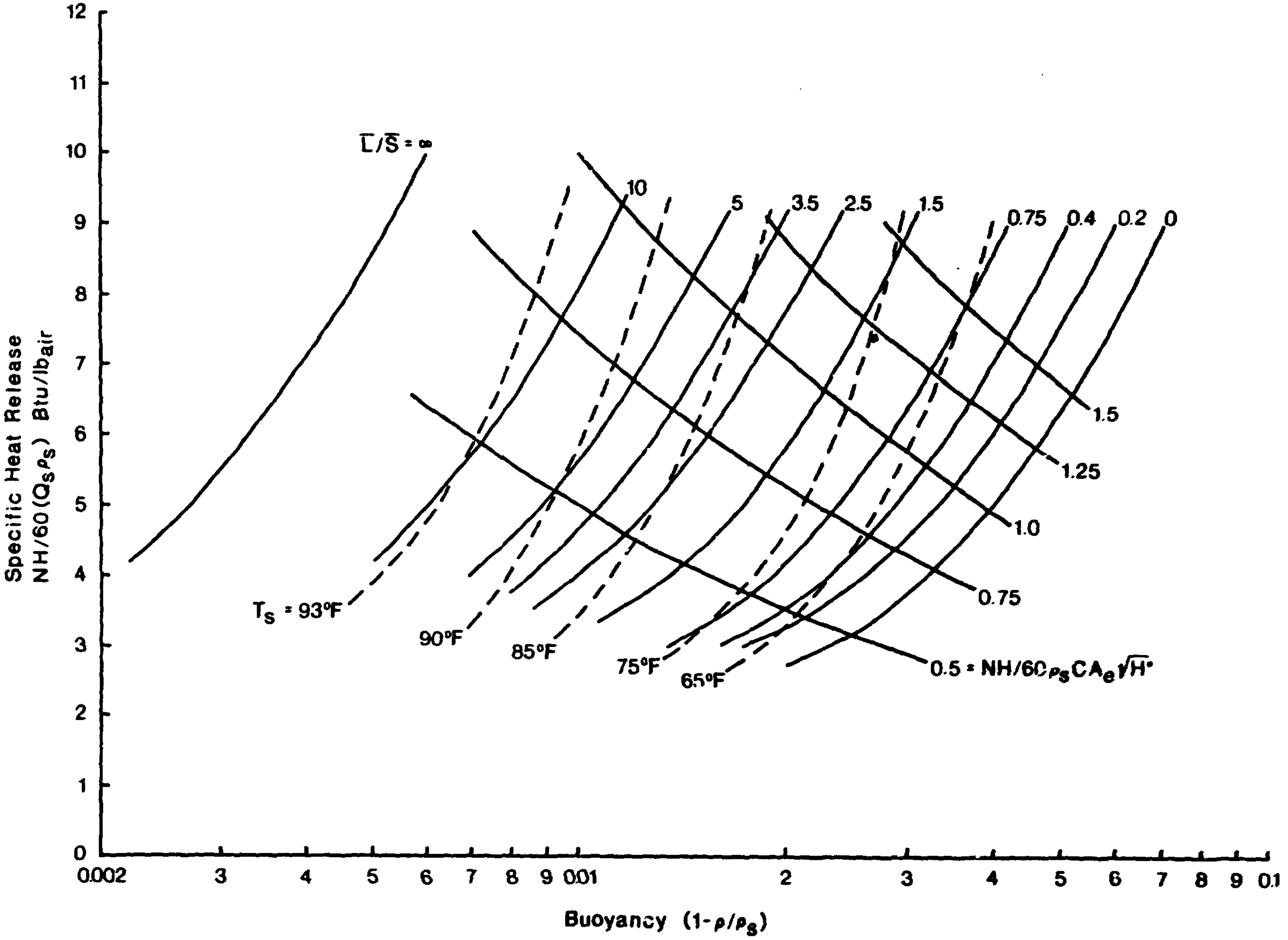
Specific Heat Release
NH/60(Q$_s\rho_s$) Btu/lb$_{air}$
12
11
10
9
8
7
6
5
4
3
2
1
0
0.002
3
4
5
6
7
8
9
0.01
2
3
4
5
6
7
8
9
0.1
Buoyancy (1-ρ/ρ_s)
$\overline{L}/\overline{S} = \infty$
10
5
3.5
2.5
1.5
0.75
0.4
0.2
0
1.5
1.25
1.0
0.75
0.5 = NH/60ρ_sCA$_e\sqrt{H^*}$
T$_s$ = 93°F
90°F
85°F
75°F
65°F

Figure B-5.

in Figure B-5 for various values of the ambient temperature T_s. At each value of T_s, $\overline{L}/\overline{S}$ is varied through the same parametric values used in Figure B-4 and $NH/60(\rho_s Q_s)$ values computed and plotted. These lines are shown as dashed lines.

The behavior of an actual shelter would then be characterized by the cross-over point between the operating-loss line corresponding to the C value for that shelter geometry and the dashed operating-partition line corresponding to the prevailing outside temperature.

