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THE CALCULATION OF NATURAL VENTILATION AND COMFORT

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THE CALCULATION OF NATURAL VENTILATION AND COMFORT

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Natural ventilation can be used to greatly reduce cooling loads and increase human comfort in buildings in hot, humid climates. Airflow rates directly affect a building's heat balance by removing internal gains and directly affect comfort levels by increasing the body's convective and evaporative heat-transfer coefficients; these airflow rates are determined by the wind pressure on the faces of the building (which is calculated from the wind speed and pressure coefficient) and the amount of open area. Wind pressure coefficients can be obtained in three ways: (1) by direct field measurement, (2) by scale-model experiments in a wind-tunnel, and (3) by comparison with standard wind-tunnel data. In this report the authors describe measurements made on two buildings at the Kaneohe Marine Corps Air Station (KMCAS) on the island of Oahu, Hawaii, during the summer of 1982. These full-scale measurements of pressure coefficients will be compared to reduced-scale measurements made at the boundary-layer wind-tunnel at the Naval Civil Engineering Laboratory (NCEL). Estimates of the indoor comfort levels for different window conditions will be used as a basis for determining the acceptability of natural ventilation for cooling.

Keywords: Natural ventilation, wind tunnel, scale model, humid climate, field measurements, comfort

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NOMENCLATURE

A	=	Basic temperature coefficient [^{o}C] [^{o}F]
B	=	Radiative temperature coefficient
C	=	Convective temperature coefficient
$\overline{C}_p$	=	Average pressure coefficient (relative static)
D	=	Evaporative temperature coefficient [$^{o}C^{-1}$] [$^{o}F^{-1}$]
F_{cle}	=	Effective thermal efficiency of clothing
F_{pcl}	=	Permeation efficiency
h_c	=	Convective heat-transfer coefficient [$W/m^{2} \cdot {}^{o}C$] [$Btu/h \cdot ft^{2} \cdot {}^{o}F$]
h_r	=	Radiative heat-transfer coefficient [4.8 $W/m^{2} \cdot {}^{o}C$] [9.1 $Btu/h \cdot ft^{2} \cdot F$]
I_{cl}	=	Basic clo value [clo]
I_{cle}	=	Effective clo value [clo]
M_o	=	Metabolic rate [58.1 W/m^2] [18.4 $Btu/hr \cdot ft^2$]
m	=	Met rate [met]
P	=	Pressure [Pa] [inches of water]
T_a	=	Air temperature [^{o}C] [^{o}F]
T_{comf}	=	Optimal effective temperature [^{o}C] [^{o}F]
T_d	=	Dew-point temperature [^{o}C] [^{o}F]
T_{eff}	=	Effective temperature [^{o}C] [^{o}F]
T_r	=	Mean radiant temperature [^{o}C] [^{o}F]
T_s	=	Skin temperature [^{o}C] [^{o}F]
U_r	=	Wind speed at roof level [m/s] [mph]
v	=	Mean airspeed [m/s] [mph]
Y_c	=	Convective comfort coefficient
Y_e	=	Evaporative comfort coefficient
Y_o	=	Basic comfort coefficient
Y_r	=	Radiative comfort coefficient
Y_t	=	Total comfort coefficient
Y	=	Predicted mean vote
$\Delta \overline{C}_p$	=	Mean difference in pressure coefficients across building
ρ	=	Density of Air [1.2 kg/m^3]

INTRODUCTION

In hot, humid climates, the energy required to maintain an acceptably cool indoor environment may be a building's single largest energy cost. In many such climates, cooling loads could be reduced or eliminated by using natural ventilation instead of mechanical cooling. Natural ventilation replaces mechanical cooling through two mechanisms: (1) ventilation sweeps away internal heat and moisture, bringing the indoor temperature and humidity closer to their outdoor counterparts; and (2) high indoor airspeed make occupants feel cooler and more comfortable than they would in still air. Thus, there is a large potential for saving energy in climates where natural ventilation can be used.

If the concept of natural ventilation is to be useful to designers and architects, design tools are required for estimating its effects. The development of these design tools requires field and laboratory measurements, as well as physical modeling. The most accurate way to measure the effects of natural ventilation is to monitor an existing building. Full-scale measurements, however, can be both time-consuming and costly. Accordingly, most wind-related design measurements are made on scale models in wind-tunnels. Of course, as in any other kind of modeling, it is necessary to ensure that the model behaves just like the real structure. Confirmed wind-tunnel data can be used to predict the airflow and velocity distribution within the occupied space; this allows calculation of the thermal acceptability of the indoor environment and the usefulness of natural ventilation for the case being tested.

In this paper the authors describe the development and validation of a design tool for estimating the effectiveness of natural ventilation in buildings in hot, humid climates. Although the subject of the validation is the Kaneohe Marine Corps Air Station (KMCAS) on the island of Oahu, Hawaii, results will be generally applicable. Specifically, the purpose of this paper is (1) to compare wind-tunnel data and full-scale field measurements for natural ventilation (2) to establish the usefulness of the NCEL computer model as an engineering tool to predict comfort levels in a building cooled by natural ventilation by comparing the model to full-scale measurements and (3) to initiate a data-base of wind-pressure coefficients for a variety of building forms, to be used as input data for the computer program.

FIELD MEASUREMENTS

Three buildings at KMCAS were chosen for study. Because the third site was more complex and requires additional time to analyze, only data from the first two sites will be presented in this report. This study includes field measurements, wind-tunnel modeling, and computer simulation. The measurements include temperature, humidity, wind velocity, and surface pressure. Although the details of the field experiment will not be presented here (Sherman and Dickerhoff 1983), a summary of the field study follows.

KMCAS is an exposed site on the windward side of Oahu. Prevailing winds are steady, in the range of 3-6 m/s (7-13 mph), and usually within a narrow (20^{o}) direction cone. During the study the outdoor temperature averaged approximately $25^{o}C$ ($77^{o}F$), with the extreme low about $20^{o}C$ ($68^{o}F$) and the extreme high about $30^{o}C$ ($86^{o}F$).

Site 1

Site 1 is a large, two-story building used for training and billeting enlisted men. Figure 1 shows sketches of this building and includes dimensions and the locations of pressure taps on the building's surface. Because occupancy on the first floor was irregular, the windows on that floor were opened and closed at irregular intervals; for security reasons they were always closed at night. The windows on the second floor were controlled and set according to the schedule in table 1.

TABLE 1

Data Log For Site #1

Date	Time	Windows
5 July	13:00	closed
6 July	09:30	open
7 July	10:30	half

The second floor of the building was, in general, unoccupied, but the authors went in and out of the building at unscheduled times, as did officers and instructors. For the most part, these unscheduled incursions were in the eastern segment of both floors. The authors' occupancy--09:00 to 10:30 on 6 July 1982 and 10:00 to 10:30 on 7 July--was kept to a minimum during data acquisition. Because access to the first floor was restricted, it was not possible to measure the internal pressure; only data from the second floor will be presented in this report.

The environmental conditions during the test were recorded: figure 2a shows the wind speed and direction, and figure 2b shows both the dry bulb and dew point temperatures. (Note that the data marked MCAS were taken by base personnel; all other data were recorded by on-site equipment.)

<u>Site 2</u>

Site 2 is a single-story residence consisting of two mirror-image units. Figure 3 shows sketches of this building and includes dimensions and the location of pressure taps on the building's surface. Although the unit adjacent to the test unit was occupied by a family and the windows were not controlled, one can assume that the windows were normally closed because an air conditioner was in operation most of the time. The internal pressure of that unit was not measured. The window configuration of the test unit is included in table 2.

TABLE 2

Data Log For Site #2

Date	Time	Windows	AC
29 July	19:30	closed	off
10 July	17:00	closed	on
11 July	08:30	open	off
11 July	20:00	closed	off
12 July	11:00	half	off
12 July	19:30	closed	off
13 July	09:00	half	off
13 July	18:00	closed	off

Except for the periods when the window configuration was arranged, the monitored portion of the building was unoccupied.

The exact environmental conditions during the test were recorded and plotted for site 1. Figure 4a shows the wind speed and direction, and figure 4b shows dry bulb and dew point temperatures.

NATURAL VENTILATION AND EFFECTIVE TEMPERATURE

Natural ventilation significantly affects human comfort. Natural ventilation decreases cooling loads by providing a comfortable environment for occupants, even though the air temperature may be above normal comfort ranges. This process depends on interior airspeed and the interaction of the human body with its environment. Other sections describe modeling and measurements that allow the prediction of the airflow based on building configuration and wind speed; this section describes how the interaction of existing environmental conditions can be used to estimate occupant comfort levels and how this can be incorporated into a computer model for predicting the effects of natural ventilation.

