No. 1917

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Analysis of Aboveground Fallout Shelter Ventilation Requirements

The fallout shelter must protect the shelter occupants from radioactive fallout and also from the detrimental effects of excessive carbon dioxide, insufficient oxygen, and excessive shelter temperatures and humidities. The shelter ventilation system insures that these additional safeguards are maintained. For example, the carbon dioxide in a shelter can be kept at an acceptable level by ventilating the shelter with 3 cfm per occupant. But, as much as 60 cfm of outside air might be required to keep the shelter temperature and humidity down to tolerable limits during the hot summer months. In some situations, ventilating with external ambient air will not sufficiently control the shelter effective temperature and air-conditioning equipment will be required.

To properly select the ventilation equipment, the shelter designer must know precisely the ventilation rate required. The major parameters for determining this are the number of shelter occupants, the shelter's geographical location, and the shelter's size and construction. The number of occupants establishes the level of latent and sensible metabolic heat that is produced in the shelter. The geographical location determines the ambient weather from which the weather design criteria can be obtained. A knowledge of the shelter's physical size and construction features defines the heat transfer coefficients that are required to compute the heat transfer to and from the shelter. When these factors and the required shelter effective temperature are known and incorporated into a prediction technique for the ventilation requirements of the shelter, the designer has a basis for selecting the ventilation equipment.

The MRD Division has been engaged in the development of such a prediction technique under the Office of Civil Defense Contract OCD-OS-63-176, Subtask 1215A. The goal of this program is to formulate a simplified procedure for predicting the ventilation requirements of shelters. This paper presents the results of several studies which are preliminary steps in the development of this simplified procedure. These studies are based upon:

1. the metabolic energy output of approximately 400 Btuh/occupant given by the sensible and latent heat expression,[1]
2. the shelter habitability criteria represented by the ASHRAE effective temperature (an empirically devised index of the various psychrometric conditions that produce similar comfort levels) (see Appendix A) and
3. the derived mathematical shelter model which is applicable to large shelters that are either above or below ground, do or do not have boundary surface heat losses, and are in a transient or steady-state condition of mass and energy transfer[1] (see Appendix B).

The mathematical model for the shelter is the most comprehensive analytical procedure that could be developed without unduly complicating the computational procedure. When used as a transient analysis, the model permits the psychrometric state of the shelter air to be computed as a function of time. The analysis considers:

1. time varying inlet air conditions,
2. time varying energy inputs to the shelter from equipment and lights,
3. time varying solar loads which have been transmitted through windows into the shelter (i.e., time varying values of transmitted solar radiation as obtained from the ASHRAE Guide And Data Book),
4. metabolic latent and sensible energy loads based upon the instantaneous psychrometric state of the shelter,[1] and
5. shelter boundary surface heat losses (or gains) based upon a one-dimensional heat transfer analysis neglecting corner effects.

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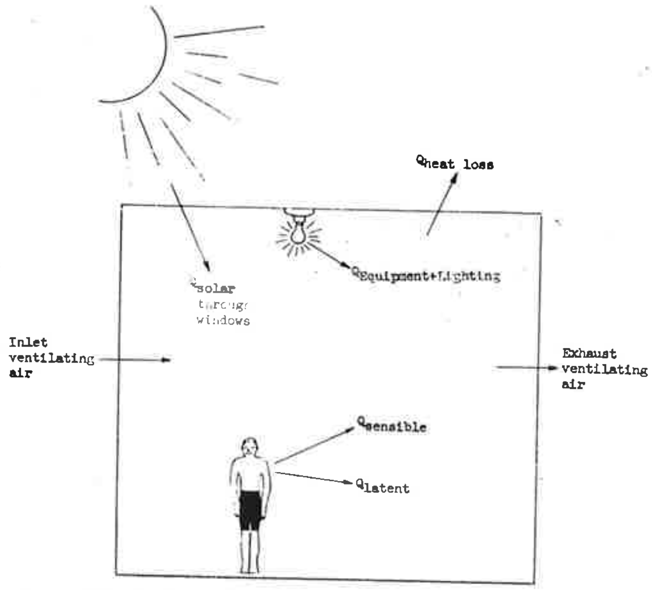


Fig. 1 Idealized shelter model

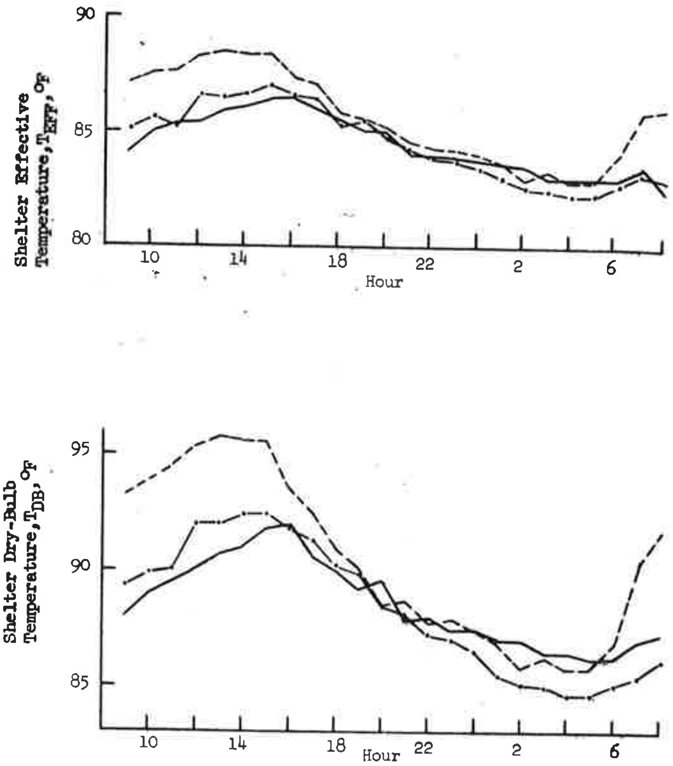
The shelter model is based upon the assumptions that

1. the air within the shelter is completely mixed and at one psychrometric condition,
2. the convective heat transfer coefficient for each external boundary surface of the shelter is not a function of temperature and has a constant value over the surface,
3. the radiative energy interchanges within the shelter can be neglected,
4. the solar radiative energy which enters the shelter windows and the equipment and lighting heat loads in the shelter can be grouped together as one time-dependent load factor which is termed the thermal load,
5. the ventilating air exhausted from the shelter is at the psychrometric condition of the shelter air,
6. the effects of condensation on the walls, floors, and ceilings of the shelter can be neglected, and
7. the solar radiation absorption on opaque shelter boundary surfaces can be neglected.

Thus the shelter is idealized as an enclosed volume in which sensible heat, latent heat, and ventilating air are introduced and from which air is exhausted and energy is lost, see Fig. 1. The governing principles for such a model are the conservation of energy and the conservation of the masses of dry air and water vapor.

The primary aim of this paper is to determine the most simple analytical model that can predict the psychrometric conditions that develop in aboveground shelters. To evaluate this model, actual shelter test data are compared to computed data; and variation of parameter approaches are applied to several types of shelters to generalize the results. The analytical shelter models studied in the paper are

1. aboveground adiabatic boundary shelter model (no heat transfer through the shelter boundary surfaces) with time-dependent parameters (i.e., the state of the inlet air and the thermal loads added to the shelter air),
2. aboveground nonadiabatic boundary shelter model with time-dependent parameters,
3. aboveground adiabatic boundary shelter model with steady-state (constant with time) parameters,
4. aboveground nonadiabatic boundary shelter model with steady-state parameters.



	Time-Average Temperatures of Shelter Environment* Dry-Bulb, T_{DB}	Effective, T_{EFF}
———— : Experimental Data	88.8 F	84.5 F
- - - - - - : Adiabatic Boundary Computation	90.5 F	85.6 F
—.—.— : Nonadiabatic Boundary Computation	88.3 F	84.5 F

Fig. 2 Comparison of computations and experimental data for Wilmington, N. C. Test 7

RESULTS OF SHELTER ANALYSIS

Transient analyses of shelters

The time-history of the temperature and humidity within a shelter is predicted by transient analysis which considers the time varying mass and energy balance around the shelter. The validity of this analysis is established by comparing several sets of analytical computations with data from actual shelter tests. The shelter tests chosen for the comparison are the MRD Wilmington, North Carolina test No. 7,[2] the University of Florida Central Stores Building test Phase IV,[3] and the MRD Houston, Texas test II.[4] The Wilmington shelter is a 210-man aboveground shelter, the Florida shelter is a 250-man basement shelter, and the Houston shelter is a 290-man basement shel-