4. References

1. Monoman Calorimeter Project Final Report, DOD, DCPA, January 1969.

APPENDIX C

METHODS AND PRACTICAL CONSIDERATIONS IN THE CREATION OF EXPEDIENT OPENINGS

APPENDIX C

METHODS AND PRACTICAL CONSIDERATIONS IN THE CREATION OF EXPEDIENT OPENINGS

1. Introduction

As a major criteria for the determination of shelter capacity, ventilation must be studied in light of its potential for increasing otherwise limited shelter capacity. Given a situation where the amount of floor space available in a shelter is limited by the amount of radiation protection provided by interior and below-grade spaces, improved ventilation can effectively increase the capacity of a shelter space. Because the Federal Emergency Management Agency (FEMA) sets minimum requirements on the net floor area or floor space allowance per person in shelters and minimum requirements on the amount of fresh air supply per occupant, greater utilization of protective space can be made by increasing ventilation. According to FEMA requirements, a minimum of 65 cubic feet of volume per person must be provided within a shelter space provided a minimum of 3 cubic feet of fresh air per minute per occupant is made available either with natural or mechanical ventilation. This requirement of 3 cfm per occupant is based on control of the chemical quality of the shelter air volume and results from a necessity to maintain carbon dioxide concentration at a level of 0.5 percent or less by volume. In addition, for thermal control, the ventilation rate in a shelter must be sufficient to maintain a daily average effective temperature of not more than 82° F for at least 90 percent of the days of the year.

Because FEMA requires shelter capacity to be determined by both net available floor space and available ventilation, it is worthwhile to study means for increasing effective ventilation capability when it is the limiting factor in the determination of a given shelter's capacity. A major assumption of the National Shelter Survey Program is that all commercial power will be off during the time of a major emergency. As a result, all air changes under a shelter scenario must be assumed to be either manually produced or to occur by natural ventilation. As part of the shelter survey process, a natural ventilation analysis is perfomed on all candidate shelter areas within a building. Since the best shelter spaces often have a small number of apertures, it is important to determine if the existing apertures such as windows, doors, etc., are sufficient to provide enough air to support all the spaces that the shelter area will hold. If the natural ventilation analysis indicates that the available air can support only a portion of the people who could otherwise be housed based on area, then consideration should be given to correcting this ventilation deficiency by adding expedient openings to shelters in the event of heightened international tensions.

This review will address methods and practical considerations in making expedient openings in shelter walls, floors, and ceilings of different construction.

2. Objective

A review of methods for making expedient openings in shelter spaces should minimally address the following five areas:

- The definition of an expedient opening
- The nature of the types of construction through which openings are to be made
- The description of alternative methods for making an opening
- The description of the environmental and material constraints involved with the use of each candidate method
- An identification of the feasible methods for creating openings under equipment and labor skill constraints

A clear discussion of these five areas of concern is the objective of this review. Insomuch as the definition of the expedient opening is central to discussion in all the areas, it will be considered first.

The concept of the expedient opening simply refers to a quickly formed aperture of some size in a ceiling, floor, or wall that serves as an air passage to increase the ventilation available in a shelter. Although the opening may have no particular shape, i.e., round or square, its size must be sufficiently large to allow an airflow from the inhabited shelter space to an adjacent unoccupied airspace. The number and size of openings needed to improve ventilation will vary with conditions and circumstances.

There are four major types of construction that will be examined in this review:

- Exterior walls and veneers
- Interior partitions
- Floors and ceilings
- Roofs

Each of these structures is commonly constructed from a number of different types of materials such as concrete masonry, gypsum, metal, glass, or wood products. Both construction material type and product configuration affect the tools, skills, and labor required to make expedient openings and will be discussed in considerable detail.

The number of ways in which expedient openings can be made in the materials and types of construction identified is actually quite limited. Perhaps the simplest and most common method that has been used for centuries is impact breaking, which uses a concentrated impacting force to fracture a target material. Another method that has been used much more in recent decades is abrasive cutting. The availability of industrial grade diamonds and other very hard abrasives has led to the wide use of saws and drills to cut openings in walls, floors, and ceilings. A third, more exotic method for making openings is the modern technique of burning and melting. In this method, very high temperatures are created at the work point or work face that burn through and/or break down the material being cut. The rapid combustion and disintegration of the material creates an increasingly large or deep opening. Variations of these three major methods will be discussed in Section 4.

Each technique for making expedient openings creates some environmental side effects and is subject to certain practical constraints in use. Site conditions and process byproducts such as noise, vibration, fumes, dust, fire, and water can create serious environmental problems in an inhabited structure. The location of the work face, whether on the floor, on a wall, or on the ceiling, has a major impact on the difficulty of making an opening. Even more important is the presence of tools and sufficiently skilled labor. An absence of special tools immediately prevents the use of the two fastest and most modern methods for making expedient openings, cutting, and burning. Finally, the availability and condition of a sufficiently skilled labor force to perform the work is a major consideration. While most burning operations require a work crew of two or more laborers, the other two methods can be performed by as few as one laborer.

The fifth area to consider when the practical considerations in making expedient openings are studied is the ease of implementation of each method. Clearly, the method with the minimum requirements for tools and skills and the greatest potential for improvisation will fill the need for making expedient openings in inhabited shelter structures for the greatest range of scenarios.

3. Site Conditions and Environment of the Shelter Space

A shelter space that is to have expedient openings added to it can be characterized as either an inhabited or uninhabited enclosed room presenting a set of constraints on activities that produce airborne byproducts that adversely affect human comfort. In a densely occupied space, for example, the work area available to produce expedient openings will be limited to a small area surrounding the site of the work. In contrast, light occupancy within a large shelter space may create a need for only one small opening far from the locations of occupant activity. Nevertheless, problems of noise, vibration, and fumes cannot be entirely avoided while demolition work is in progress.