To estimate the usefulness of increasing interior airspeed and total ventilation, there must be a model to predict the impact of these changes on comfort. Much research has been done on the human body and comfort (Fanger and Valbjorn, 1979; Gagge et al. 1972; Fanger 1972). The authors do not wish to repeat any of this work and have elected to use a slightly simplified version of these comfort models as the criterion for acceptable comfort (Sherman N.d.); the concept of effective temperature is used to judge the occupant's comfort level. The effective temperature corrects the air temperature for the effects of radiant temperature, humidity, and air movement, so it reflects any change in environmental conditions, including the increase in air exchange that natural ventilation causes.

In order to define a single variable, T_{eff}, as the comfort variable, a set of standard conditions must be defined for the other environmental parameters. Under these standard conditions, the effective temperature is equal to the air temperature. The standard conditions are low airspeed, air and mean radiant temperature equal to the effective temperature, and a standardized dew point.

The effective temperature is defined as follows:

$$T_{eff} = A + B\ T_r + C\ T_a + D\ T_d^2 \qquad (1)$$

The definition of coefficients A, B, C, and D are given in the appendix.

The effective temperature depends on four environmental parameters--air temperature, mean radiant temperature, dew point, and wind speed--as well as on two personal parameters--clothing insulation levels and metabolic rate. Specification of these six parameters is sufficient to calculate the effective temperature from the above expression. All the effective temperatures calculated from the field data use this formalism for effective temperature.

Effective temperature alone does not indicate whether most individuals will find conditions comfortable; to decide this the comfort temperature must be defined. Figure 5 displays the acceptable values of effective temperature (i.e., the comfort temperature) for different combinations of personal variables. The formula for this comfort temperature and the acceptable range of effective temperatures are also given in the appendix.

WIND-TUNNEL MEASUREMENTS

The Marine Corps Air Station atmospheric boundary layer was modeled by the modified NCEL wind-tunnel, which is partially shown in figure 6a, with a cross-sectional test area of 2.5 feet (.76 m) by 3.0 feet (.91 m) (test section height and width) and a 24-foot (7.32m) length; the free-stream velocity in the tunnel ranges from 3.5 to 20 m/s (65.6 ft/s). Scale models of both sites were constructed for use in the wind-tunnel. A combination of a wire mesh and a step board positioned upwind of the model at 3 ft (.91 m) and 18 ft (5.5 m), respectively, produced a mean wind velocity profile (power-law exponent 0.20) and a turbulence intensity at a maximum of 4% along the vertical axis, as seen in figure 6b. The building Reynolds number for all models ranged from 0.03×10^6 to 0.14×10^6, with a boundary layer thickness of at least twice the building model height. From wind-speed data taken at the site and data recorded by the local weather station, terrain was classified as characteristic of a country with scattered windbreaks. For the distribution of mean wind speed with height, the power-law expression was used with a power-law exponent of 0.20. All measured wind-tunnel coefficients were based on wind speed at roof level. Maximum model blockage was limited to up to 5% of the cross-sectional test area. Scale of models ranged from 1:46 to 1:80. The values of all pressure coefficients are based on a reference pressure measured at the height of the building in the approach flow.

Models used represent the Navy buildings tested in Hawaii. All were tested with the same mean wind velocity profile. The building geometry is described by two ratios: the side ratio and the aspect ratio. The side ratios of 0.125, 0.3, and 0.35 were tested for a range of aspect ratios from 0.3 to 0.5. Model 1 was made of clear acrylic plastic and instrumented at 20 locations with pressure taps. Model 2 was made of plywood and instrumented at 20 locations with pressure taps.

Pressure and wind speed measurements were made using strain-gauge pressure transducers, hot-wire anemometers, and a 32-channel intelligent data logger. Each pressure measured was the difference between instantaneous local pressure at a location on a building and the static pressure in the ambient flow over the model building. Mean pressure coefficients were averaged over an entire side of a building. The pressure coefficient used was defined by

$$\overline{C}_p = \frac{\overline{P-P_o}}{0.5\,\rho\,U_R^2} \tag{2}$$

$\overline{C}_p$ is the nondimensional ratio of $\overline{P-P_o}$ (the difference between the pressure at a location on the building and the local static pressure) to $0.5\,\rho\,U_R^2$ (the dynamic pressure based on the wind speed in the approach flow measured at the level of the roof of the building, U_R).

Measurements were obtained at six to nine wind directions from 0 to 90 degrees. Model 1 was placed in an isolated and sheltered environment with and without wall openings. Model 2 was placed in an isolated environment with no adjacent structures present, with and without wall openings. Interior airspeeds and pressures were measured for each wind direction for model 2.

Comparison of Wind-tunnel Results

Since adequate wind-tunnel modeling should reproduce the important aspects of the field data, the full-scale data were compared with the scale-model measurements. The mean pressure difference coefficient, $\Delta\overline{C}_p$, for long walls of buildings as measured in the wind-tunnel, is shown in figures 7a and 7b. The values are compared to the experimental values obtained from field tests and existing data (Akins 1979).

Values of the pressure difference coefficient between long walls of field test data are in close agreement with NCEL wind-tunnel test data for all models. Figures 7a and 7b show the effect of openings on the pressure difference coefficient. Wind-tunnel measurements show that wall openings equivalent to 60% of windward and leeward walls (inlet openings equal to outlet openings) cause an estimated 33% decrease in the pressure difference coefficient at high wind incidence.

For model 2, wall openings ranged from 0 to 15% of windward and leeward walls and tended to slightly increase the mean pressure difference coefficient. The sheltering effect of trees and buildings located close to the building (model 1) is also shown in figure 7a; and average decrease in the mean pressure difference coefficient of 30% is noted for various wind incidence.

Since only an average pressure difference coefficient, $\underline{\triangle}\,\overline{C}_p$, is needed to estimate the airflow within the building and thus in design criteria for natural ventilation, only an average pressure difference coefficient is needed to predict the comfort limits. Therefore, basic data that supply the required pressure difference coefficient within a 20% error are needed.

Existing wind-tunnel data (Jensen and Franck 1962; Chien et al. 1951) of pressure coefficients of flat-roofed, rectangular buildings tend to overestimate the actual pressure coefficients, and consequently overestimate the mean pressure difference coefficient, $\underline{\triangle}\,\overline{C}_p$, for different side ratios (Ashley 1983). Since most of the buildings have some form of sheltering (trees, buildings, etc.), an assumption was made to force the leeward pressure coefficient to zero and set the windward pressure coefficient, Cb_3, to represent the pressure difference coefficient, $\triangle\,\overline{C}_{3-1}$, for long walls. These values were compared to experimental values obtained from the field test and the wind-tunnel test. Figures 7a and 7b show that at high wind incidence the pressure difference coefficient (as assumed) is underestimated for most of the models but shows a close agreement at lower wind incidence. At 0^{o} to 15^{o} wind incidence, a pressure difference coefficient to ± 0.15 can be assumed due to the fluctuation of the wind direction. Since architectural features of the building, such as projecting end walls, tend to increase the pressure difference coefficient, the existing data (Akins, et al. 1979) (where $\underline{\triangle}\,\overline{C}_p$ is set to the windward pressure coefficient, with the leeward pressure coefficient set to zero) can be used as basic data (no special architectural features) in conjunction with other existing data for architectural features (Aynsley 1979; Jensen and Franck 1963; Chien et al. 1951; Ashley 1983).

Most Navy buildings have a pitched-roof or flat-roofed rectangular building form; therefore a basic data set of pressure difference coefficients for these building types was developed (see figures 8a and 8b). These curves were developed by combining existing wind-tunnel data and field test data (Aynsley 1979; Akins et al. 1979, Jensen and Franck 1963; Chien et al. 1951; Ashley 1983). More data is needed in order to validate the curves. The proposed curves reflect the pressure difference coefficient expected for a one-story building with a basic rectangular building form. Any deviation from the basic design will cause a change in the pressure difference coefficient.