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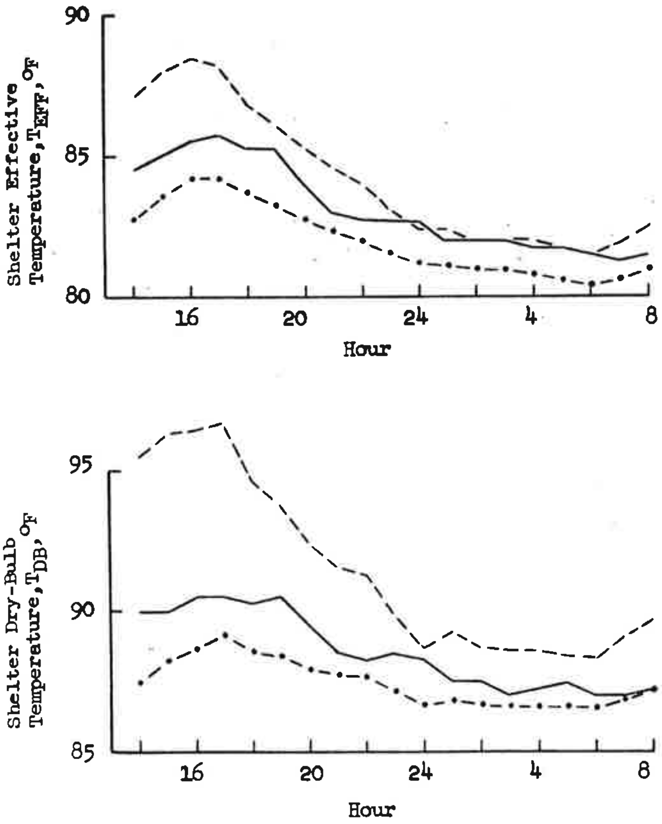
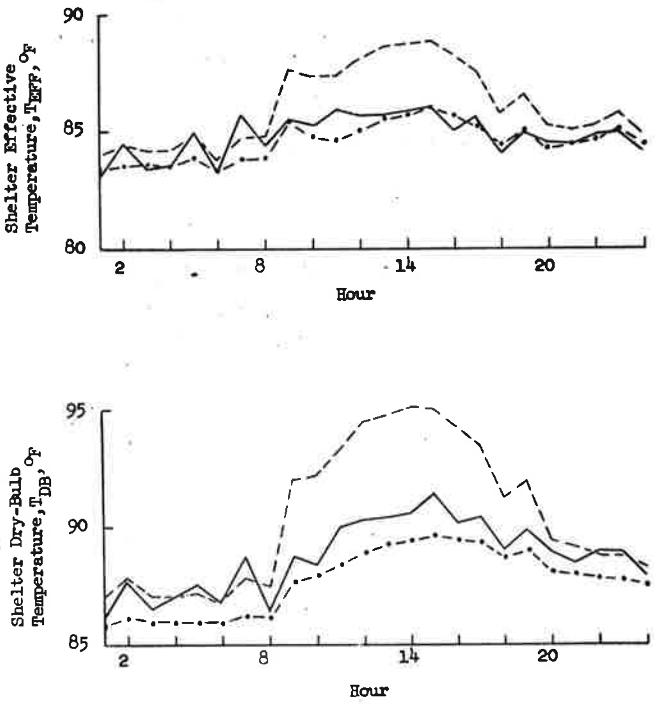
* For 20.0 cfm/occupant ventilation rate, 83.9 F average inlet air db temperature and 80 F average inlet air effective temperature.



	Time-Average Temperatures of Shelter Environment*	
	Dry-Bulb, T_{DB}	Effective, T_{EFF}
———— : Experimental Data	88.6 F	83.2 F
- - - - - - - : Adiabatic Boundary Computation	91.5 F	84.2 F
—·—·—: Nonadiabatic Boundary Computations	87.5 F	82.0 F

Fig. 3 Comparison of computations and experimental data for Central Stores Building, Test Phase IV, Gainesville, Fla.



	Time-Average Temperatures of Shelter Environment**	
	Dry-Bulb, T_{DB}	Effective, T_{EFF}
———— : Experimental Data	88.7 F	84.8 F
- - - - - - - : Adiabatic Boundary Computation	90.5 F	86.1 F
—·—·—: Nonadiabatic Boundary Computation	87.7 F	84.5 F

Computation

Fig. 4 Comparison of computation and experimental data for Houston, Texas Test II

ter. Using the observed inlet air data and the shelter dimensions and construction details, the transient analysis computed the dry-bulb and effective temperatures for the shelter air as a function of time, see Figs. 2, 3, and 4. The instantaneous values are generally within 2 F of the experimental data for the shelter dry-bulb temperature and within 1 F for the shelter effective temperature.

When the shelter is assumed to have adiabatic boundaries (no heat transfer through the shelter boundary surfaces), the analytical and experimental results agree on the 24 hr average to within 2 F for the dry-bulb temperature and within 1 F for the effective temperature. The adiabatic boundary results are consistently at or greater than the experimental values. This means that all of the tested shelters lost energy through their boundary surfaces and that the transient analysis considering energy loss slightly overestimates the amount of this loss.

Steady-state analysis of shelters with boundary heat loss

The time-average psychrometric condition of the shelter can be determined by the steady-state analysis which considers the time-average values of the psychrometric condition of the inlet air and the heat loads generated within the shelter on a per-occupant basis. The heat loss from the boundary surfaces of an aboveground shelter is determined by the temperature difference that exists between the shelter air and the ambient air external to the shelter, the number of occupants, and by the heat loss coefficient, UA. The UA value for a shelter is determined by the size, geometry, and composition of its walls, floor, and ceiling; and its value is determined by

$$UA = \frac{\Sigma_{i=1}^{m} U_i A_i}{P} \qquad (1)$$

where:

U_i = overall heat transfer coefficient of boundary surface i

A_i = surface area of boundary surface i

P = number of shelter occupants

To evaluate the accuracy of the analysis, the

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* For 13.9 cfm occupant ventilation rate, 81.5 F average soil temperature, 85 F average inlet air db temperature and 78.3 F average inlet air effective temperature.

** For 12.8 cfm/occupant ventilation rate, 87.9 F average soil temperature, 83.0 F average inlet air db temperature and 79.0 F average inlet air effective temperature.

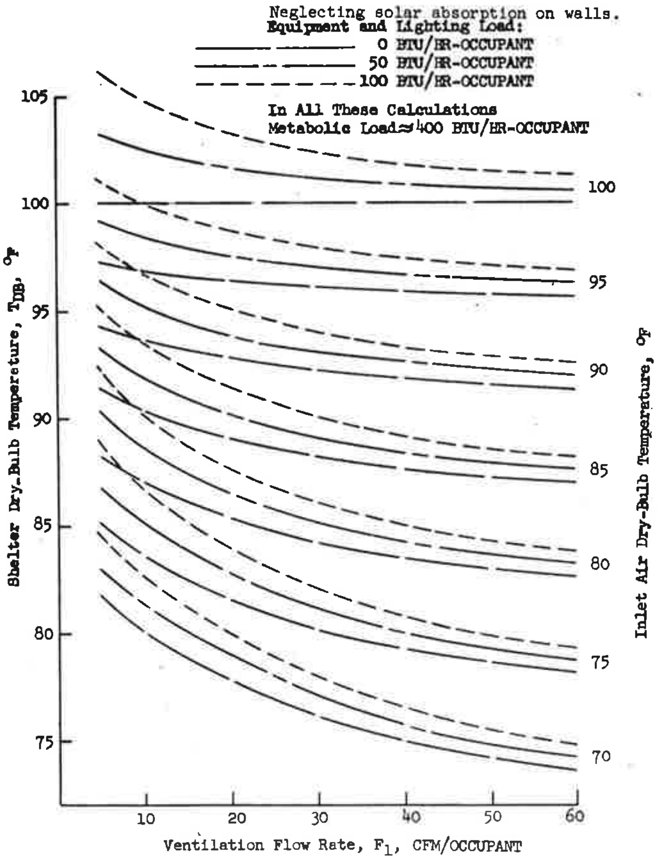


Fig. 5 Nonadiabatic boundary shelter db temperatures for all inlet air rh's and UA = 20 Btu/hr-F-occupant

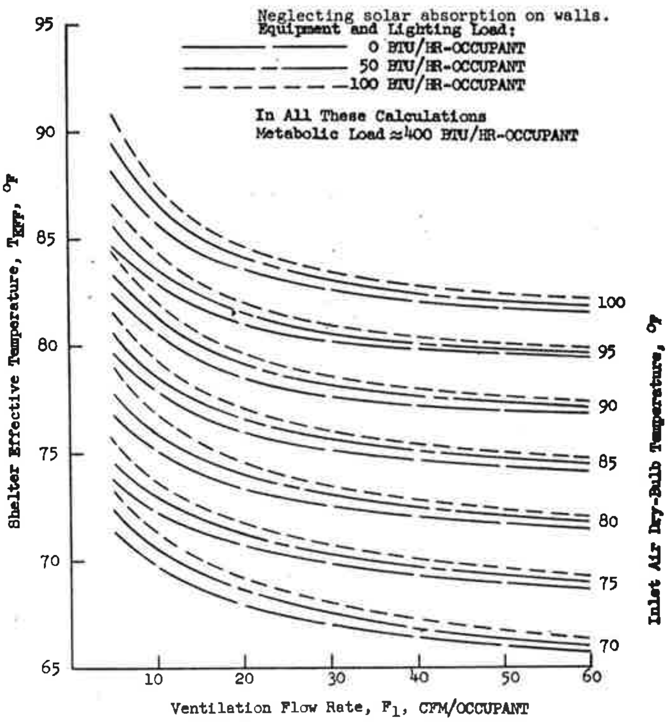


Fig. 6 Nonadiabatic boundary shelter effective temperatures for 15% inlet air rh and UA = 20 Btu/hr-F-occupant

Wilmington aboveground shelter test data are compared to the results computed by the steady-state analysis with boundary heat loss. The comparison shows that the time-average shelter dry-bulb temperature is determined to about 1.5 F and the time-average shelter effective temperature is determined to about 2 F, see Table I.