The types of construction likely to be encountered in shelter spaces consists of four major types, as stated earlier. If a shelter space is on the perimeter of a building, the walls may be load-bearing or nonload-bearing and may or may not have a masonry veneer. Often the outside walls of single-story structures will be of wood or metal stud construction with a covering of masonry veneer. The construction materials used for the exterior walls of multistory structures can vary from concrete to brick, stone, glass, and metal as shown in Table C-1. Poured concrete construction, whether precast or cast-in-place, will virtually always be reinforced, whereas concrete block construction may or may not be reinforced. Similarly, brick construction may or may not be reinforced, as is the case with stone or tile construction.

In exterior nonload-bearing walls commonly referred to as curtain walls, the wall carries no load other than its own weight. Masonry curtain walls are usually made from concrete block, brick, tile, stone, and precast concrete panels. Sandwich panels consisting of an insulating core encased in steel or some other metal such as aluminum have become a major form of curtain wall construction in many modern steel frame buildings. The interior partition walls found within a structure may also be load-bearing or nonload-bearing. Small buildings with exterior bearing walls often have major load-bearing interior partitions that save on the amount of floor and roof framing because of shorter spans between load-bearing elements. Larger skeleton-frame

TABLE C-1. CLASSIFICATION OF CONSTRUCTION TYPES AND MATERIALS USED

Exterior Wall Types/ Interior Partition Types	Bearing Walls		Nonload-Bearing Wall		Masonry Veneer	Interior Load-Bearing Partition	Interior Nonload-Bearing Partition
	With Masonry Veneer	Without Masonry Veneer	With Masonry Veneer	Without Masonry Veneer			
Concrete-Cast-in-Place	X	X	X	X		X	X
Concrete-Precast	X	X	X	X		X	X
Concrete Block-Reinforced	X	X	X	X		X	X
Concrete Block-Nonreinforced	X	X	X	X		X	
Brick-Reinforced	X	X	X	X		X	X
Brick-Nonreinforced	X	X	X	X		X	X
Timber-Studwall	X	X	X	X		X	X
Timber-Heavy	X	X				X	
Stone	X	X					
Metal Panel			X	X			
Tile			X			X	X
Glass Panel				X			
Brick					X		
Stone					X		
Precast Concrete Panels					X		
Moveable Partitions							X
Gypsum Block							X

buildings commonly employ nonload-bearing partitions that are made of lightweight masonry materials. For single-story buildings, generally 4 inch or 6 inch thick concrete block or tiles with plaster finishes are used. In multistory buildings, lighter interior partitions are often constructed from metal or wood studs and gypsum board with or without plaster coverings. Vinyl covered gypsum panels have become very popular for interior partition walls in many modern buildings.

If expedient openings are needed in the floor or ceiling of a shelter, the type of construction likely to be encountered is not dissimilar to that of exterior load-bearing walls. A very common form of construction for floors and roofs in multistory buildings is the reinforced concrete slab. This slab construction can either be flat or employ ribs or joists in one or more directions. In either case, steel reinforcing is used to carry the tension loads experienced by floor and roof spans. This steel reinforcing significantly increases the resistance to impact loading of any type of floor, roof, or wall construction. Fortunately, most necessary slab penetrations can be made at locations that avoid reinforcing wires and bars. Even when reinforcing cannot be avoided the major task of trying to cut the metal can be ignored since the reinforcing would not significantly impede airflow through the opening. Other factors that reduce the difficulty of penetrating floor and roof slabs are the lightweight aggregates contained in and the thin sections designed into floor and roof decks to minimize the structural mass necessary to safely carry the loads involved. As a result, most cast-in-place and precast concrete floor and roof decks provide a demolition workman with large areas of the work surface that are only a few inches thick. In smaller buildings, the floor and roof surfaces are usually even thinner where the structures that support the floors and roof are wood trusses, steel bar joists, or small steel beams.

Another characteristic of construction type that impacts the selection of a method for making expedient openings is the configuration of the material used in that construction. Even though building materials differ in their physical and mechanical properties they come in three primary configurations:

- Continuous (cast-in-place concrete)
- Panel (plywood, gypsum board, precast concrete)
- Standard construction unit (bricks, concrete blocks, tile, etc.)

A breakdown of these configurations by material type is shown in Table C-2. Because the configuration of the building material in any given type of construction determines the nature of the point on the work surface where the penetration is to actually take place, it is necessary to look at the susceptibility to penetration of each material configuration. A continuous configuration as in the case of poured-in-place concrete provides great structural strength in the directions of the major loads but usually contains much thinner sections in other areas. These weaker areas of the continuous slab (which are much more susceptible to penetration) are located midway between the deep, thick beams that carry the major loads. Panels are similar to flat slabs in their uniform thickness. Because they are almost always secured to some preexisting structural frame, panels are also most susceptible to penetration at a point between the supporting frame elements. Panels made from uniform materials such as gypsum are very easily penetrated, while laminated materials such as plywood are much more resistant. Plywood's major weakness is the low density of its organic constitutents. Metal panels by contrast are very tough and are highly resistant to penetration in the absence of special equipment. The third and final material configuration, bricks or blocks, has characteristic strengths and weaknesses also. Both the materials and geometry of all bricks and blocks are highly resistant to