In table 3, the expected changes in pressure difference coefficient due to architectural changes in the basic design (figures 8a and 8b) are summarized. These changes were observed in the NCEL wind-tunnel. Estimated pressure difference coefficients for most of the models are in

TABLE 3:
Effect Of Architectural Characteristics On Pressure Coefficients*

	Architectural Characteristic	$\Delta \bar{C}_p$ [% increase]
1.	Basic design (one story)	0
2.	Two or more stories	40
3.	Single-story elevated above ground	30
4.	Single-story with extended eaves and end walls	25
5.	Single-story elevated above ground with extended verandas and end walls	50
6.	Single-story with windward wall projections or insets	25

*If two or more architectural characteristics are combined, the average of the percent increase is taken with a maximum of 50% increase total. These corrections should be used only for the calculation of natural ventilation.

agreement with field test and wind-tunnel tests at high angles of wind incidence (60-90°), but may tend to underestimate at 30 to 60° wind incidence.

Assuming orifice flow, a sensitivity analysis shows that an increase or decrease of 25% to 60% of the pressure difference coefficient will cause an increase or decrease in flow rate into the building of 10 to 22%, assuming that the effective inlet area and wind velocity at the site remain constant.

Comparison of Computer Model and Field Test Results

Both field studies and wind-tunnel studies are expensive and time-consuming ways to model natural ventilation. A more satisfactory method for the designer is to have a computer program that can be used as a design tool. Such computer programs require information about the weather and pressure coefficient information; they must have within them all the information about wind/building/occupant interactions, including airflows and comfort levels. Although pressure difference coefficient information can come from field or wind-tunnel measurements, a catalog of typical coefficients for different building designs is more convenient.

The NCEL computer program (Ashley 1983), which is such a program, consists of two main routines: the flow routine calculates airflow through the building, and another routine estimates temperatures based on results of flow routine. The program calculates expected wind speed at site, airflow rates, direction of flow, internal pressures, air changes, interior and exterior effective temperatures, interior dry- and wet-bulb temperatures, and humidity ratios. (The effective temperature algorithm in the computer program differs from the equations used to reduce the field data; both are presented in the appendix.) Corresponding inputs, in general, are weather data of region, pressure coefficients, size of openings (exterior and interior, such as windows, doors, etc.), and building heat loads.

Figure 8 shows the pressure difference coefficients at each building site for various wind directions. The program can use this value as the windward pressure coefficient by setting the leeward value to zero. Although this will affect the absolute pressure calculations, it does not affect the airflow predictions; furthermore, our wind-tunnel studies suggest that the leeward pressure coefficient for clustered buildings actually tends toward zero.

For the validation of the computer program, pressure coefficients obtained from the field test were used as input data. The daily weather data obtained from the Marine Corps Air Station weather tower (MCAS data) were used; the corresponding effective temperatures and airflows were calculated for each site. Figure 9 compares computer program results of airflow into the building with field test results. The results are within a ±10% accuracy for a closed building (no openings) and ±15% for buildings with openings. Ambient and interior effective temperature comparisons between field tests and the computer model results are shown in figure 10. For full open inlet area, there is a close agreement between field test and computer test results but there is non-neglible deviation for the non-open conditions.

DISCUSSION AND SUMMARY

The comparison of the laboratory measurements with the field measurements is encouraging. Not surprisingly, the use of wind-tunnel data can be substituted for full-scale data on pressure coefficients. From the reasonably substantial existing database of wind-tunnel measurements, average pressure coefficients can be cataloged for a variety of building types and architectural designs. Computer programs that use this information, such as the NCEL program, can then be used as design tools to estimate the efficacy of natural ventilation for cooling.

In order to use the NCEL computer model as a design tool for natural ventilation, two sets of input data are needed: (1) surface pressure coefficients and (2) weather data (information on surface wind velocities and psychometric summaries). For typical calculations, average weather data (e.g., TRY tapes) may be used for the weather data; for determining extreme conditions, the design data can be used or extreme weather data recorded for that region for the past five years. The final output of the model is time series data for internal effective temperature, from which the designer can decide the acceptability and effectiveness of various natural ventilating strategies. The NCEL computer program can be used to establish the suitability of a particular region and a specific building design for natural ventilative cooling.

This paper has done the following: (1) presented summary data from full-scale field measurements (2) compared pressure coefficients using full-scale field data from three existing Navy buildings with data measured using the NCEL wind-tunnel (3) used wind-tunnel data in the development of a design tool for the prediction of the effects of natural ventilation and (4) compared this computer model to the field data for both airflow and effective temperature.

REFERENCES

Akins, R.E., Paterka, J.A., and Cermack, J.E. 1979. "Average Pressure Coefficients for Rectangular Buildings." Colorado State University, Fort Collins.

Ashley, S.K. 1983. "Wind-tunnel Studies of Pressure Distributions on Three Navy Buildings." Navy Civil Engineering Laboratory, Technical Memorandum, Port Hueneme, Ca.

Ashley, S.K. 1983. "Computer Simulation of Buildings Cooled by Natural Ventilation." Navy Civil Engineering Laboratory, Technical Note-1666. Port Hueneme, Ca.

Aynsley, R.M. 1979. "Wind-generated Natural Ventilation of Housing for Thermal Comfort in Hot Humid Climates." University of Sydney, Sydney, Australia.

Chien, N., Fong, Y., Wang, W., and Siao, T. 1951. "Wind-tunnel Studies of Pressure Distribution on Elementary Building Forms." Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City.

Fanger, P.O. 1972. Thermal Comfort. New York: McGraw-Hill.

Fanger, P.O. and Valbjorn, O. eds. 1979. Indoor Climate. Copenhagen: Danish Building Research Institute.

Gagge, A.P. and Nishi, Y. N.d. "Heat Exchange Between Human Skin Surface and Thermal Environment. Handbook of Physiology - Reactions to Environmental Agents (5).

Gagge, A.P., Nishi, Y., and Gonzalez, R.R. 1972. "Standard Effective Temperature," CIB Commission W45 - Symposium on Thermal Comfort and Moderate Heat Stress.

Houghten, G.C., Teague, W.W., Miller, W.E., and Yant, W.P. 1929. "Heat and Moisture Losses from the Human Body and Their Relation to Air Conditioning Problems." ASHVE Transactions 35, pp. 245-268.

Jensen, M. and Franck, N. 1963. Model-scale Tests in Turbulent Wind, Part I and II. Copenhagen: The Danish Technical Press.

Sherman, M.H., N.d. "A Simplified Model of Thermal Comfort." Lawrence Berkeley Laboratory Report LBL-15923. Submitted to Energy and Buildings.

Sherman, M.H. and Dickerhoff, D.J. 1983. "Project Report: Field Testing of Wind Cooling Effects on Navy Buildings." Lawrence Berkeley Laboratory Report LBL-14925.

APPENDIX:

Definition of Effective Temperature

This appendix presents the definitions we used for calculating effective temperature. Two different algorithms were used to calculate an effective temperature. The LBL algorithm was used to calculate the effective temperature from the field data, and the NCEL algorithm was used to estimate the effective temperature within the computer simulation. Since the two algorithms are not equivalent, they will both be presented in this appendix.

LBL EFFECTIVE TEMPERATURE

The LBL effective temperature calculation (Sherman N.d.) is based on a thermal balance calculation similar to that others have used (Fanger and Valbjorn 1979; Gagge et al. 1972; Fanger 1972); and, as such, it requires knowledge of the subject's activity and personal insulation levels as well as the environmental conditions. The outcome of this derivation (as given in the text and used for the reduction of the field data) is a simple expression for the effective temperature as a function of environmental variables:

$$T_{eff} = A + B\ T_r + C\ T_a + D\ T_d^2 \tag{A1}$$

whose constants are a function of airspeed and the personal variables.

The temperature coefficients used above are defined as follows:

$$A = \frac{T_s}{Y_t^*}\left(1/2Y_e^* + Y_o - Y_o^* \right) \qquad B = \frac{Y_r}{Y_t^*} \tag{A2}$$

$$C = \frac{Y_c}{Y_t^*} \qquad D = \frac{1}{T_s}\frac{Y_e}{Y_t^*}$$

where the Ys are called comfort coefficients.

DEFINITIONS FOR USE IN THE LBL CALCULATION

The comfort coefficients, (Y_x), used in the defintions of the comfort coefficients are defined as follows:

Radiative comfort coefficient:

$$Y_r = \left[F_{cle}\frac{h_r\ T_s}{M_o} \right] x \left[1.6+17.6e^{-2.1m} \right] \tag{A3.1}$$

Convective comfort coefficient:

$$Y_c = \left[0.0014\ T_s\ m + F_{cle}\frac{h_c\ T_s}{M_o} \right] x \left[1.6+17.6e^{-2.1m} \right] \tag{A3.2}$$

Evaporative comfort coefficient:

$$Y_e = \left[0.0024\ T_s\ m + .132F_{pcl}\frac{h_c\ T_s}{M_o} \right] x \left[1.6+17.6e^{-2.1m} \right] \tag{A3.3}$$

Basic comfort coefficient:

$$Y_o = \left[0.42 + 0.58m \right] x \left[1.6{+}17.6e^{-2.1m} \right] - Y_r - Y_c - Y_e \quad \text{(A3.4)}$$

For convenience the authors have defined the total comfort coefficient as follows:

$$Y_t = Y_r + Y_c + Y_e \quad \text{(A3.5)}$$

The standard comfort coefficients (Y_x^*) are calculated using the same formulae as the unstarred versions, except that the low airspeed of the convection coefficient is used.