These results are similar to the agreement obtained with the transient analysis. If the steady-state shelter values of test No. 7 are compared to the time-average shelter values of the transient study for test No. 7, the results are within 2 F of each other. This shows that the steady-state shelter condition approximates the time-average shelter condition determined by the transient analysis.

The steady-state analysis with boundary heat losses was used to determine the psychrometric condition of the shelter as a function of the ventilation rate per occupant, the equipment and lighting load per occupant, the psychrometric conditions of the inlet air, and the heat loss coefficient, UA, see Figs. 5, 6, and 7. The shelter dry-bulb temperature variation

Fig. 7 Nonadiabatic boundary shelter effective temperatures for 80% inlet air rh and UA = 20 Btu/hr-F-occupant

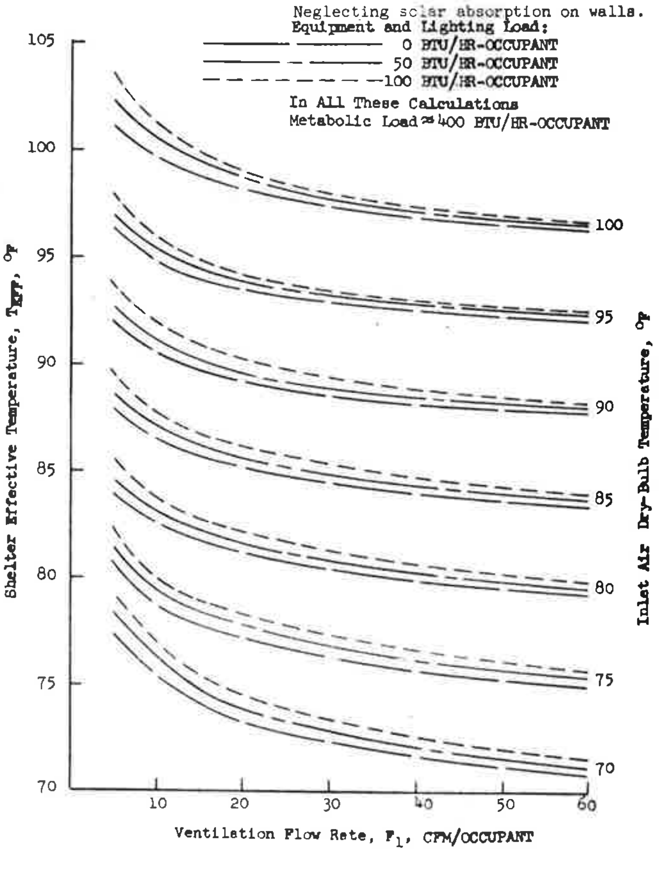


Table I. Summary of Wilmington, N. C. Aboveground Shelter Test[a]

Observed Data	Test Nos. 5	7	8	10A
Ventilation rate, cfm/occupant	9.0	20.0	7.0	13.0
Average inlet dry-bulb temp, F	83.1	83.9	77.5	90.4
Average inlet effective temp, F	78.6	80.7	74.4	80.1
Average inlet relative humidity	0.68	0.78	0.72	0.41
Average shelter dry-bulb temp, F	90.0	88.8	89.8	94.9
Average shelter effective temp, F	85.7	84.5	86.1	85.4
Values Predicted by Steady-State Analysis With Boundary Heat Loss				
Shelter dry-bulb temp, F	90.3	90.2	87.3	95.6
Shelter effective temp, F	86.1	86.7	84.2	85.6

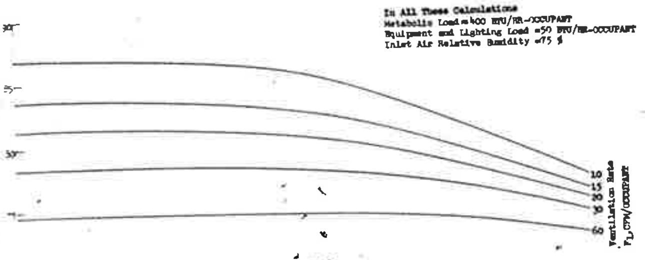


Fig. 8 Influence of magnitude of UA value on shelter db temperature for various ventilation rates

due to changes in the relative humidity of the inlet ventilation air is negligible (less than 0.01 F). This is not true of the effective temperature of the shelter, and, therefore, inlet air relative humidities of 15 and 80% are presented.

The main effect of the heat loss coefficient, UA, is to decrease the sheter dry-bulb and effective temperatures as the UA value increases. But, the temperature reduction decreases as the flow rate increases, see Fig. 8. Generally, less than 20% of the total energy input to the shelter is lost through the shelter boundaries; however, this percentage can become as high as 30-50% for external ambient dry-bulb temperature below 70 F and flow rates below 20 cfm/occupant.

Steady-state analysis of adiabatic boundary shelters

The adiabatic boundary shelter model differs from the nonadiabatic boundary shelter model in that it neglects any heat loss through the shelter boundary surfaces. This is not an unrealistic assumption, because the heat losses of the aboveground shelter can be a small percentage of the total heat input to the shelter. In the belowground shelter, a quasi-adiabatic boundary condition is reached when the wall temperature approximates the shelter average dry-bulb temperature. For example, consider the Houston basement shelter tests. In these shelter tests, the time-average soil temperature was 87.9 F whereas the time-average shelter dry-bulb temperatures varied from 82 to 87 F. When the Houston shelter is considered as an adiabatic boundary shelter by the steady-state analysis, the computed data agree with the test data to within 2 F in dry-bulb temperature and 1.5 F in effective temperature, see Table II.

In test II, the steady-state and transient results agree to within 0.5 F when the shelter is considered to have adiabatic boundary walls. This again confirms the relationship of the time-average values of the transient analysis with the adiabatic boundary steady-state analysis.

The shelter's dry-bulb and effective temperatures

Table II. Summary of Houston Shelter Test'

Observed Data	Test Nos. I	II	III	IV
Ventilation rate, cfm/occupant	9.25	12.8	9.25	18.5
Average inlet dry-bulb temp, F	82	83	77	79
Average inlet effective temp, F	78	79	76	77
Average inlet relative humidity	0.77	0.75	0.87	0.79
Average shelter dry-bulb temp, F	89.5	88.7	87	84
Average shelter effective temp, F	87	84.8	84	82
Values Predicted by Steady-State Adiabatic Boundary Analysis				
Shelter dry-bulb temp, F	90.9	90.1	88.6	86.2
Shelter effective temp, F	87.4	85.9	85.6	82.2

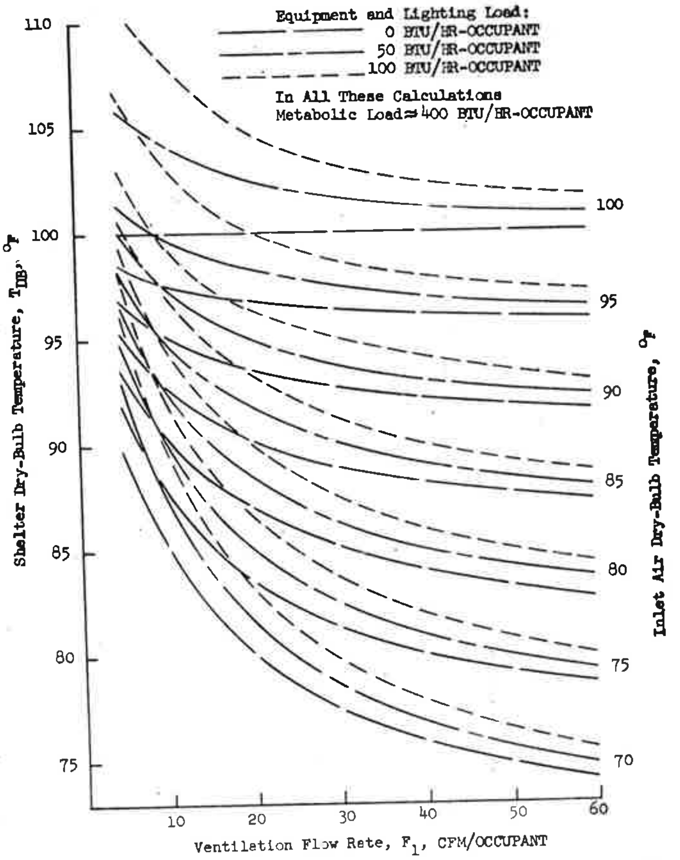
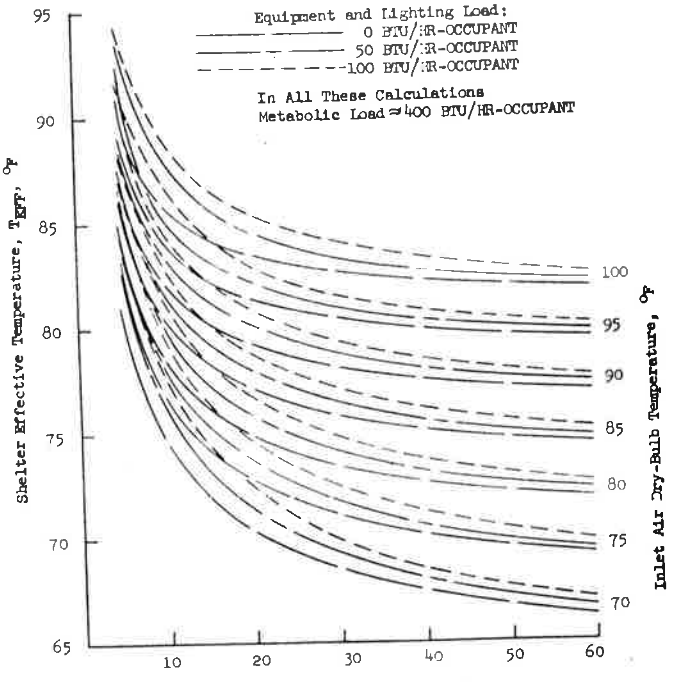