TABLE C-2. MATERIALS TO RECEIVE CUTOUTS

- Masonry (Reinforced and nonreinforced)

  - Concrete (Precast or cast-in-place)
  - Concrete Block (Units laid up with mortar)
  - Brick (Units laid up with mortar)
  - Stone (Units laid up with mortar)
  - Tile (Units laid up with mortar)

- Gypsum Products

  - Gypsum Block (Units laid up with mortar)
  - Gypsum Panels (Nailed or tacked in place)

- Metal Products

  - Metal Panels (Hollow core, insulated)
  - Metal Decking

- Glass Products

  - Glass Blocks (Units laid up with mortar)
  - Glass Panels (Sealed with mastic compound)

- Wood Products

  - Wood Planks and Boards (Nailed in place)
  - Plywood (Nailed in place)

distributed compressive loads. However, they are very weak in tension and will easily fracture if subjected to excessive tensile stresses or bending moments. This property is used to advantage when structures built of standard construction units like bricks and blocks are pierced and wedged with pointed tools and wedging equipment.

Other practical considerations must be taken into account when a method is selected for making expedient openings in a given shelter space. One consideration is the work area needed at a work face that will allow one or more workmen to perform the necessary manual labor to form an opening. Since all of the three major methods--impact breaking, cutting, or burning--minimally utilize one workman engaged in manual labor involving two hands, a circular work area with a radius equal to the combined length of the workman's arms and any wielded tool can be used as a rough guideline for the work area required. If two or more workmen are involved in the opening making activity, the overlap in the required work space will reduce the total area required by the group for safe movement and circulation.

A second work site consideration is the location of the work face with respect to the workman. A vertical location of the work face above shoulder height or even overhead at some point on the ceiling will make the task of forming an opening very difficult. In most cases some form of scaffolding will have to be improvised and erected to make the work even feasible. If the work face is at or below shoulder height or on the floor below, hand tools can be used normally to produce openings.

A final work site consideration involves the specific nature of the work point on the wall, floor, or ceiling. When an opening is to be made in construction of a continuous form, such as cast-in-place concrete, worker judgment will have to be used to find the thinnest allowable section at any location selected for an expedient opening. If the construction material is of the panel type, worker judgment is again required to determine where the structural supports for the panel are located and where the panel can be more easily penetrated by either breaking, cutting, or burning. When the material is of the standard construction unit type such as brick or block, weak points in the structure of an individual unit or the mortar jointing should be used as a starting point for any penetration. This follows the key principle used in penetrating any form of stone or masonry: cut a small hole and then enlarge it.

4. Construction Breaching Techniques

Modern tools and techniques used to cut and form building materials have evolved from techniques that are thousands of years old. The simple hammer and chisel has evolved into the modern rock drills and pneumatic hammers of today. Old stone wedging techniques are now performed hydraulically with greater control. Modern techniques of diamond and abrasive sawing and drilling have superseded earlier quarrying techniques such as wires and grit slurries. Only modern methods for high-temperature flame cutting of both metals and masonry such as thermic lances and thermic powder cutting have no antecedents in history.

Unfortunately, most recent developments in methods for construction breaking and cutting involve mechanical improvements that preclude their use under a civil defense scenario. Virtually all modern mechanized techniques suffer from a need for power or gas supplies of some kind, usually oxygen and a fuel component. Modern diamond cutting, although very fast in cutting through very hard materials, requires either a large supply of water or highly compressed air to cool the tool at its point of contact with the work. This is true for both drilling and sawing with diamond blades. All flame processes such as thermic lances and powder torches require a controlled flow of oxygen gas to the outlet of the tool. Hazards of the flame, fumes, and dust byproducts of these processes plus the unlikely availability of oxygen for cutting purposes within a shelter make flame cutting impractical for in-shelter civil defense purposes. The only method for making expedient openings in a shelter space that requires only generally available tools and human labor is impact breaking.

Impact breaking involves accelerating a relatively large mass prior to colliding it with the work face or a tool in contact with the work face where the kinetic energy of the mass is dissipated by reducing the work face to rubble. Manual impact tools such as the sledge hammer have been used for centuries, and force concentrating tools such as chisels and tracers have been used to localize the fracturing effect of the heavy tool. A common example on a larger scale of this form of construction breaking is the steel wrecking ball, which is swung from the jib of a crane or other type of suspension. A modern form of this type of tool is the two-man battering ram normally found in fire departments and used for penetrating doors and walls.

The use of methods involving heavy hand held hammers and pointed tools is most applicable to situations where the destructive nature of the process is not critical. Close control in the accuracy and finest of the cutting work usually is not important when impact breaking is being used. This is reflected in the mechanized extensions of impact breaking hand tools, the percussion tools such as compressed air jack hammers, and hydraulic hammers. These tools differ in one principle from hand impact breaking in that they rely on a rapid succession of light blows in contrast to the use of irregular massive blows. The principle by which these tools work in accomplishing the breaking process is to combine the action of the sledge hammer and the spike to wedge material apart. These tools share a major disadvantage of all hand held impact breaking in that they are best used at ground level and become very difficult to use when they must be held above shoulder height.