The remaining definitions are ones that have been used elsewhere in both comfort (e.g., Fanger and Valbjorn 1972; Gagge et al. 1972; Fanger 1972) and heat transfer equations; they are repeated herein without derivation:

Skin Temperature:

$$T_s = 35.7 - 2.16m \quad \text{(A4)}$$

Convective Heat-Transfer Coefficient: The larger of the two values for h_c, as defined by Gagge (N.d.) are used:

$$h_c = 8.3\ v^{0.53} \quad \text{(A5.1)}$$

$$h_c = 5.66\ (m - 0.85)^{0.39} \quad \text{(A5.2)}$$

Radiative Heat-Transfer Coefficient:

$$h_r = 4.8 \left[\frac{W}{m^2\ {}^oC} \right] \quad \text{(A6)}$$

Effective Thermal Efficiency of Clothing:

$$F_{cle} = \frac{1 + 0.23I_{cle}}{1 + 0.178I_{cle}(h_c+h_r)} \tag{A7}$$

Permeation Efficiency of Clothing:

$$F_{pcl} = \frac{1}{1 + 0.143I_{cle}h_c} \tag{A8}$$

Clo Value: One clo is equal to 0.155 $m^2 \cdot {}^oC/W$ (0.088 $hr \cdot ft^2/Btu$). A clo value is usually quoted as either a basic clo value, I_{cl}, or an effective clo value, I_{cle}. The average relationship between these two values is as follows:

$$I_{cl} = 1.16\ I_{cle} \tag{A9}$$

Metabolic Rate: The activity level of the body, m,is given in units of met, M_o:

$$M_o = 58.1\ \frac{W}{m^2} \tag{A10}$$

COMFORT TEMPERATURE

The effective temperature gives a corrected temperature value for existing conditions but does not directly indicate the comfort level. However, since there is an expression that calculates the effective temperature as a function of predicted mean vote, one can use it to find the effective comfort temperatures. These comfort temperatures then become functions of the personal variables alone--they are independent of environmental conditions.

The optimal value of the effective temperature for comfortable conditions is given by the following expression:

$$T_{comf} = \frac{T_s}{Y_t^*} \left(1/2Y_e^* - Y_o^* \right) \tag{A11}$$

Because both personal and environmental parameters vary, a comfort value alone is often insufficient. A range of acceptable temperatures is required. Even at the comfort temperature, no more than 95% of individuals report that they are comfortable. The comfort band is defined as the range of effective temperature in which at least 90% of the individuals report that they are comfortable:

$$\Delta T_{comf} = \frac{T_s}{Y_t^*} \tag{A12}$$

The comfort band range begins at approximately 2°C for lightly clothed, sedentary situations and increases with both clothing level and metabolic rate (e.g., clo = 2, met = 2 implies over a 7°C comfort band).

Figure 5 displays the optimal value of effective temperature (i.e., the comfort temperature) and the acceptable range thereof for different metabolic rates as a function of clothing value. Lightly clothed implies a clo value of from 0.3 to 0.6; sedentary individuals have a met rate of approximately 1.0-1.2. For these conditions the comfort zone is 25°C to 28°C

NCEL EFFECTIVE TEMPERATURE

As stated in Ashley (1983), the NCEL effective temperature‡ is based on an empirical relationship between heat loss and comfort (Houghten 1929).

‡ In the "NCEL Effective Temperature" section, the expressions are all taken directly from the original work. All quantities are in Inch-Pound units; the effective temperature should be converted only after all calculations are made.

The expression for effective temperature at low airspeeds is as follows:

$$T^{o}_{eff} = \frac{107.5T_a - 45.2T_w}{T_a - T_w + 62.3} \tag{A13}$$

where

T^{o}_{eff} = the effective temperature a low airspeed (^{o}F),

T_a = the dry bulb temperature (^{o}F), and

T_w = the wet bulb temperature (^{o}F).

This effective temperature estimate is for still air, but for the airspeeds expected of natural ventilation it must be corrected. The following formulae adjust the effective temperature for the effect of non-zero airspeed:

$$T_{eff} = T^{o}_{eff} - DT*DV \tag{A14.1}$$

$$DT = (1 - .00466(T_a + T_w))\sin(\frac{\pi}{180}(30 - .7(T_a - T_w))) \tag{A14.2}$$

$$DV = 0.124 (v - 20) (1 - .000355v) \tag{A14.3}$$

where

T_{eff} = the effective temperature (^{o}F) and

v = the airspeed (ft/min).

This calculation is assumed to be equivalent to the ASHRAE effective temperature (ET^*) and the comfort range is 72^{o}F to 78^{o}F independent of clothing or activity levels.

