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Predicting Thermal Comfort of People in Naturally Ventilated Buildings

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ABSTRACT

A new procedure for predicting the thermal comfort of people in naturally ventilated buildings is described. The procedure starts by obtaining, for each important wind direction, velocity ratios between points of interest inside the proposed building and the wind-measuring height outside. This is best done with a wind-tunnel test of a scale model of the building, but there are also published sources of such ratios. The ratios, plus building-induced temperature changes, are applied to a weather tape representing the site, in order to produce an hour-by-hour record of indoor climate. This record is used in a program simulating human thermal comfort. The program puts out the percentage of time, by season and by periods of day, that thermal comfort is expected in the proposed building. This information enables architects and engineers to make more rational decisions in designing naturally ventilated buildings.

INTRODUCTION

The increased cost of energy has stimulated new interest in buildings designed to cool their occupants by ventilation rather than by mechanical cooling. The ventilation may be passively induced by external wind or internal buoyancy effects, or induced with relatively small energy expense by ceiling fans or whole-house ventilating fans. The wind-driven ventilation is particularly appealing, since it requires only openings in the building envelope. The ventilation cools the occupant by increasing convective sensible and evaporative heat loss, thereby allowing the occupant to be comfortable in higher temperatures and humidities than would be possible in still air conditions.

It has been difficult in the past to predict the success of such designs for ventilation. All the climatic factors, including the wind, are variable; the influence of the wind on the interior air movement in a given building is complex; and standards for human thermal comfort have not included high air-movement rates. Most traditional design was done by intuition and by following previous designs judged to be successful. Olgyay (1963) introduced the first systematic attempt to deal with each of the issues above, but he found it necessary to make a large number of simplifying assumptions that seriously reduce the general usefulness of the results. In his method, the needed indoor air velocity for a given climate is estimated by plotting each month's average daily range of temperature and humidity on a "bioclimatic chart." This chart presents the human comfort zone in terms of temperature, humidity, wind velocity, and radiation; so at given combinations of temperature and humidity in a hot environment, one can see both that radiant gains should be avoided (by providing shade and isolation from hot sources) and that specific levels of wind will restore the body to a comfortable condition. Olgyay's method then obtains average monthly wind velocities, modifies them to represent indoor conditions by an equation giving generalized indoor/outdoor velocity ratios, and determines whether the indoor velocities exceed or equal the velocities required to ensure comfort. The periods when overheating occurs are then used to decide whether the design is acceptable.

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There are several problems impairing the use of this method. First, the monthly averages of wind, humidity, and temperature are a poor representation of the widely varying coincident occurrences of these variables. Second, the generalized indoor/outdoor wind ratios are not likely to be accurate for any particular design. Third, the comfort chart is based on older work and does not correspond closely with the comfort requirements specified by ASHRAE Standard 55-81 or with results obtained by detailed simulation of human comfort in a wide range of environmental conditions (Arens et al. 1980). Fourth, there is no provision for changing clothing and activity levels throughout the day or seasons. Finally, the result of the graphic method is not a measurable quantity: during some months it will be seen that ventilation is inadequate to provide comfort, but the number of hours in which this occurs during these months cannot be determined.

The method described here surmounts these problems through the use of a weather tape containing hour-by-hour data and computer simulation of thermal comfort for each hour. The coincident occurrences of outdoor temperature, humidity, wind direction, and wind velocity over the building are present in the weather tape record. The wind and temperature values are modified to represent the indoor climate before performing the comfort simulation. For wind, the modification is performed with velocity ratios obtained from tests of a building model in an appropriate wind tunnel. For temperature, the effects of internal gains or temperature sinks can be either computed hour by hour or approximated as a constant indoor-outdoor temperature difference, depending on the extent to which the building is ventilated. The comfort simulation model runs on this indoor climate record and an hourly schedule of occupant activity and clothing levels. The hourly comfort/discomfort outcomes are summed for the season of interest. Because the comfort model considers each hour's coincident occurrence of climatic and occupant variables, it is capable of predicting thermal comfort more accurately and meaningfully than has been previously possible.

BASIS FOR COMFORT PREDICTION

The thermal comfort program has as its base a two-node mathematical model of the human thermoregulatory system developed originally by Pharo Gagge. The model is a simplification of a more complex and specialized thermoregulatory model developed by Stolwijk and Hardy (1966), and has been found effective at predicting physiological response near the comfort zone under conditions of low to moderate activity. This program has been extensively tested against experiments with human subjects (Berglund and Stolwijk 1980).

The model considers man as two concentric thermal compartments representing the skin and core of the body. The skin compartment simulates the epidermis and dermis, with a thickness of approximately 1.6 mm and weighing about 10% of total body weight. The temperature within each compartment is assumed to be uniform, so that the only temperature gradients are between compartments. All the major heat-transfer mechanisms are simulated, including perspiration mechanisms. The model is described in detail in two reports (Gagge et al. 1976; Berglund and Stolwijk 1980), although some further development has taken place since their publication. The measure for comfort/discomfort is based on skin temperature alone in cold conditions and on skin wettedness (fraction of skin covered by unevaporated perspiration) in hot conditions. This measure was developed by Gagge from experimental findings that discomfort (as opposed to thermal sensation) is more closely linked to skin wettedness in hot conditions than to skin temperature. In this application of the model, the comfort levels resulting from the environmental conditions prescribed in ASHRAE Standard 55-81 are used as the criteria for determining comfort at any of the wide range of activity levels, clothing levels, and environmental conditions that the model can simulate.