Fig. 9 Adiabatic boundary shelter db temperatures for all inlet air rh's

Fig. 10 Adiabatic boundary shelter effective temperatures 15% inlet air rh



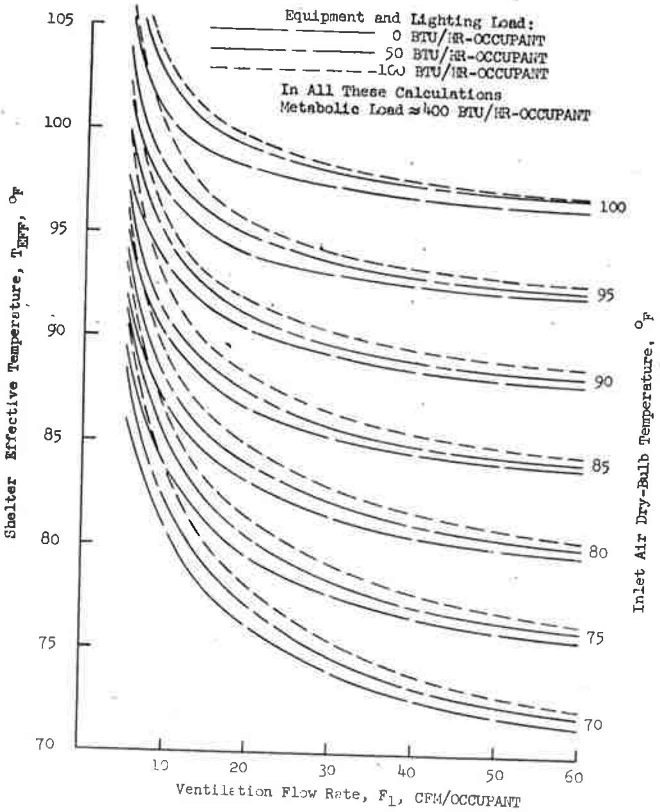


Fig. 11 Adiabatic boundary shelter effective temperatures for 80% inlet air rh

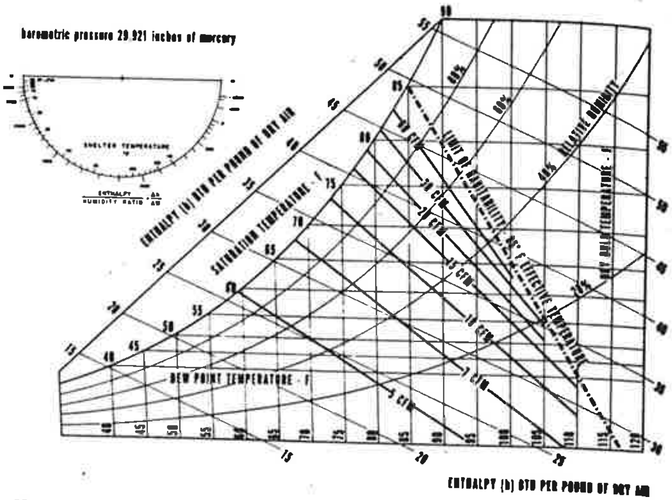


Fig. 12 Ventilation rates to maintain an average effective temperature of 85% F

were computed by the adiabatic boundary steady-state analysis for the same range of parameters used with the nonadiabatic boundary analysis, see Figs. 9, 10, and 11. When these data are compared with the data for the nonadiabatic boundary shelter, the inlet air conditions that produce high rates of energy loss are found to occur when energy loss is the least needed to control the shelter environment. For example, at inlet dry-bulb temperatures below 70 F, the adiabatic boundary shelter's effective temperature never exceeds 85 F except at flow rates of 6 cfm/occupant and below, see Figs. 10, and 11.

If the effective temperature index is accepted as the shelter habitability criteria, a psychrometric chart can be used as a means of determining the relationship between the psychrometric condition of the inlet air and the ventilation flow rate.[8] For instance, if an average effective temperature of 85 F is chosen as the habitability limit, the loci of the average psychrometric conditions of the inlet air that produce an 85 F effective temperature in the shelter can be plotted for various ventilation rates, see Fig. 12.

Local ventilation rates

To determine the ventilation rate required for any given shelter, weather design criteria must be selected. Several weather data studies are currently available upon which the weather design criteria could be based,[7,8,9] but the weather design criteria selected for a shelter must be based upon a detailed study of the relationship between the psychrometric state of the ambient weather and the effect that ventilation air from this ambient has on the shelter environment. This relationship will be influenced by the interval of time chosen for the comparison. Possibly none of the available weather data studies will be applicable and a new set of criteria will have to be established. In addition, more information must be garnered concerning the effect of environmental conditions on the human body; especially when these conditions are changing with time, and when the body is under a high level of emotional stress. However, this paper has shown that the regional ventilation requirements for shelters can be determined, once the weather design criteria and habitability criteria are known.

CONCLUSIONS

The transient analysis can predict an aboveground shelter's instantaneous dry-bulb temperature to within 2 F and the shelter's instantaneous effective temperature to within 1 F. The time-average values of a shelter's dry-bulb and effective temperature can be predicted by a steady-state analysis to within 2 F. Either of these analyses can be used to determine the environmental condition of a shelter with a reasonably high degree of accuracy. The steady-state analysis has established that the energy loss that can occur through the boundary surfaces of an aboveground shelter is generally less than 20% of the total thermal energy introduced into the shelter air during hot summer weather. All of these results indicate that the mechanism of heat loss through the boundary surfaces of an aboveground shelter cannot be depended upon to remove energy from the shelter during hot weather. At most, boundary surface heat loss should be regarded as a possible safety-factor in ventilation system design. It is therefore recommended that the ventilation systems for aboveground shelters be designed to remove the entire thermal load generated within the shelter.

The flow rate predicted by the analysis of a shelter without boundary surface heat loss is the maximum flow rate that can be required (assuming the solar radiation absorption effects on opaque shel-

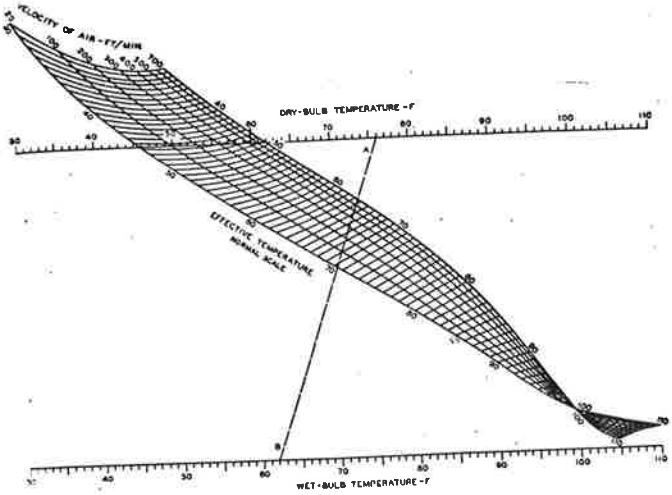


Fig. A1 ASHRAE *effective temperature nomogram*

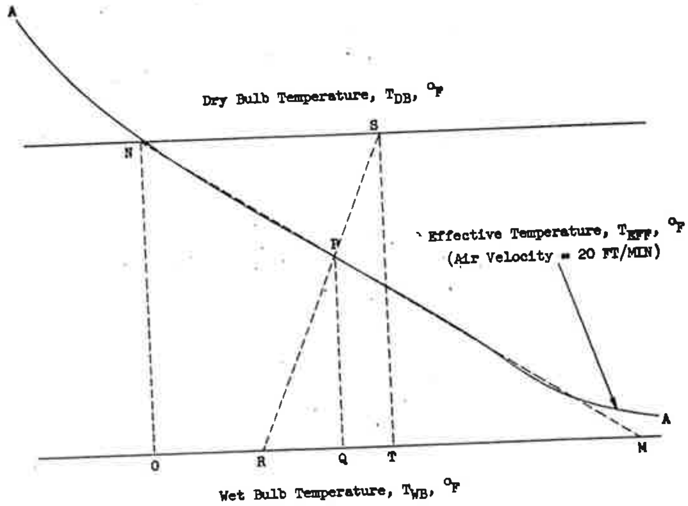


Fig. A2 *Schematic of nomogram of effective temperature*

ter boundary surfaces are negligible[*]); and thus provides a means for establishing an upper limit on the size of the ventilation equipment for an aboveground shelter. The reasonable agreement between the 24 hr average value calculations for a shelter without boundary surface heat loss and the shelter test data insures that the equipment size based upon this ventilation rate is not overly conservative.

This paper has shown that with metabolic heat load data and weather design criteria the ventilation requirements for aboveground shelters (e.g., the shelters surveyed in the National Fallout Shelter Survey) can be determined analytically. The reliability of these predictions is primarily dependent upon the reliability of the metabolic and weather design data used in the calculation procedure.