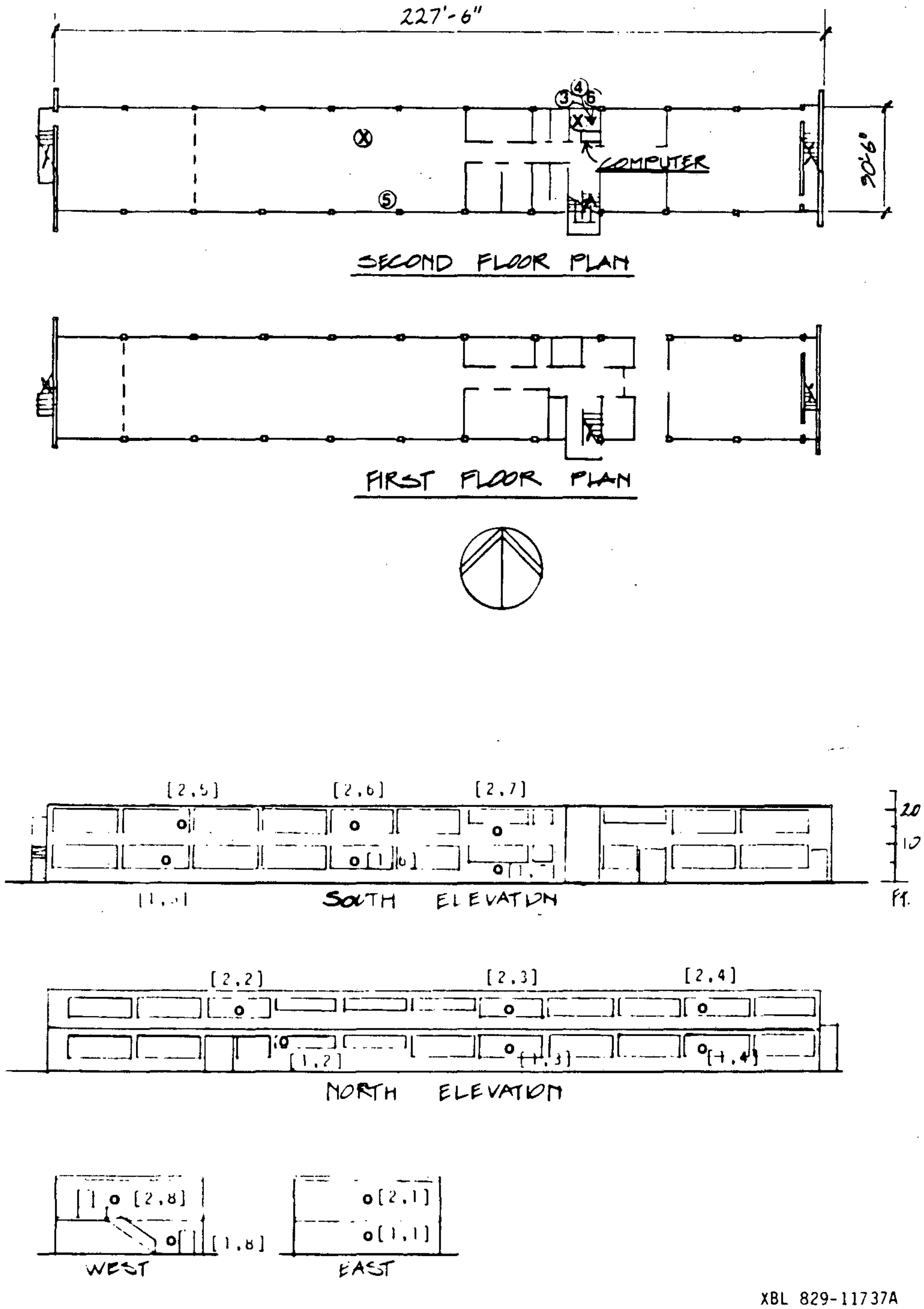

Figure 1. Site 1: a) elevations; b) plan view

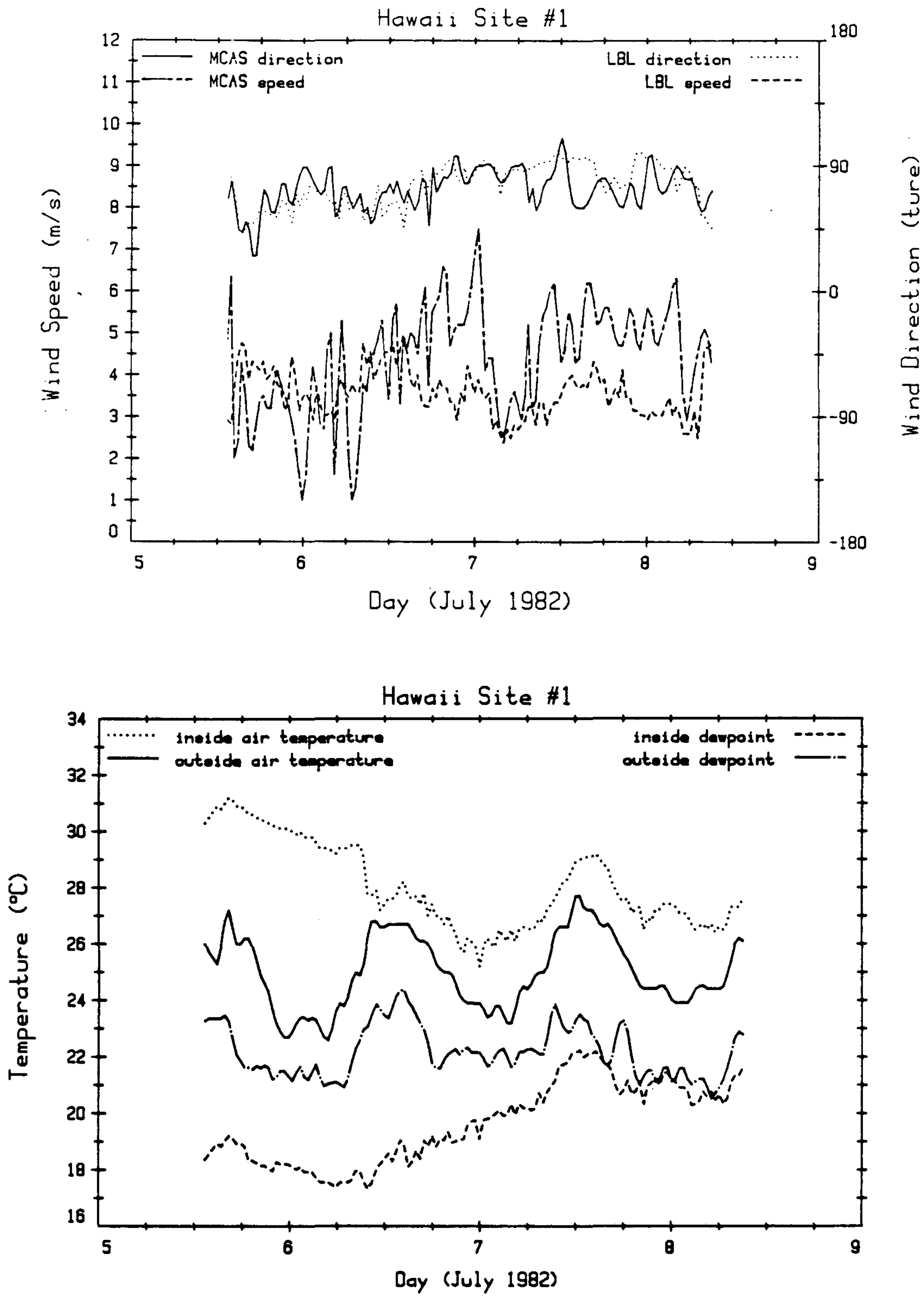

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Figure 2. Site 1 weather during test period: a) windspeed and directions; b) temperature