Whether impact breaking is performed with powered equipment or performed manually, the guiding principle is to create a wedging action with the breaker point to move the portion of material to be broken free, often called the burden, towards a free edge of an opening. This free edge can already exist in the form of an existing hole in a wall, floor, or ceiling or can be created as a small pilot hole formed specifically to provide a free edge that can be worked toward. On very hard materials, such as stone or mass concrete, pointed tools may not be effective and an alternative method can be adopted from an old stone mason's practice for stone splitting. This technique involves using a rock or masonry drill (powered or manual) to drill a line of holes into which are fitted split steel linings called feathers. Wedges are driven between the feathers to produce a splitting force. Typically, holes are drilled about 2 inches in diameter to a depth suited to the length of the feathers available. These holes are usually spaced several inches apart according to the material being broken so as to give a clean fracture along a line. All wedges are driven in gradually to create an even tension all along the break line until a maximum breaking tension is produced. When the maximum tension has been produced, the wedges closest to the free edge are driven home, breaking the body of material along the prepared line.

A variation of this technique is the use of hydraulic bursters. As with the use of steel wedges, the concept involves lining predrilled holes to spread the expansion force so that it stresses the mass of material rather than causing local breaking. In this case, however, the expansion force is obtained from a hydraulic mechanism rather than a hammer driven wedge. This hydraulic wedging technique is found in two common forms, the plunger burster and the wedge burster. In the plunger burster hydraulic pressure is applied to a series of plungers that are forced out from a central cylindrical core. These plungers expand out in only one direction; therefore, the device must be carefully oriented according to the direction in which breaking is to occur, usually in the direction of the opening. The wedge burster employs hydraulic power to retract a steel wedge between tapered steel liners much as with the manual wedge and feather configuration. In this device the feathers are an integral part of the down-hole portion of the device. In either case the bursters can be fed from a manually operated hydraulic supply. Hydraulic bursters have a distinct advantage over many other breaking methods in that they are almost free of noise and vibration. Although they are generally not capable of breaking reinforcement hydraulic bursters are quite often used in reinforced concrete where other appropriate cutting methods have removed the reinforcement and provided preparatory openings for burster placement.

When cutting through walls and floors of large buildings, workers should locate sections of the structure that can be penetrated most quickly and safely. This involves steps to assure that cuts through walls do not weaken support beams and columns.

Openings large enough for air exhaust purposes usually can be made in brick walls without danger of the masonry falling. The bricks or blocks from any other type of standard unit construction should be removed so the opening is arch-shaped.

Concrete walls and floors, especially when they are reinforced, are difficult to cut through. With the exception of concrete, the best method for making a penetration in all walls and floors is to cut a small hole and then enlarge it. With concrete, a better alternative would be to cut around the edge of the opening to be made. In this way, if the concrete is reinforced, the reinforcing bars can then be cut by a hacksaw or torch, and the material removed in one piece. If a burning process is to be used to cut the reinforcing, care must be taken to ensure that flammable materials are not ignited. A fire extinguisher should always be kept nearby.

The range of techniques found within each major cutting method and their characteristics are shown in Tables C-3 through C-6.

5. Environmental Considerations

Noise is one of the less desirable byproducts of demolition activities regardless of the material involved. Powered machinery is invariably noisy and ear protection is recommended if sound levels reach 90 dbA. A more likely situation with impact·breaking demolition would be the intermittent noise from heavy work with hand tools. The noise of hand tools will be a nuisance to the human occupants of a shelter space but should only become a source of major aggravation if very deep holes through hard materials result in many hours of intermittent noise.

The only significant hazards likely to arise from the formation or expedient openings will come from any fumes or dust produced in an already limited airspace. Due to the slowness of material removal found with manual methods, airborne particles produced by tool impacts will be more of a nuisance than a real health hazard. On the other hand, if flame cutting equipment is both available and to be used, significant amounts of smoke and fumes would be produced that may be hazardous not only to the worker but to the other shelter occupants. Often the dust or the smoke that is usually produced from these different construction cutting processes is not particularly harmful, but this is often not true of certain types of finishes that may have been applied to the construction surface. It is of course

TABLE C-3. BREAKING PROCESSES

Process	Applications	Degree of Skill	Characteristics
Impact breaking (Sledge hammer, battering ram)	Destructive demolition	Low	Relatively fast and cheap if construction is not thick; very labor intensive.
Hand held breaker ("Jack hammer")	Limited demolition	Low	Widely available and cheap, but labor intensive, noisy, and dusty.
Hand held sledge and pointed tool	Pilot holes and tracing of opening boundaries	Low	Slow and labor intensive, can be fatiguing.
Borehole charges	Controlled demolition and fairly accurate breaking	Medium/high plus experience	Can be cheaper and faster than alternative demolition methods, if circumstances are expertly assessed. Preparation requires study of structure and predrilling of holes.
Steel wedge bursting	Controlled breakout of blocks of material	Medium plus experience	Cheap and effective but slow if holes cannot be drilled with powered tools.
Hydraulic bursters	Limited and fairly accurate breaking	Low	Quiet, vibrationless, and controllable but slow and limited effect. Preparation requires predrilling holes for placement.
Hydraulic jacks	Heavier breaking of reinforced concrete	Low	Useful for large mass or reinforced concrete, often in conjunction with thermic lancing. Preparation requires preforming holes for placement.