APPENDIX A

Derivation of effective temperature equation

Many different sets of psychrometric conditions provide the human body with similar levels of physiological comfort. The effective temperature scale has been established as an empirically derived index of the various psychrometric conditions which produce similar comfort levels. The effective temperature is a function of the dry-bulb temperature, wet-bulb temperature, and velocity of the air in which a person resides. Generally, these data have been presented in nomographic form or by approximating equations. For the purposes of this study, the nomograms were inconvenient to use since they were not in equation form, and the existent equations were not of sufficient accuracy. As a result, an accurate mathematical expression for effective temperature was derived.

The derivation was based upon the ASHRAE nomogram for effective temperature, see Fig. A1. Because the ventilating air velocities in shelters is generally low, only the 20 fpm flow velocity curve of the nomogram was considered. This eliminated the air velocity as a parameter in the determination of effective temperature. A schematic of the curve AA which represents the 20 fpm flow velocity in the nomogram is shown in Fig. A2. Curve AA is linearized by a straight line which intersects the wet-bulb (T_{WB}) and dry-bulb (T_{DB}) temperature scales at the points M and N respectively. By geometric similarity

$$\frac{P\text{-}Q}{N\text{-}O} = \frac{M\text{-}Q}{M\text{-}O} \tag{A1}$$

and

$$\frac{P\text{-}Q}{S\text{-}T} = \frac{R\text{-}Q}{R\text{-}T} \tag{A2}$$

but

$$N\text{-}O = S\text{-}T$$

then

$$\frac{M\text{-}Q}{M\text{-}O} = \frac{R\text{-}Q}{R\text{-}T} \tag{A3}$$

where

M = 107.5 F
N = 45.2 F
O = 45.2 F
S = T_{DB}
R = T_{WB}
P = T_{EFF}
Q = T_{EFF}
R = T_{DB}

Substituting the above values in Eq. (A3) yields

Table AI. Error in Calculated Effective Temperatures by Equation (A4)

T_{DB}, F	T_{WB}, F	T_{eff}, cal'd by Eq. (A4)	T_{eff}, read from Fig. (A1)	% Error
110.0	98.0	99.4	94.0	0.45
110.0	90.0	94.2	94.0	0.21
110.0	30.0	73.5	74.0	0.68
90.0	80.0	83.9	83.9	0
90.0	60.0	75.5	75.6	0.13
90.0	40.0	70.0	70.0	0
80.0	60.0	71.5	71.5	0
80.0	40.0	66.3	66.3	0
80.0	30.0	64.7	64.3	0.62
70.0	60.0	66.6	66.5	0.15
70.0	50.0	63.9	64.0	0.15
45.0	30.0	45.1	45.0	0.22

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[*] This assumption is presently under detailed evaluation by the MRD Division.

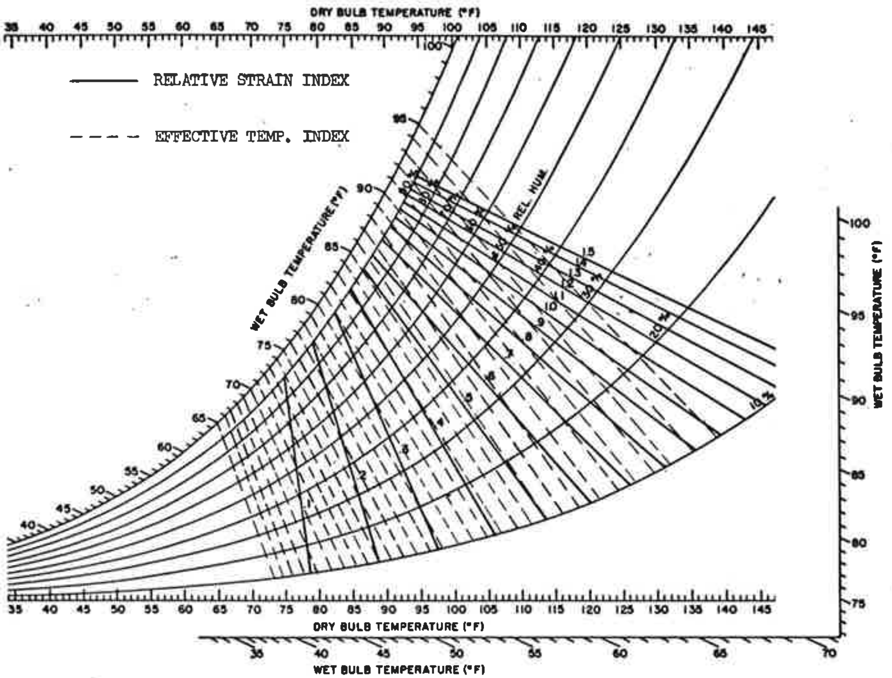

Fig. A3 Relationship of effective temperature and relative strain indices

$$T_{EFF} = \frac{107.5\,(T_{DB} - T_{WB}) + 62.3(T_{WB})}{62.3 + (T_{DB} - T_{WB})} \qquad \text{(A4)}$$

This relationship is limited to low air velocities and is restricted to the temperature range of

$$45\ \text{F} \leq T_{DB} \leq 110\ \text{F}$$

and

$$30\ \text{F} \leq T_{WB} \leq 100\ \text{F}$$

The temperature range restrictions are imposed because the T_{EFF} curve of the nomogram cannot be considered a straight line beyond these temperature limits. Table AI shows that Eq. (A4) has an average error of less than 1%.

The effective temperature values are correlated to the relative strain indices with a 0.5 relative strain index being essentially an 85 F effective temperature, see Fig. A3. Almost all people are comfortable at zero relative strain index and physical failure is rapid and severe at 1.0 relative strain index.[11] This comparison illustrates the convertability of the effective temperature index to other indices of physiological comfort.

APPENDIX B

Derivation of mathematical shelter model

The study of the ventilation requirements for a shelter is based upon the philosophy that whether a shelter is above or belowground and whether it is single story or multi-story, the shelter can be represented by a single mathematical model. Furthermore, the model is developed with the idea that it should be the simplest model that can be devised and still adequately explain the phenomena. In accord with this philosophy, the assumptions are made that:

1. the air within the shelter is so completely mixed that all of the shelter air is at one psychrometric condition,
2. the convective heat transfer coefficient for each external boundary surface of the shelter is not a function of temperature and has a constant value over the surface,
3. the walls and floors that are internal to the shelter volume are at the dry-bulb temperature of the shelter air,
4. the radiative energy interchanges within the shelter can be neglected,
5. the solar direct and indirect radiative input to the shelter and the equipment and lighting heat loads in the shelter can be grouped together as one time dependent load factor which is termed the thermal load,
6. the ventilating air exhausted from the shelter is at the psychrometric condition of the shelter air,
7. the effects of condensation on the walls, floors, and ceilings of the shelter can be neglected,
8. the soil about belowground structures is an infinite extension of the thickness of the shelter's external boundary surfaces.
9. the thermal-physical properties of the structural materials are not temperature dependent.

The model of the shelter is established by these assumptions. Thus the shelter is idealized as an enclosed volume in which sensible heat, latent heat, solar heat, equipment heat, and ventilating air are introduced and from which air is exhausted and energy is lost. The governing principles for such a model are the conservation of energy and the conservation of the masses of dry air and water vapor.

The conservation of energy requires that[12]

rate of change of enthalpy in ventilating air + rate of change in shelter air + rate of metabolic heat input by shelter occupants + rate of thermal load to shelter + rate of energy transfer across shelter boundary surfaces = 0 (B1)

or upon integrating Eq. (B1) over the time interval $\Delta\tau$

$$(H_1 - H_2) + (H_{S,1} - H_{S,2}) + Q_M + Q_T - Q_B = 0 \qquad \text{(B2)}$$

where

H_1 = enthalpy of ventilating air entering the shelter, Btu

H_2 = enthalpy of ventilating air leaving the shelter, Btu
$H_{s,1}$ = enthalpy of shelter air at beginning of time increment $\Delta\tau$, Btu
$H_{s,2}$ = enthalpy of shelter air at end of time increment $\Delta\tau$, Btu
Q_M = energy due to metabolism of shelter occupants, Btu
Q_T = energy input due to thermal load (see assumption No. 5 above), Btu
Q_B = energy loss or gain through shelter boundary surfaces, Btu

The conservation of the mass of water vapor necessitates that

rate of change of water vapor in ventilating air + rate of change of water vapor in shelter air + rate of water vapor introduced by shelter occupants = 0 (B3)

and integrating Eq. (B3) over the time increment $\Delta\tau$

$$(M_{v,1} - M_{v,2}) + (M_{v,s,1} - M_{v,s,2}) + M_{v,M} = 0 \tag{B4}$$

where

$M_{v,1}$ = mass of water vapor in the entering ventilating air, lb
$M_{v,2}$ = mass of water vapor in the exhausting ventilating air, lb
$M_{v,s,1}$ = mass of water vapor in the shelter at the beginning of the time increment $\Delta\tau$, lb
$M_{v,s,2}$ = mass of water vapor in the shelter at the end of time increment $\Delta\tau$, lb
$M_{v,M}$ = mass of water vapor introduced by the shelter occupants, lb