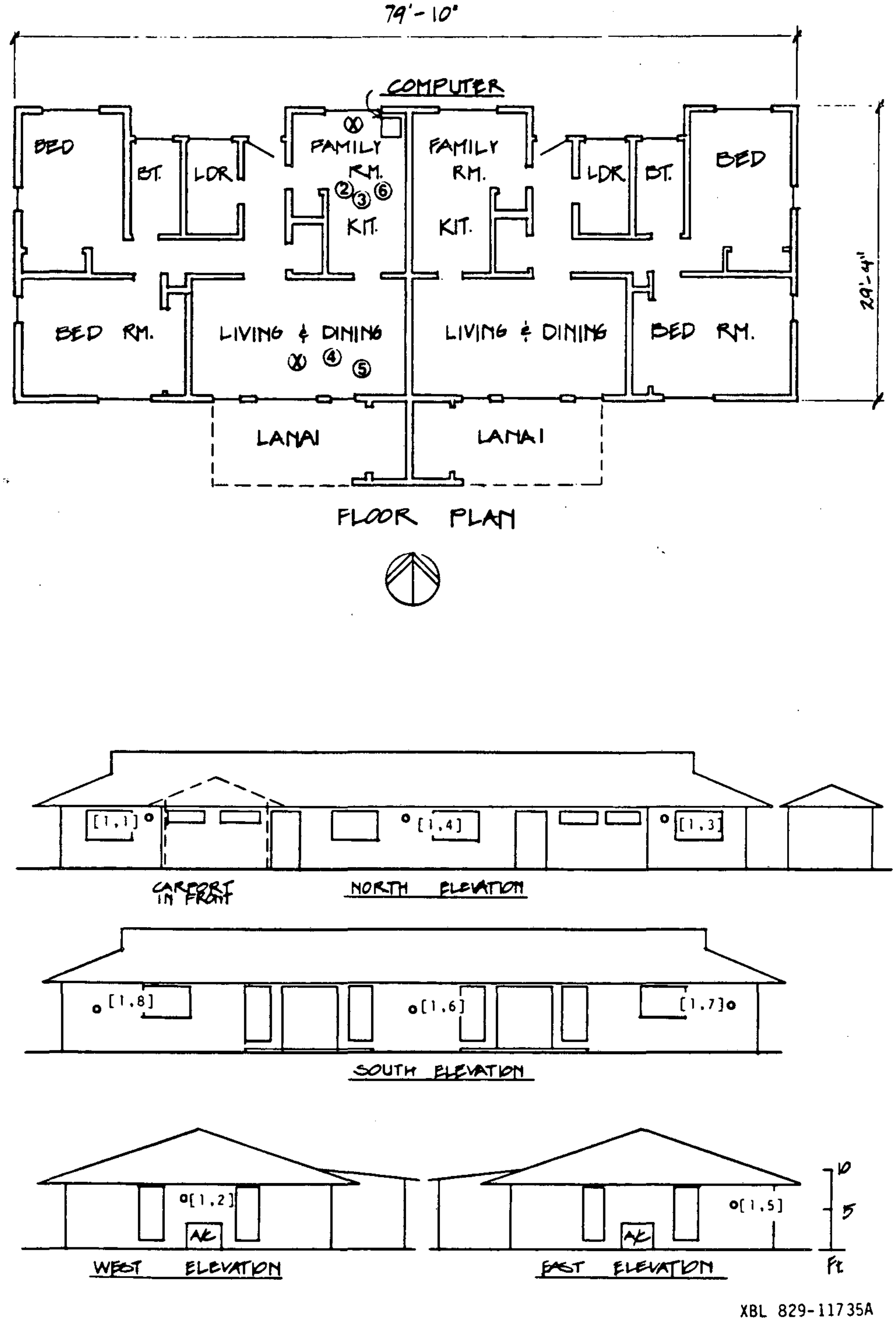

Figure 3. Site 2: a) elevations; b) plan view

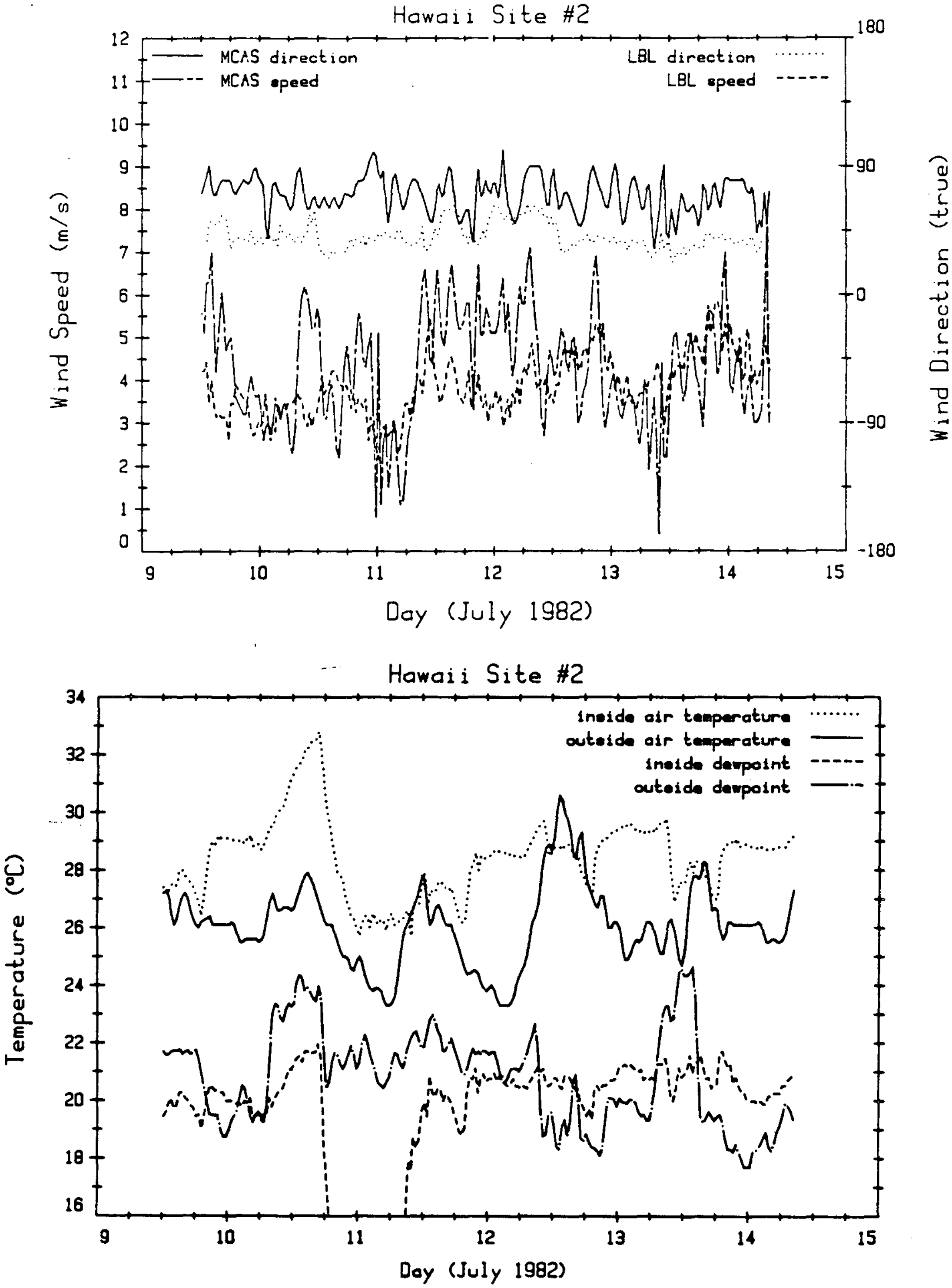

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Figure 4. Site 2 weather during test period: a) windspeed and directions; b) temperature

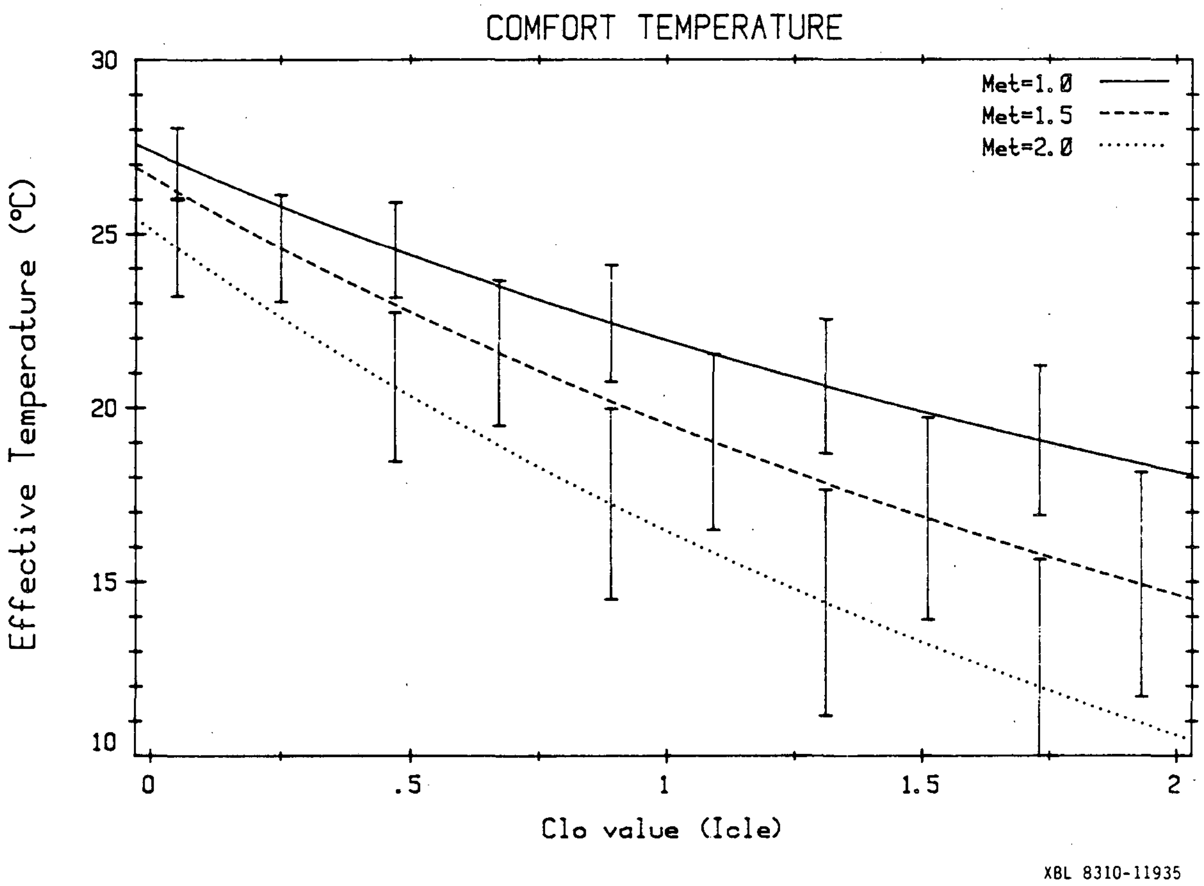
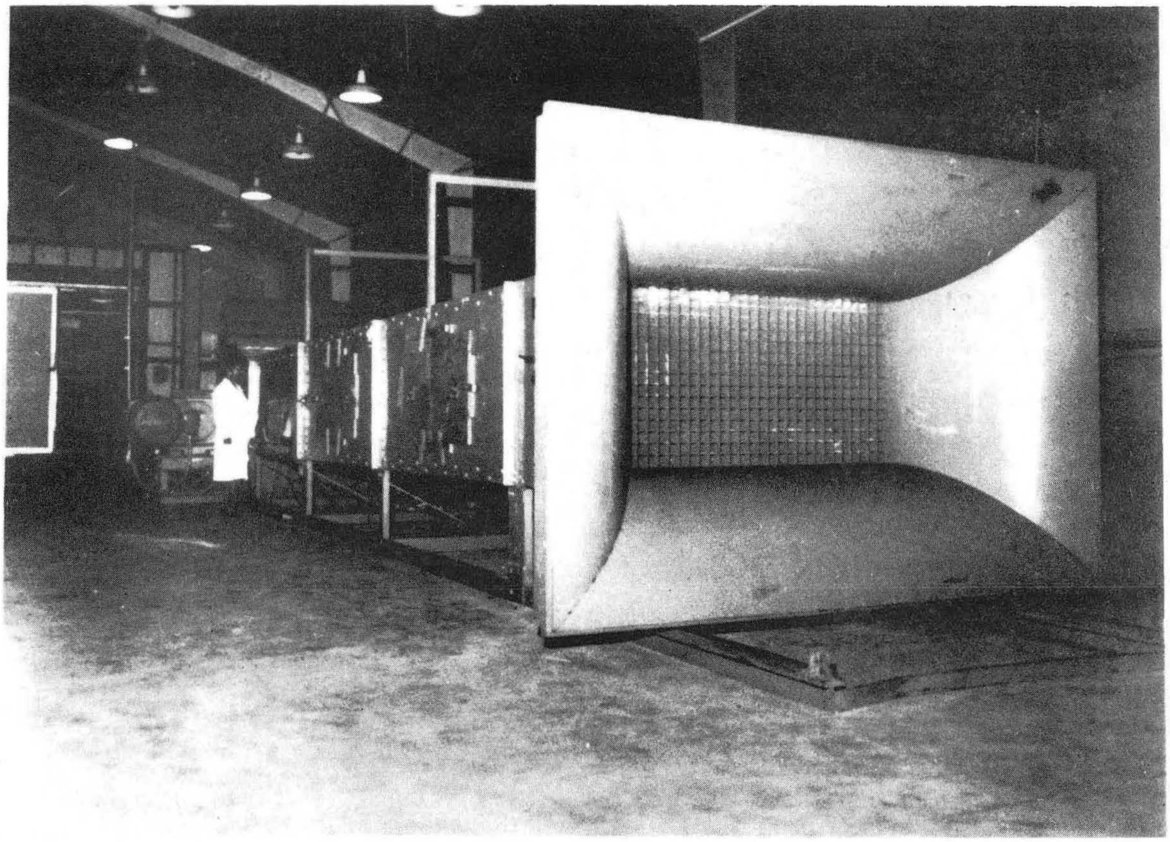