TABLE C-4. SOFT CUTTING PROCESSES

Process	Applications	Degree of Skill	Characteristics
Abrasive discs	Quick cutting jobs on pipes, bars, and for grooving slabs	Low	Easy to handle but noisy and produce dust. Blades relatively cheap but rapidly consumed.
Tungsten carbide and other wear-resisting tools	Small drills, chisels, breaker points, and scabbing tools for general use	Low/ medium	Widely available but performance and suitability depend on circumstances.

TABLE C-5. HARD CUTTING (DIAMOND TOOLS) PROCESSES

Process	Applications	Degree of Skill	Characteristics
Core-drills	Forming holes and extracting core samples	Medium	Smooth, accurate holes to considerable depth. Preparation requires machine setup.
Floor-saws	Grooves or openings in slabs	Medium	Smooth, accurate cutting with high output. Machine generally large.
Wall-saws	Grooves or openings in vertical members	Medium/ high	Smooth, accurate cutting. Preparation requires machine and track setup.
Reciprocal saws	Openings through slabs in any plane	Medium	Smooth, accurate cutting to greater depth in one pass. Blade must pass through slab. Preparation requires machine and track setup.

TABLE C-6. FLAME PROCESSES

Process	Applications	Degree of Skill	Characteristics
Oxygen cutting	Ferrous metals	Medium	Most common method for dismantling steel structures.
Powder cutting	Metals, especially high melting point alloys and silica-bearing materials such as concrete	Medium/ high	High cost sensitive equipment not suited to rugged open-site conditions.
Thermic lancing	Cutting and boring most metals and silica-bearing materials such as concrete	Low/ medium	Lances are rapidly consumed and may make up a large bulk and weight to be taken to work sites for extensive work.
Flame spalling	Surface treatment of concrete for improved traction	Low	Quiet vibrationless procedure but with major fire hazard. Best suited to outdoor work.

impossible to know all of the dangers involved when cutting into a wall of unknown composition, but it is essential to proceed with caution if a known health threatening material has to be cut, drilled, or burned. Dusts that create health hazards are shown in Table 7. It should be specially noted that fumes given off by many materials when they are heated may be more hazardous than the dust produced by cutting or breaking, and in this context flame cutting techniques can emit both flames and dust.

While the byproducts of manual impact breaking methods usually cannot be considered true hazards, certain precautions can be taken on the part of the workmen. Dust from masonry and gypsum products is a common occurrence and, while it is not a true health risk, overexposure should be avoided. Workers should wear facemasks incorporating dust filters or should improvise in other ways to avoid breathing in dust particles. When this work has to be done in shelter spaces that are occupied, steps should be taken to make the work area as enclosed as possible with screens of plastic sheeting held securely in position. A simple light frame of wooden battens will perform this job very effectively.

6. Work Content Considerations In Breaching, Walls, Floors, Ceilings, and Roofs

Regardless of the method used to provide expedient openings in a shelter wall, the activity involves penetration from a direction that is normal to the surface of the work face. Because a free edge is not present from which to work, significant effort is required to make the right-angled penetration. In the cases of flame cutting and abrasive cutting, the pressure applied by the workman is only that necessary to provide a proper cutting action by the tool. In both processes, excessive pressure degrades cutting action and causes unnecessary wearing of the tool. With these two methods, the proportion of worker fatigue caused by applying tool pressure to the work face is a small

TABLE C-7. RELATIVE HEALTH RISKS FROM INHALING DUSTS

I. Very dangerous

- Beryllium
- Silica that has been heated (calcined)
- Blue asbestos

II. Dangerous

- Other asbestos
- Silica
- Mixed dusts containing 20 percent or more free silica
- Fireclay dust

III. Moderate risk

- Mixed dust (less than 20 percent free silica)
- Talc
- Mica
- Kaolin
- Carbides of some "hard" metals
- Cotton dust and many other vegetable dusts
- Graphite
- Coal dust
- Aluminous fireclays
- Synthetic silicas

IV. Low risk (though exposure often is far too high)

- Alumina
- Baryteo
- Carborundum
- Cement
- Emery
- Ferrosilicon
- Glass and glass fiber
- Iron oxides
- Limestone
- Mineral wool
- Slag wool
- Perlite
- Silicates (other)
- Tin-ore and oxides
- Zinc oxide

fraction of that caused by having to support the tool in proper position with both hands. In contrast, impact breaking methods require the worker to transmit as much physical force through the tool and into the work face as is necessary to effectively penetrate a given type of material and construction. Interior partition walls made of gypsum board can be easily penetrated with almost any kind of hand held tool while reinforced concrete can require massive blows from a heavy object if pointed tools are not available. In all three cases use of the tool requires two hands with the exception of the hand held hammer and chisel combination. A list of the tools commonly used for cutting construction materials is shown in Table C-8.

The level of skills required among the three types of construction cutting or breaking ranges from very low to high. Understandably, the level of skill required reflects the complexity of the equipment and the amount of support each process requires. With the exception of the use of explosives for borehole charges, breaking processes require only a low level of skill. Cutting tools and equipment involving more exotic materials such as tungsten carbide and diamond require a medium degree of skill as additional forms of support for these processes must be provided. The degree of skills required to perform different flame cutting processes ranges from low to medium and high. Simple penetration of thick construction by thermic lancing requires low to medium levels of skill, but more sophisticated methods such as oxygen cutting and powder cutting require medium to high levels of skill because of the ever-present dangers of high-temperature flames and explosive gases.