The conservation of the mass of dry air demands that

rate of change of dry air in ventilating air + rate of change of dry air in shelter = 0 (B5)

and after integrating over the time increment $\Delta\tau$

$$(M_{a,1} - M_{a,2}) + (M_{a,s,1} - M_{a,s,2}) = 0 \tag{B6}$$

where

$M_{a,1}$ = mass of dry air in the entering shelter air, lb
$M_{a,2}$ = mass of dry air in the exhausting shelter air, lb
$M_{a,s,1}$ = mass of dry air in the shelter at the beginning of the time increment, lb
$M_{a,s,2}$ = mass of dry air in the shelter at the end of the time increment, lb

Denoting

$$\Delta Q = H_1 + H_{s,1} + Q_M + Q_T - Q_B \tag{B7}$$

$$M_{v,0} = M_{v,1} + M_{v,s,1} + M_{v,M} \tag{B8}$$

$$M_{a,0} = M_{a,1} + M_{a,s,1} \tag{B9}$$

and substituting Eq. (B7) through (B9) into Eqs. (B2), (B4), and (B6) gives

$$\Delta Q = H_{s,2} + H_2 \tag{B10}$$

$$M_{v,0} = M_{v,2} + M_{v,s,2} \tag{B11}$$

$$M_{a,0} = M_{a,2} + M_{a,s,2} \tag{B12}$$

where

$$H_{s,2} = M_{a,s,2}\, h_{a,s,2} + M_{v,s,2}\, h_{v,s,2} \tag{B13}$$

$$H_2 = M_{a,2}\, h_{a,2} + M_{v,2}\, h_{v,2} \tag{B14}$$

From the assumption that the exhaust air has the same psychrometric condition as the shelter air

$$h_{a,2} = h_{a,s,2} \tag{B15}$$

and

$$h_{v,2} = h_{v,s,2} \tag{B16}$$

With Eqs. (B11) to (B16) substituted into Eq. (B10)

$$\Delta Q = M_{a,0}\, h_{a,s,2} + M_{v,0}\, h_{v,s,2} \tag{B17}$$

The specific enthalpies of dry air and water vapor are given by

$$h_a = 0.24\,(T_{DB} + 459.69) \tag{B18}$$

and

$$h_v = 1061 + 0.444\,(T_{DB}) \tag{B19}$$

for $32\text{ F} \leqq T_{DB} \leqq 150\text{ F}$

where

T_{DB} = dry-bulb temperature, F

Combining Eqs. (B17) to (B19) and solving for the dry-bulb temperature results in

$$T_{DB,2} = \frac{\Delta Q - 857\, M_{v,0}}{0.444\, M_{v,0} + 0.24\, M_{a,0}} \tag{B20}$$

where

$T_{DB,2}$ = dry-bulb temperature of shelter air at end of time increment $\Delta\tau$ F

Also have the relationships that

$$M_{a,2} = 60\, F_2\, \rho_{a,2} \tag{B21}$$

$$M_{v,2} = 60\, F_2\, \rho_{a,2} \tag{B22}$$

$$M_{a,s,2} = V\rho_{a,s,2} \tag{B23}$$

and

$$M_{v,s,2} = V\rho_{v,s,2} \tag{B24}$$

where

V = shelter volume, ft^3
$\rho_{a,2}$ = density of dry air leaving shelter, lb/ft^3
$\rho_{v,2}$ = density of water vapor leaving shelter, lb/ft^3
$\rho_{a,s,2}$ = density of dry air in shelter at end of time increment, lb/ft^3
$\rho_{v,s,2}$ = density of water vapor in shelter at end of time increment, lb/ft^3
F_2 = volumetric flow rate of exhaust air, lb/hr

But have assumed that

$$\rho_{a,2} = \rho_{a,s,2} \tag{B25}$$

and

$$\rho_{v,2} = \rho_{v,s,2} \tag{B26}$$

Substituting Eqs. (B21) through (B26) into Eqs. (B11) and (B12) yields

$$M_{v,0} = \rho_{v,2}\,(60\, F_2\Delta\tau + V) \tag{B27}$$

and

$$M_{a,0} = \rho_{a,2}\,(60\, F_2\Delta\tau + V) \tag{B28}$$

When Eqs. (B27) and (B28) are solved for F_2, they result in

$$F_2 = \frac{M_{a,0} - \rho_{a,2}V}{60\Delta\tau \quad \rho_{a,2}} \tag{B29}$$

$$= \frac{M_{v,0} - \rho_{v,2}V}{60\Delta\tau \quad \rho_{v,2}}. \tag{B30}$$

The densities of the dry air and water vapor are assumed to obey the perfect gas law. Thus

$$\rho_v = \frac{P_v}{R_v(T_{DB} + 459.69)} \tag{B31}$$

and

$$\rho_a = \frac{P_B - P_v}{R_a(T_{DB} + 459.69)} \tag{B32}$$

where

P_B = barometric pressure, psf
P_v = partial pressure of water vapor, psf
R_v = gas constant for water vapor, ft-lb/lb$_{mole}$-R
R_a = gas constant for dry air, ft-lb/lb$_{mole}$-R

The partial pressure of water vapor is expressed by

$$P_V = r\ P_S \qquad (B33)$$

where

r = relative humidity
P_S = saturation pressure of water vapor, psf

$$P_S = 5.132e^{0.0320(T_{DB})} \qquad (B34)$$
$$\text{for } 32\text{ F} \leqq T_{DB} \leqq 150\text{ F}$$

which is an analytical expression for the tabulated values of saturated vapor pressures as a function of dry-bulb temperature.[13]

From Eqs. (B30) through (B33) with

R_a = 53.35 ft-lb/lb_{mole}-R

and

R_V = 85.71 ft-lb/lb_{mole}-F

can obtain the expressions

$$P_V = r\ [5.132e^{0.0320(T_{DB})}] \qquad (B35)$$

$$\rho_V = \frac{1}{(T_{DB} + 459.69)}\ [0.05987\ r\ e^{0.0329(T_{DB})}] \qquad (B36)$$

and

$$\rho_a = \frac{1}{(T_{DB} + 459.69)}\ [0.01874\ P_B - 0.0962\ r\ e^{0.0329(T_{DB})}] \qquad (B37)$$

Equating Eqs. (B29) and (B30) gives

$$\frac{M_{a,o}}{\rho_{a,2}} = \frac{M_{V,o}}{\rho_{V,2}} \qquad (B38)$$

Evaluating Eqs. (B36) and (B37) at the shelter dry-bulb temperature, $T_{DB,2}$, and substituting the results into Eq. (B38) gives the partial pressure of the water vapor, P_V, as

$$P_V = \frac{P_B}{1 + 0.6224\left(\dfrac{M_{a,o}}{M_{V,o}}\right)} \qquad (B39)$$

And from Eq. (B33), the relative humidity of the shelter at the end of the time increment is given by

$$r = \frac{P_V}{P_S} \qquad (B40)$$

Substituting Eqs. (B34) and (B39) into Eq. (B40) results in

$$r = \frac{P_B}{5.132e^{0.0329(T_{DB})}\left[1 + 0.6224\dfrac{M_{a,o}}{M_{V,o}}\right]} \qquad (B41)$$

By the derivation of these equations, the psychrometric conditions within the shelter can be determined as a function of time through the use of the following procedure:

1. Determine the psychrometric conditions of the air introduced into the shelter and the air within the shelter along with the heat inputs and losses of the shelter,
2. compute the quantities ΔQ, $M_{V,o}$, and $M_{a,o}$ from Eqs. (B7), (B8), and (B9) respectively,
3. assume that these quantities do not change over the time interval, $\Delta\tau$, and compute the dry-bulb temperature of the shelter at the end of the time interval from Eq. (B20),
4. calculate the relative humidity of the shelter air at the end of the time interval from Eq. (B41),
5. set the psychrometric conditions of the shelter at the end of the time increment equal to those in the shelter at the beginning of the next increment and repeat the entire procedure.

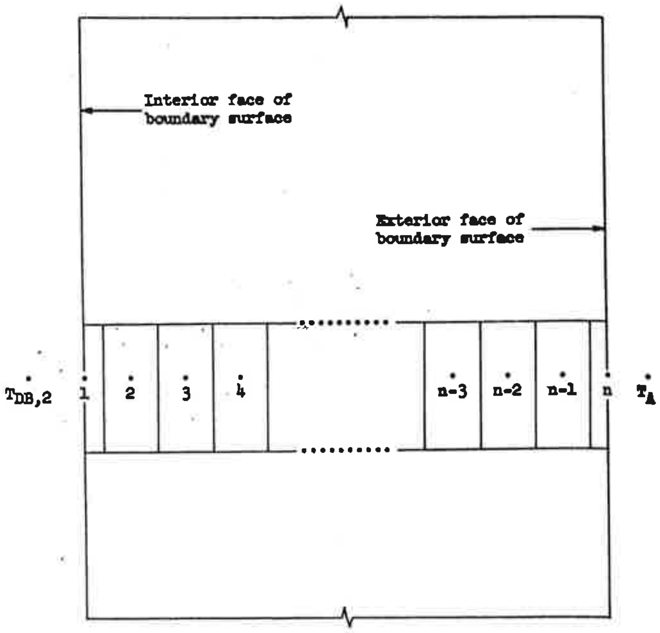

Fig. B1 Arrangement of nodal points in shelter boundary surface

By the continuous application of this procedure, the shelter's psychrometric condition can be obtained as a function of time for any time period. The computation method that has been developed constitutes a transient analysis of the shelter environment under the influence of time varying parameters.