Figure 5. Acceptable values of effective temperature (comfort temperature) Bars show acceptable ranges.



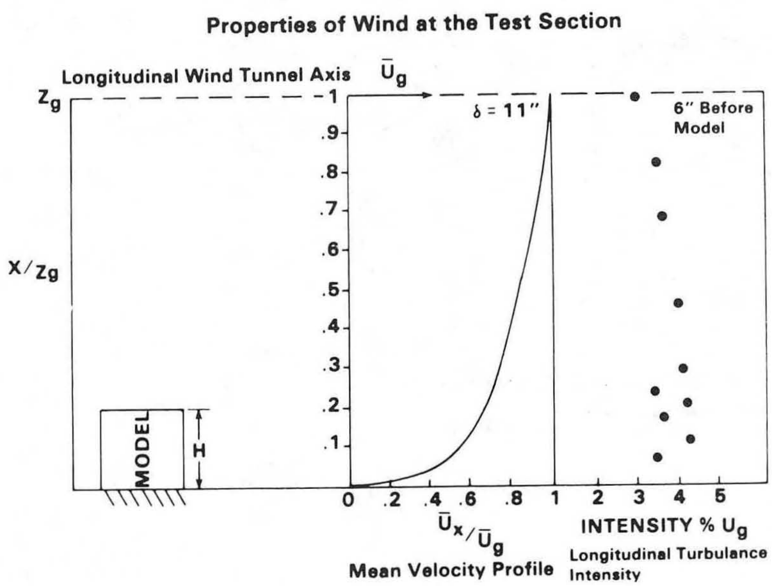


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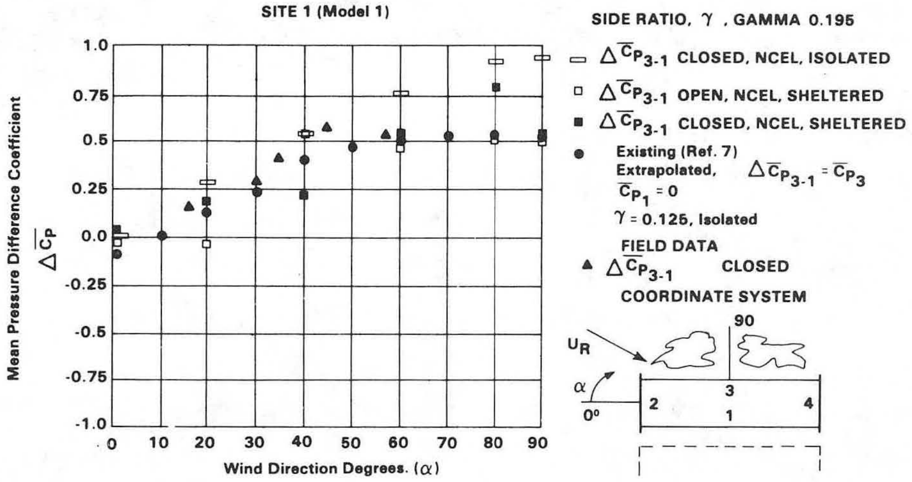
Figure 6. a) NCEL wind-tunnel; b) properties of wind at test section



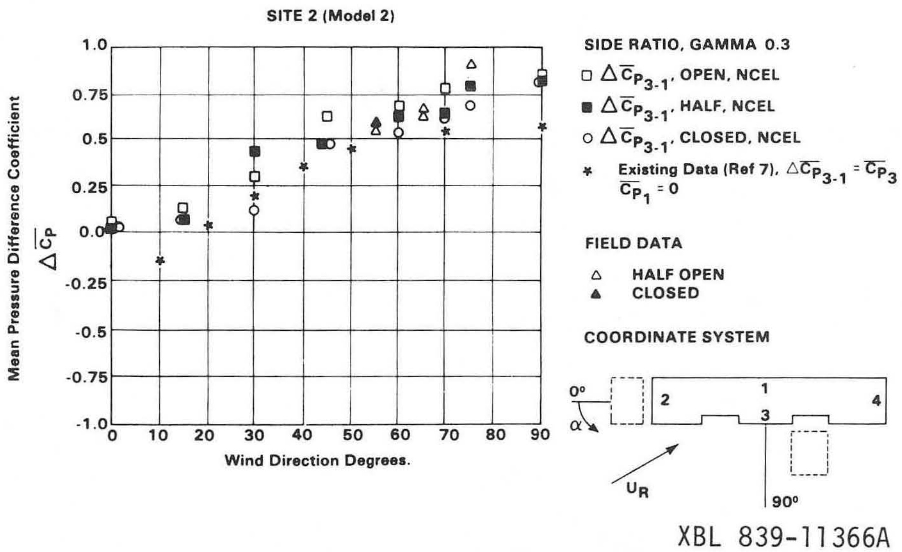


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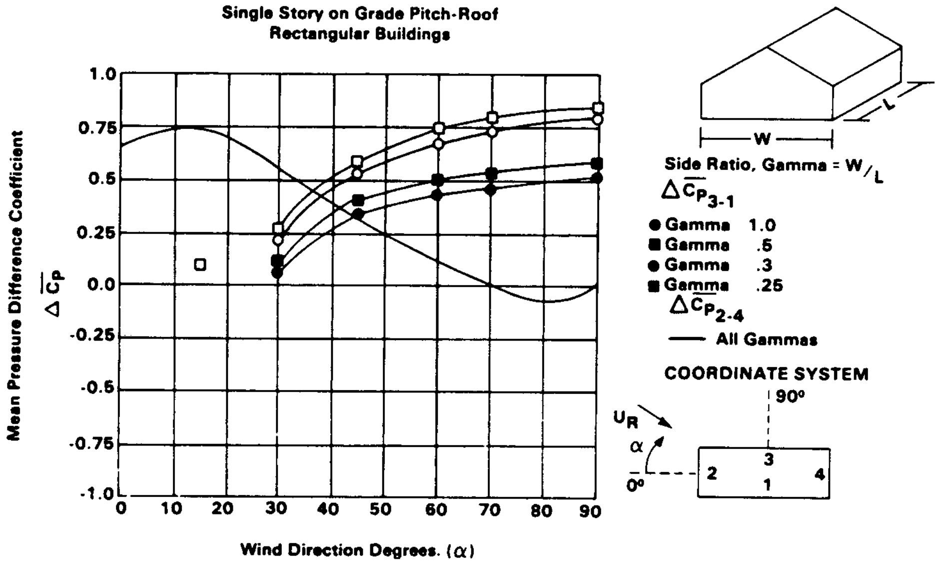
Figure 7. Average pressure difference coefficient, $\Delta\overline{C}$