It is apparent from this review that techniques exist that can be used rapidly and effectively to provide expedient ventilation openings in both occupied and unoccupied shelter spaces. However, under varying circumstances, different methods may not be practical or even possible. For example, under

TABLE C-8. CANDIDATE TOOLS AND EQUIPMENT FOR PROVIDING OPENINGS

I. Breaking Tools and Equipment

- A. Powered Equipment
  - 1. Pneumatic breakers (hammers)
  - 2. Hydraulic bursters and jacks
- B. Manual Tools and Equipment
  - 1. Rams and Bars
    - a. Two-man battering ram
    - b. Ram bar
    - c. Pinch point crowbar
    - d. Goose neck wrecking bar
    - e. Huxbar tool
  - 2. Hammers
    - a. Sledge (all sizes)
    - b. Claw
    - c. Geologist's
  - 3. Picks and Axes
    - a. Point and chisel pick
    - b. Poll or mining pick
    - c. Crash axe
    - d. Emergency axe
    - e. Pry axe
    - f. Pick-head axe
    - g. Flat-head axe
    - h. Pulaski axe
  - 4. Pointed Tools
    - a. Cold chisel
    - b. Hand chisel
    - c. Star drills
  - 5. Jacks and Wedges
    - a. Hydraulic jack
    - b. Screw jack
    - c. Rachet jack
    - d. Hydraulic bursters
    - e. Steel feathers
    - f. Hand held tracers

(Continued)

TABLE C-8. CANDIDATE TOOLS AND EQUIPMENT FOR PROVIDING OPENINGS (Continued)

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        6. Explosives
            a. Borehole charges
- II. Cutting Tools and Equipment
    - A. Powered Equipment
        - 1. Drills (core and hole cutting)
            - a. Pneumatic drills
            - b. Electric drills
        - 2. Saws (floor and wall cutting)
            - a. Gasoline powered saws
            - b. Pneumatic saws
            - c. Electric saws
    - B. Manual Tools and Equipment
        - 1. Saws
            - a. Hand saw
            - b. Hack saw
            - c. Bow saw
            - d. Keyhole saw
- III. Burning Tools and Equipment
    - A. Gas Supplied Equipment
        - 1. Oxy-acetylene torch
        - 2. Iron or iron-aluminum powder torch
        - 3. Iron or mild steel thermic lance

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increasing constraints of time or availability of special tools and/or skilled labor, the number of alternative ways of making expedient openings would be quickly reduced to the impact breaking method using heavy hand tools. Under even more extreme conditions where neither time nor heavy hand tools are available, hand tools would need to be improvised from such things as metal table legs or other heavy metal objects found in the home or office. A breakdown of the feasible methods for providing openings is shown by construction type in Table C-9.

TABLE C-9. FEASIBLE METHODS FOR CREATING OPENINGS UNDER CONSTRAINTS

1. Special Tools and Necessary Skilled Labor Available (Shelter Uninhabited)

Construction	Material to be Cut	Cutting Method	Comments
Walls			
Exterior	Precast Concrete (rfd)*	Pneumatic concrete breaker	Any of the several methods listed can be used interchangeably for the crude cutting required to make an expedient opening.
	Cast Concrete (rfd and non-rfd)	Drill and hydraulic burst	
	Concrete Block (rfd and non-rfd)	Stitch drilling with circular diamond drill	
	Brick (rfd and non-rfd)	Thermic lance	
	Stone (rfd and non-rfd)	Explosive charges	
	Timber (with and without veneer)	Gasoline powered saw with nail cutting blade	Will need to change blade when layer of veneer is reached.
	Metal Panel	Powered saw with metal cutting blade	Risk of fire hazard.
	Tile	Powered saw with ceramic cutting blade	Can also be impact broken.
	Glass Panel	Circular diamond drill	Rarely practical.

(Continued)

TABLE C-9. FEASIBLE METHODS FOR CREATING OPENINGS UNDER CONSTRAINTS (*Continued*)

1. Special Tools and Necessary Skilled Labor Available (Shelter Uninhabited)

Construction	Material to be Cut	Cutting Method	Comments
Interior	Cast Concrete (rfd and non-rfd)	Drill and hydraulic burst	Same as for exterior walls, but major fire safety steps must be taken if burning is to be employed.
	Concrete Block (rfd and non-rfd)	Powered saws	
	Brick (rfd and non-rfd)	Thermic lance	
	Timber (Studwall)	Gasoline powered saw	Nail cutting blade required.
	Tile	Powered saw with ceramic cutting blade	Mask and goggles needed to protect against dust produced.
	Gypsum Panels (Studwall)	Powered saw with abrasive blades	Very fast but produces large amounts of dust. Dust filters should be worn by workers.
	Gypsum Block		
	Movable Partitions		
Floors and Ceilings	Cast Concrete (rfd)	Pneumatic concrete breaker	Same as for exterior walls. Thermic lancing finds best application in piercing very thick cross sections.
	Precast Concrete (rfd)	Stitch drilling	
		Thermic lance	

(Continued)

TABLE C-9. FEASIBLE METHODS FOR CREATING OPENINGS UNDER CONSTRAINTS (Continued)