The shelter's psychrometric condition is described in the analysis by its dry-bulb temperature and relative humidity. Instead, the wet-bulb and dry-bulb or effective temperatures can be used. The wet-bulb temperature is determined from the equation[11]

$$P_V = P_S' - \frac{(P_B - P_S')(T_{DB} - T_{WB})}{2800.0 - 1.3\ (T_{WB})} \qquad (B42)$$

where

P_S' = saturation pressure at wet-bulb temperature, psf
T_{WB} = wet-bulb temperature, F

with P_S' evaluated by Eq. (B34)

$$P_S' = 5.132\ e^{0.0320(T_{WB})} \qquad (B43)$$

and P_V obtained from Eq. (B39). The result is a transcendental equation that can be solved for the wet-bulb temperature, T_{WB}. When the value of the wet-bulb temperature is known, the effective temperature can be determined from Eq. (A4).

Boundary surface heat loss

The heat loss or gain of the shelter boundary, Q_B, over a time interval $\Delta\tau$ is determined by the temperature of the inner surface of the boundary, T_1. In the computations, the value of T_1 is obtained from the temperature distribution that existed through the boundary during the previous time increment. This temperature distribution is deduced from a transient analysis of the energy transfer in the boundary. In order to accomplish this analysis, the boundary is divided into a finite number of slabs of thickness $\Delta\chi$ except for the inner and outer surfaces which are made into slabs of thickness $\Delta\chi/2$, with each slab assumed to be at a single temperature. This temperature is assigned to the midpoint of each slab except for the innermost and outermost slabs which are assigned temperatures at the external surfaces of the slab, see Fig. B1. These locations of slab temperature are termed nodal points. The external nodal points of the boundary transfer energy by convection with surrounding air and by conduction with the next internal nodal point. All of the rest of the nodal points transfer energy by conduction with the two adjacent nodal points. The energy balance about an internal nodal point m is

energy conducted to point m from point m − 1	−	energy conducted to point m + 1 from point m	=	energy stored in the slab of point m

(B44)

or

$$-kA\frac{(T_m - T_{m-1})}{\Delta\chi} + kA\frac{(T_{m+1} - T_m)}{\Delta\chi} = \frac{\Delta\chi\, A\, \rho\, C_P\, (T_m' - T_m)}{\Delta\tau} \qquad (B45)$$

and the temperature at the nodal point is

$$T_m' = B_1(T_{m-1} + T_{m+1}) + (1 - 2B_1)T_m \qquad (B46)$$

with

$$B_1 \leq \frac{1}{2} \qquad (B47)$$

where

$B_1 = \dfrac{\alpha\Delta\tau}{\Delta\chi^2}$

$\alpha = \dfrac{k}{\rho C_p}$

k = thermal conductivity of composite boundary material, Btu/hr-ft-F

ρ = density of composite boundary material, lb/ft^3

C_P = specific heat of composite boundary material, Btu/lb-F

$\Delta\chi$ = thickness of boundary slab, ft

T_m = temperature of nodal point m at beginning of time increment, F

T_{m-1} = temperature of nodal point m−1 at beginning of time increment, F

T_{m-1} = temperature of nodal point m+1 at beginning of time increment, F

T_m' = temperature of nodal point m at end of time increment, F

The energy balance about the inner surface of the boundary is

energy convected from shelter air to boundary	−	energy conducted to nodal point 2 from nodal point 1	=	energy stored in the slab at nodal point 1

(B48)

or

$$h_i A(T_{DB,2} - T_1) + kA\frac{(T_2 - T_1)}{\Delta\chi} = \frac{\Delta\chi}{2} A \frac{\rho C_p}{\Delta\tau}(T_1' - T_1) \qquad (B49)$$

and the temperature at the inner boundary surface is

$$T_1' = B_2B_3T_{DB,2} + B_3T_2 + (1 - B_3 - B_2B_3)T_1 \qquad (B50)$$

$$\text{with} \quad B_3(B_2 + 1) \leq 1 \qquad (B51)$$

where

$B_2 = \dfrac{h_i\Delta\chi}{k}$

$B_3 = 2B_1$

h_i = heat transfer coefficient on the inner surface of the boundary, Btu/hr-ft^2-f

$T_{DB,2}$ = temperature of shelter at beginning of time increment, F

T_1 = temperature of nodal point at inner surface of boundary at beginning of time increment, F

T_2 = temperature of nodal point 2 at beginning of time increment, F

T_1' = temperature of nodal point at inner surface of boundary at end of time increment, F

The energy balance about the outer surface of the boundary n, is

energy conducted from (n−1) nodal point to outer surface point n	−	energy convected from outer surface point n to external ambient air	=	energy stored in the slab at the outer surface

(B52)

or

$$-kA\frac{(T_n - T_{n-1})}{\Delta\chi} - h_oA(T_n - T_A) = \frac{\Delta\chi}{2} A \frac{\rho C_p}{\Delta\tau}(T_n' - T_n) \qquad (B53)$$

and the temperature at the outer boundary surface is

$$T_n' = B_3T_{n-1} + B_4B_3T_A + (1 - B_3 - B_4B_3)T_n \qquad (B54)$$

$$\text{with} \quad B_3(B_4 + 1) \leq 1 \qquad (B55)$$

where

$B_4 = \dfrac{h_o\Delta\chi}{k}$

h_o = heat transfer coefficient on the outer surface of the boundary, Btuh-ft^2-F

T_n = temperature of nodal point n at outer surface of boundary at beginning of time increment, F

T_{n-1} = temperature of nodal point n−1 at beginning of time increment, F

T_A = temperature of external ambient air at beginning of time increment, F

T_n' = temperature of nodal point n at outer surface of boundary at end of time increment, F

The heat transfer at the boundary, as expressed by Q_B, is applicable to both above and belowground shelters. The equations that have been formulated are for an aboveground shelter. When an underground shelter is to be analyzed, Eqs. (B46) and (B50) are used with the number of internal points increased until there is a sufficient number of points to insure that the temperature of the outermost nodal point does not change during the calculations. This last point represents a thermally undisturbed section of the soil at its original temperature. As a result, no equation like Eq. (B54) is required at this last point.

The boundary surface heat loss, as defined by Eqs. (B46), (B50), and (B54), is applicable to the one dimensional heat transfer from a boundary surface. If the boundary surfaces of a shelter are large, corner effects are negligible and each boundary surface can be considered to be conducting energy from or to the shelter uni-directionally. However, the problem in solving for the heat energy loss or gain from the shelter boundary surfaces is dependent upon the designation of a temperature, T_A, in Eq. (B54), and upon the properties of the boundary surface, i.e., density, ϱ, thermal conductivity, k, specific heat, C_p, and thickness, L, with $\Delta\chi = \frac{L}{n-1}$ where n = number of nodal points. To simplify the analysis, the shelter boundary surfaces are grouped together to form one slab surface exposed to the temperature of the shelter on one side and the temperature, T_A, on the other side. The procedure of replacing all of the separate boundary surfaces by one slab surface is based upon the determination of area weighted average values for the various properties of the boundary surface. That is, for the boundary surface property, X, the area weighted average value of X for the slab surface $\overline{X}$ is given by

$$\overline{X} = \frac{\Sigma^m{}_{i=1} A_i X_i}{\Sigma^m{}_{i=1} A_i} \qquad \text{(B56)}$$

where

A_i = surface area of boundary surface i
m = number of boundary surfaces
X_i = property X of the boundary surface i

Then have

$$\rho = \frac{\Sigma^m{}_{i=1} A_i \rho_i}{\Sigma^m{}_{i=1} A_i} \qquad \text{(B57)}$$

$$\overline{k} = \frac{\Sigma^m{}_{i=1} A_i k_i}{\Sigma^m{}_{i=1}} \qquad \text{(B58)}$$

$$\overline{C}_p = \frac{\Sigma^m{}_{i=1} A_i (C_p)_i}{\Sigma^m{}_{i=1} A_i} \qquad \text{(B59)}$$

and

$$\overline{L} = \frac{\Sigma^m{}_{i=1} A_i l_i}{\Sigma^m{}_{i=1} A_i} \qquad \text{(B60)}$$

The values $\overline{\varrho}$, $\overline{k}$, $\overline{C}_p$, and $\overline{L}$ determine the values of the composite boundary surface slab.

In general, the exterior sides of shelter boundary surfaces are exposed to three types of environments. The boundary surface can be exposed to the ambient weather (e.g., an outside wall), to the soil (e.g., the floor), or to a space interior to the structure but exterior to the shelter (e.g., a first floor shelter ceiling exposed to a second floor space of the building). In each of these situations, the value of T_A for each boundary surface will be different. In general, the area weighted average value of T_A would be

$$\overline{T}_A = \frac{\Sigma^m{}_{i=1} A_i (T_A)_i}{\Sigma^m{}_{i=1} A_i} \qquad \text{(B61)}$$

where

$(T_A)_i$ = temperature to which the exterior side of boundary surface i is exposed

Letting

$$p_i = \frac{A_i}{\Sigma^m{}_{i=1} A_i} \quad \text{with } i = 1,2,\ldots,m \qquad \text{(B62)}$$

then

$$\overline{T}_A = \Sigma^m{}_{i=1}\ p_i(\overline{T}_A)i \qquad \text{(B63)}$$

With the fact that the exterior side of the boundary surface can be exposed to only three types of environments

$$\overline{T}_A = p_o(T_A)_o + p_s(T_A)_s + p_i(T_A)_i \quad \text{with } i = 1,2,\ldots,q \qquad \text{(B64)}$$

where

p_o = percentage of shelter boundary surfaces exposed to the ambient weather temperature $(T_A)_o$
p_s = percentage of shelter boundary surfaces exposed to soil at the temperature $(T_A)_s$
p_i = percentage of shelter boundary surfaces exposed to each of the interior space temperatures, $(T_A)_i$ for each of the q interior spaces.