There are some limitations to the model's use in more extreme environments. The assumption that there are no temperature gradients within compartments may limit its effectiveness at predicting the effect of asymmetrical (directional) wind and radiation, but the extent of this cannot be determined at present. Similarly, because the model does not differentiate body surfaces into clothed and exposed skin portions, it may underestimate convective heat loss at higher wind velocities, and underestimate radiant gain under conditions of strong radiation. The extent of these effects is also unknown but is not expected to be great in the tempered environment within buildings.

PROCEDURE FOR ANALYSING VENTILATION AND PREDICTING COMFORT

A climate's potential for ventilative cooling may be assessed from weather records. Since an hourly weather tape is used in the procedure described here, it is possible to obtain a detailed breakdown of the number of hours in various temperature and humidity bins by processing the tape. Figure 1 is an example, for Honolulu, presented on a psychrometric chart. Superposing a still-air comfort chart, such as ASHRAE Standard 55-81, over this allows the number of potentially uncomfortable hours to be assessed. Superposing a bioclimatic chart (Arens et al. 1980), as in figure 2, would show the specific levels of indoor air movement required to obtain comfort for each temperature/humidity bin in the overheated zone.

If it will be necessary to rely on air movement to provide acceptable levels of comfort, the following procedure is proposed. The first step is to determine the building's interior air velocities as a function of the exterior wind recorded on the weather tape. This information is most effectively obtained through wind-tunnel studies of the proposed building design. The wind-tunnel test procedure is well known and need not involve highly complex facilities or apparatus (Holleman 1953; Aynsley et al. 1977; Cermak et al. 1982). The data gathered in the wind tunnel are in the form of velocity ratios, interior wind divided by exterior wind, for as many compass directions as are necessary or applicable to the design and the climate it is to be in. The directions to be tested are determined by judgment or initial trials. The important considerations are the directions most frequent during the hot season and the directions of local site effects, such as wind blockage or channeling by the surroundings. Velocity ratios for the unimportant directions are either estimated from known ratios for other directions or conservatively assumed to be zero. A set of velocity ratios may be determined for several points within the building.

To be most useful, the wind-tunnel models should be simply built and easily modified. Once the initial testing has identified problem areas in the design, the model is modified, often while in the wind tunnel, to assess the effectiveness of design changes to reduce or eliminate the problems. The easier this process of modification is made, the larger the number of possible design alternatives that can be tested. Some of this flexibility can be built into the model beforehand, but the problems and their possible solutions often cannot be predicted or foreseen in advance. The usual practice is to construct the models of either foam-core board or corrugated cardboard. Interior partitions and major furnishings should be modeled also.

Interior velocity ratios may be estimated without tunnel testing by referring to published results (Olgyay 1963; Aynsley 1977; Givoni 1981) of generalized ventilation tests. Most building designs tend to be more complex than these, with widely varying interior airflow patterns, so such published ratios should be used with care.

The second step is to determine the interior temperatures in the building. The exterior temperature for each hour are available from NOAA weather tapes in various widely available formats. Many well-ventilated buildings, particularly in the tropics, have high air-change rates sufficient to quickly remove typical levels of internal heat gains. For these buildings, it is reasonable to assume that the indoor temperatures will be the same as or close to the outdoor temperature. In the comfort analysis, the interior temperature can be taken either as the exterior temperature or as the exterior temperature increased by a small fixed amount.

If the building under analysis has a small amount of wind-driven ventilation or high levels of internal heat generation, then a separate computer simulation of the building will be necessary to determine the hour-by-hour inside air temperature. Here such hourly values have been read from the output file of the DOE-2 program, but simpler programs would function as well for this purpose.

The third step is to run the comfort prediction program. The basic program variables that the user can set are as follows:

1. Wind velocity ratios (inside velocity/outside velocity) for up to 16 compass directions, as obtained from the tunnel tests. These may be set for several points of interest within the building interior.

2. Activity and clothing levels. These levels can also be scheduled to vary over the course of the day.

3. Interior air temperature modification as described above.

For a given point in the building's interior, the program reads in one hour from the weather tape and adjusts the exterior wind velocity by the velocity ratio corresponding to the wind direction for that hour, giving the interior velocity at that point. The exterior temperature is then adjusted to represent interior temperature. The activity and clothing levels for the time of day are read, and the program iterates in one-minute time steps to compute whether the hour has a comfort level equivalent to that specified in ASHRAE Standard 55-81. The hour is compiled as comfortable or uncomfortable, by period of day. The program then repeats the process with the next hour, continuing through the season or year of interest.