1. Special Tools and Necessary Skilled Labor Available (Shelter Uninhabited)

Construction	Material to be Cut	Cutting Method	Comments
Floors and Ceilings (Continued)	Construction Tile (with concrete covered metal decking)	Powered saws with metal/ceramic cutting blades	Physical labor much easier if performed from above
	Steel Beams or Joists		
	Wooden Joists or Trusses	Powered saws with nail cutting blade	Damage or weakening of beams, joists, or trusses can and should be avoided. Best to make openings in structurally noncritical locations.
Roofs	Steel Beams, Joists, or Rafters (with concrete covered metal decking plus built up roofing)	Powered saws with metal/ceramic cutting blades	General lightweight construction of roofs suggest controlled cutting methods. Light insulating aggregate and metal decking are easily cut. Tool handling unwieldy if work performed from below.

(Continued)

TABLE C-9. FEASIBLE METHODS FOR CREATING OPENINGS UNDER CONSTRAINTS (Continued)

2. No Special Tools or Skilled Labor Available (Shelter Uninhabited)

Construction	Material to be Cut	Cutting Method	Comments
Walls			
Exterior	Precast Concrete (rfd)	Battering ram	Slow and labor intensive. Possible *difficulty in* localizing *damage*. Easily penetrated by impact breaking. Care needed in controlling shock transmitted to surrounding areas.
	Cast Concrete (rfd and non-rfd	Construction picks Wrecking bar	
	Concrete Block (rfd and non-rfd)	Sledge hammer	
	Brick (rfd and non-rfd)	*Hand sledge and pointed tool*	
	Stone (rfd and non-rfd)	Wedges and jacks with pilot holes	
	Timber (with and without veneer)	Axe or hachet	Difficult to control area of material destruction.
	Metal Panel	Crash axe	Very difficult penetration.
	Tile	*Hammer and tool*	Other alternatives should be pursued, if possible.
	Glass Panel	-	*Brittle material* easily penetrated.

(Continued)

TABLE C-9. FEASIBLE METHODS FOR CREATING OPENINGS UNDER CONSTRAINTS (*Continued*)

2. No Special Tools or Skilled Labor Available (Shelter Uninhabited)

Construction	Material to be Cut	Cutting Method	Comments
Interior	Cast Concrete (rfd and non-rfd)	Same as exterior walls	*Same as exterior walls.*
	Concrete Block (rfd and non-rfd)		
	Brick (rfd and non-rfd)		
	Timber (Studwall)	Cut with axe	Damage to wooden structural units should be avoided.
	Tile	Hammer and tool	Easily penetrated; eyes should be protected from chips and shards.
	Gypsum Panels (Studwall)	Cut with axe	Soft material easily penetrated; dust usually produced.
	Gypsum Block	Sledge hammer	Material surface often stabilized with plastic covering. Material destruction can be localized.
	Movable Partitions		
Floors and Ceilings	Cast Concrete (rfd)	Sledge hammer and pointed tool	Same as exterior walls.
	Precast Concrete (rfd) —	Wrecking bar	
		Wedges with pilot holes	

(Continued)

TABLE C-9. FEASIBLE METHODS FOR CREATING OPENINGS UNDER CONSTRAINTS (Continued)

2. No Special Tools or Skilled Labor Available (Shelter Uninhabited)+

Construction	Material to be Cut	Cutting Method	Comments
Floors and Ceilings (Continued)	Construction Tile (with concrete covered metal decking)	Sledge hammer followed by crash axe	Metal decking presents a major penetration problem. Labor involved minimized if performed from above.
	Steel Beams or Joists		
	Wooden Joists or Trusses	Emergency or crash axe	Damage to structural member should be avoided.
Roofs	Steel Beams, Joists, or Rafters (with concrete covered metal decking plus built up roofing)	Same as floors and ceilings	Same as floors and ceilings.

* rfd = reinforced.

\+ For inhabited shelter spaces, generally the same conditions hold as for uninhabited spaces when the only methods available for making openings are manual. The major difference is the need to limit the ejection of dust and debris from the demolition activities into the inhabited shelter space. A curtain of plastic sheeting or other material around the work site will usually provide sufficient protection from the rate and volume of dust and debris producted by manual methods.

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Wright, M. D., W. Berryhill, and R. Wallace
December 1981 (UNCLASSIFIED) 258 pages

The objectives of this project were to investigate the effects of partitions, dense occupancy, and expedient openings on the airflow patterns in fallout shelters. Both experimental and theoretical techniques were used in the study.

The experimental program examined airflow patterns for both mechanically driven and thermally driven ventilation. Mechanical ventilation was supplied by an axial fan driven by an electric motor. The thermal ventilation was supplied by simulating the metabolic heat load of the shelter occupants. Because metabolic heat is a combination of sensible and latent heat, a theoretical analysis was made of the relative effect of each type of heat on buoyance. The result showed that latent heat has a much smaller buoyancy effect and, consequently, only the sensible heat input was simulated during the experiments using thermally driven ventilation.

Ventilation tests were made using 25 shelter configurations. Airflow patterns and temperature distributions were measured in each configuration using both natural and forced ventilation.

An evaluation of the applicability of expedient openings was made using data from the literature and personal contacts. The evaluation addressed a wide variety of construction types and cutting techniques.

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