But experience and experimental test results have shown that the temperature values of the soil and interior surfaces adjacent to the shelter can be closely approximated by

$$(T_A)_s = \frac{T_s + T_{DB,1}}{2} \qquad \text{(B65)}$$

and

$$(T_A)_i = \frac{(T_A)_o + T_{DB,1}}{2} \qquad \text{(B66)}$$

where

T_s = well water temperature at location of interest as given by Collins[15]
$T_{DB,1}$ = shelter dry-bulb temperature at time for which boundary surface heat loss or gain is computed

Substituting Eqs. (B65) and (B66) into Eq. (B64) gives

$$\overline{T}_A = p_o(T_A)_o + \frac{p_s}{2}[T_s + T_{DB,1}] + \frac{p_{i,T}}{2}[(T_A)_o + T_{DB,1}] \qquad \text{(B67)}$$

or

$$\overline{T}_A = \left(p_o + \frac{p_{i,T}}{2}\right)(T_A)_o + (p_s + p_{i,T})\,T_{DB,1} + \frac{1}{2}p_s T_s \qquad \text{(B68)}$$

where

$p_{i,T}$ = total percentage of shelter boundary surfaces exposed to interior spaces

The value of $\overline{T}_A$ of Eq. (B68) is used as the value of T_A in Eq. (B54). With these area weighted average property values and the relationship for $\overline{T}_A$, the value of the boundary surface heat loss or gain, Q_B, can be computed.

It is remarked that in this procedure, Eq. (B54) does not include a term for solar radiation absorption. But the inclusion of this term is a simple modification of Eq. (B54).

Steady-state shelter analysis

In the steady-state analysis of the shelter environment, none of the parameters vary with time including the psychrometric condition of the shelter. This reduces the complexity of the computation program. The transient calculation procedure can be used to obtain steady-state environmental results if all of the parameters are made constant with time. This process is an iteration procedure which converges to the steady-state values. The steady-state calculation is otherwise identical to the transient shelter model.

Under steady-state conditions, the conservation of energy equation becomes

$$(H_1 - H_2) + Q_M + Q_T - Q_B = 0 \qquad \text{(B69)}$$

the conservation of the mass of water vapor is

$$(M_{v,1} - M_{v,2}) + M_{v,M} = 0 \qquad \text{(B70)}$$

and the conservation of dry air mass is

$$M_{a,1} - M_{a,2} = 0 \qquad \text{(B71)}$$

Introducing the quantities ΔQ, $M_{v,o}$ and $M_{a,o}$ as

$$\Delta Q = H_1 + Q_M + Q_T - Q_B \quad \text{(B72)}$$

$$M_{v,o} = M_{v,1} + M_{v,M} \quad \text{(B73)}$$

$$M_{a,o} = M_{a,1} \quad \text{(B74)}$$

Then Eqs. (B69) through (B71) become

$$H_2 = \Delta Q \quad \text{(B75)}$$

$$M_{v,2} = M_{v,o} \quad \text{(B76)}$$

$$M_{a,2} = M_{a,o} \quad \text{(B77)}$$

All of the other relationships remain the same as in the derivation of the transient analysis. The shelter's dry-bulb temperature is still defined by Eq. (B20), and its relative humidity is still defined by Eq. (B41), with the exception that the terms ΔQ, $M_{v,o}$, and $M_{a,o}$ must be defined as in Eqs. (B72) through (B74). One consequence of the steady-state derivation is that the shelter dimensions and volume do not enter into the calculations of the shelter's psychrometric condition.

Computational criteria

The time increment used in a computation cannot be arbitrarily chosen without introducing instability into the computations. Practice has shown that if the volume of the ventilating air introduced into the shelter during a time increment is less than a fixed percentage of the internal shelter volume, the calculations will be stable. That is

$$60(F_1)(\Delta\tau) \leq C(HH)(GG)(W) \quad \text{(B78)}$$

or

$$\Delta\tau \leq \frac{C(HH)(GG)(W)}{60(F_1)} \quad \text{(B79)}$$

where

C = 0.1 (by experience)
$\Delta\tau$ = computational time increment, hours
F_1 = volumetric flow rate of entering ventilation air, ft³/min
GG = interior length of shelter, ft
HH = interior height of shelter, ft
W = interior width of shelter, ft

When a shelter's stability conditions are computed, the above stability criterion is the relationship that requires the smallest time increment, $\Delta\tau$, and not the relationships of Eqs. (B47), (B51), or (B55). Therefore, the size of the time increment is determined by Eq. (B79).

Two other computational procedures that are followed in the mathematical model of the shelter are

1. the input data are linearly interpolated for time increments that are smaller than those for which the data are given, and
2. the relative humidity of the shelter is always kept less than or equal to unity. If the computed relative humidity is greater than unity, the latent heat input to the shelter is reduced until the relative humidity is equal to unity.

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DISCUSSION

P. R. ACHENBACH, Washington, D. C.: I think Mr. Baschiere and his associates are to be complimented for presenting this data and for gathering data in the field and for the kind of probabilities they were working on. This is a tough job. I know, because I visited some of their experimental sites.

The graphical data in Figs. 2, 3 and 4 in the paper, I think, demonstrate rather clearly that the heat capacity of the buildings and heat transfer of the buildings have a significant effect on the effective temperature level that is generated inside the building, and indicates both that we should try to find a way to take this into account and also that the diurnal effects are important. These two things are rather difficult to account for, but I think this paper shows that they definitely should be considered.

I also would like to compliment the authors on the U.A. concept of trying to evaluate the heat transfer potential of different kinds of construction. The value of the heat transfer varies rather radically, as indicated by the graphs with ventilation rate. The more the ventilation rate, the less valuable this heat transfer is, and, of course, this points up a relation with the paper I presented.

If there is any way in which you can safely and logically reduce the ventilation rate and lower the values that the paper suggests, it will be beneficial toward making greater use of heat transfer that is available from the walls.

AUTHOR BASCHIERE: I agree with you that these parameters do affect the heat transfer from the shelter, however, I have to disagree with you in regards to whether or not these complexities must be brought always into account. I think the paper has shown that the higher rates of heat loss can only occur with the lower values of ambient temperature and lower shelter ventilation flow rates. As a result the ambient temperatures must be coupled with the construction features of the shelter boundary surfaces to ascertain whether or not shelter heat losses through the boundary surfaces can occur. Hence, only in certain situations must you account for the heat transfer effects.

If you have high ambient temperatures existing, the possibility of heat loss is almost completely out of the question. But if, on the other hand, we are talking about a location like Spokane, Wash., which has low temperatures most of the year, we can start looking at the heat loss that can occur and pick up the added advantage that these heat losses can produce in reducing shelter ventilation rates. Thus, it is the interplay of ambient temperature magnitudes and frequencies of occurrence that are important.

W. F. SPIEGEL, Jenkintown, Pa.: I would like to comment that, to those of us who have been following this subject, the authors have presented a rather exciting development in the method for determining ventilation of above-ground shelters.

As Mr. Carroll pointed out, when ventilation rates approach the range of 30 cfm per person, the installation of ventilating equipment becomes extremely expensive, and any procedure that can be devised to accurately determine a safe ventilation rate of lower magnitude would be most useful in design applications.

The concept previously outlined in the paper by Kusuda and Achenbach identified the parameters of simultaneous occurrence of maximum dry- and wet-bulb temperatures. This paper identifies the magnitude of heat conduction effects. A third factor is the flywheel effect of the shelter structure itself; this appears to be a difficult parameter to evaluate, since peak weather would be required to verify theoretical analysis, and testing periods are severely limited by weather.

It would appear very difficult at this stage of the art to intelligently interpret the ventilation adequacy factor between 80 and 95%, and the data presented in this paper should certainly contribute toward developing a general solution. Further development of both of the concepts presented today should be encouraged, with the thought that some method might be found to combine the concepts of adequacy factor, heat transfer and flywheel effect of the structure.

If the data presently available are applied to a site in the southwest part of the United States, the various methods will yield widely different solutions.

If all of the concepts could be combined into a single method, including means to identify the effect of massiveness, and, if the separate mechanisms could be identified and combined, then it might be possible to develop a procedure whereby a designer could select an economical ventilation rate with confidence.

AUTHOR BASCHIERE: Your comments in regard to the flywheel effects go along with an item I had mentioned before. Namely, the fact that MRD is presently studying the effects of solar radiation absorption on the outside walls of shelters. Whether or not high shelter heat losses can occur assumes, among other things, that the energy can be removed from the outside surfaces of the shelter walls. Yet, at the same time, there can be an incident solar heat flux which raises the exterior temperatures of the walls. As a result, the amount of heat loss from the shelter will be reduced and possibly eliminated, thus making the shelter environment more intolerable than would have originally been anticipated. As a consequence, the solar radiation absorption effects also must be considered within the overall shelter analysis scheme.