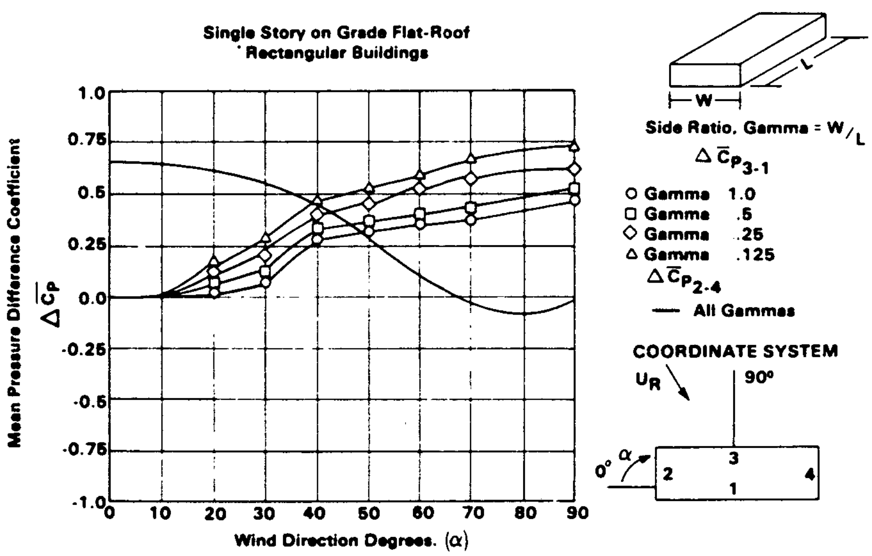


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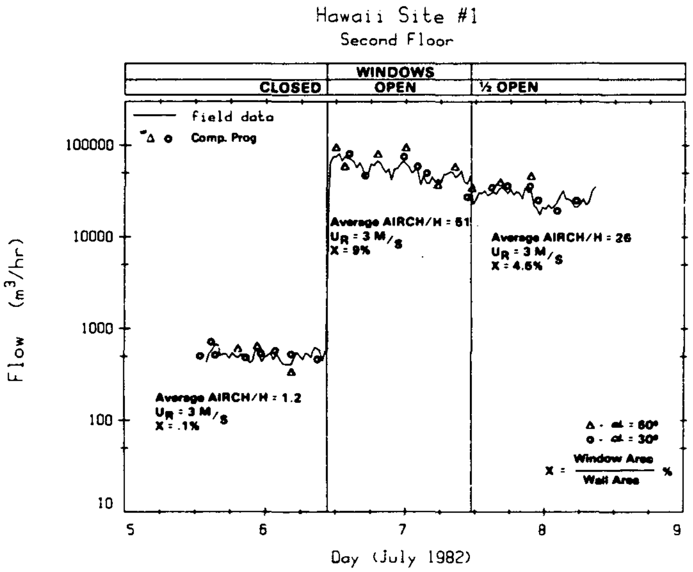
Figure 8. Mean pressure difference coefficient for single-story, on-grade rectangular building: a) pitched roof; b) flat roof



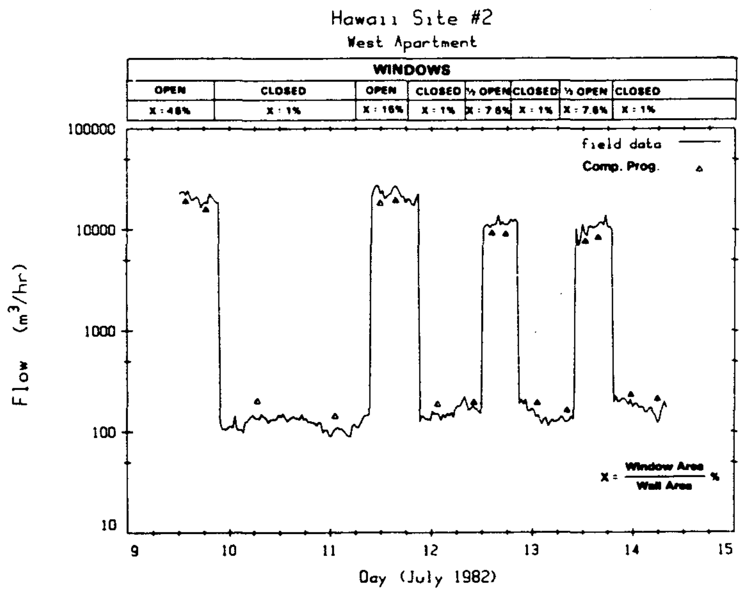


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Figure 9. Comparison of airflow from both field data and computer modeling: a) site 1; b) site 2

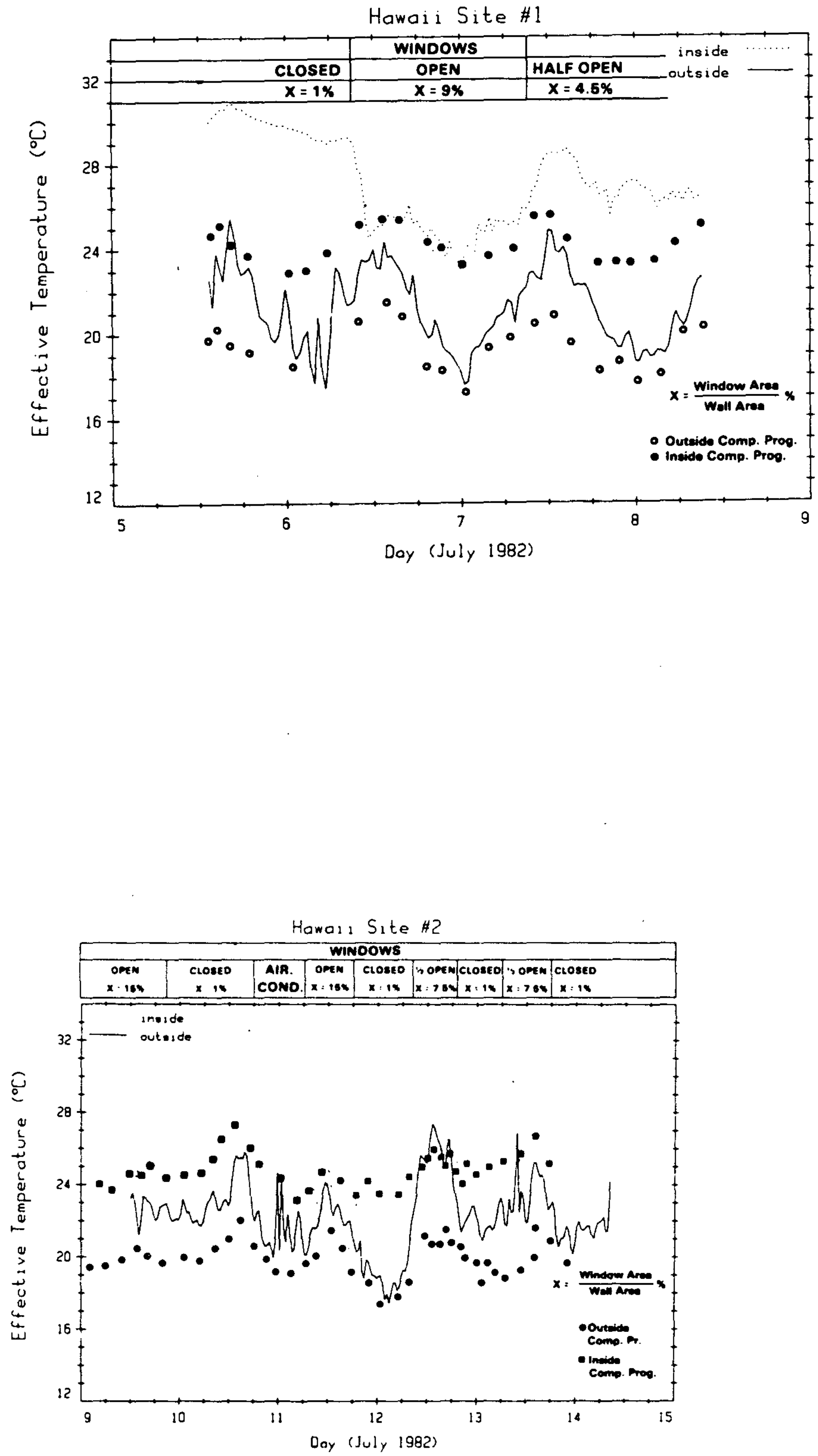

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Figure 10. Comparison of effective temperature from field data and computer modeling: a) site 1; b) site 2

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