The output of the program is a table of the percentage of time that comfort is achieved at that point, broken down by periods of day. The designer must decide the comfort-time percentage that is acceptable since there are no standards available for such a criterion at present. The criterion is, however, rational and intuitively obvious, so that designers can use it both in making absolute judgements about a given design (i.e., is it good enough?) or in comparing the comfort consequences of alternative schemes.

The authors are also currently working on developing the program for comfort analysis to where it is capable of operating interactively on a micro-computer in the wind tunnel itself. An anemometer reading taken in the building at a given wind direction is to be automatically translated into percentage of comfortable time out of the total time the wind comes from that direction. For this, both weather data and comfort requirements are initially processed into bins to speed the analysis in the tunnel itself. Such a program has promise to influence the design of naturally ventilated buildings. It would provide designers, working in the wind tunnel facility, immediate feedback on their design and proposed alternatives, allowing them to come to acceptable configurations quickly. Once a model in the tunnel shows a level of comfort acceptable to the designer, further development of the design is not necessary and the experimenting can stop.

A CASE STUDY

As a test of the comfort program and its usefulness as an analytical and design tool, a study was done of natural ventilation in a proposed U.S. Navy housing project near Honolulu, Hawaii. The housing was designed by the architect to take maximum advantage of Hawaii's relatively mild temperatures and strong trade winds by using natural ventilation to cool the building's structure and occupants. The coincidence of the strongest winds and lowest humidity levels in the hot summer months in Hawaii makes cooling by natural ventilation a very promising means of maintaining thermal comfort there.

Orienting the building's long axis north-south, perpendicular to easterly trade winds, maximizes the potential for natural ventilation, but also makes solar control difficult and expensive. The architect determined that this project was most effectively oriented with the long axis of the building facing 10 degrees west of south.

Airflow patterns and velocities for both the interior and exterior of the buildings were determined by boundary-layer wind-tunnel tests of a scale model, performed in a facility designed specifically for the testing of architectural models. It has the capability to simulate, to scale, both the velocity and turbulence intensity profiles caused by roughness upwind of the building site.

Floodlit smoke was used to determine flow patterns in and around the buildings and to establish representative points for velocity measurement. All air-velocity measurements were made with a constant temperature anemometer with hot film probes. The wind velocities were recorded as a percentage of the undisturbed wind velocity approaching the site at a reference height of 30 feet in smooth terrain. The velocity ratios are unaffected by changes in the magnitude of the reference velocity. The reference velocity corresponds to the wind record taken from Honolulu International Airport, which could be used without adjustment for site effects because of the close proximity of the airport and the flatness of the intervening terrain. In this study, a Test Reference Year (TRY) tape was used to represent the long-term climate. Although TRY tapes are not designed to serve this purpose, the Honolulu tape works well because of Hawaii's year-to-year climate uniformity.

Site Study. The first stage of the wind-tunnel study was to evaluate the proposed site plan. The primary concern here was to determine the direction and velocity of airflow to the housing unit as affected by the other structures on site. A styrofoam model of the site and proposed building was constructed at a scale of 1/8 in = 1 ft. The natural-ventilation potential of the site was found to be excellent, as there were few significant obstructions to the airflow in the easterly direction, from which the trade winds are expected a large proportion of the time. (see figure 3).

Interior Airflows. Once the airflow to the building itself was determined, a larger 3/8 in = 1 ft scale model of the building was built to determine interior airflow velocities. The larger scale model was needed in order to have enough room inside the model for scale furniture and the anemometer probe. Figure 4 shows the model row of housing units in the wind tunnel. There are two detailed modules that are tested within a row of foam dummies to ensure proper airflow around the entire row. The detailed models were built primarily from styrofoam, foam core board, and corrugated cardboard. Transparent acrylic walls, roofs, and ceilings were used in order to allow the experimenter to see the smoke introduced for flow visualization and the anemometer probe. Windows and louver systems are interchangeable, as is the position of the detailed unit within the row. The interior door position is adjustable. (figures 5, 6 and 7).

Anemometer readings were taken at a 3.5 foot height for representative points inside the rooms in order to establish ventilation velocities. Readings were also taken just inside the inlet windows so that an estimate of the air-change rate in the room could be made. Figure 8 shows a vertical axis hot wire probe inserted through the roof; during measurements the other holes were taped over.

Many different design configurations were tested with this model:

1. Various setbacks between four units in the housing block.

2. The effects of bush, tree, and wall windbreaks at the edge of each housing unit.

3. Window-opening sizes.

4. Operable louver positions.

Figure 9 shows an example of one such configuration with velocity readings inside.

Interior Temperatures. DOE-2 analysis of a typical unit was performed using the air-change rates established in the wind tunnel. The program produced interior temperatures averaging 2.6°C (4.7°F) above the outdoor air temperature during the afternoon hours in summer months This difference (admittedly a peak one) was used to adjust the weather tape's dry-bulb temperature value upward over the whole year.

Comfort Analysis. With the adjustment to the temperature and the optimal configuration of window sizes and louver positions, the comfort model predicted the following frequencies of comfortable conditions:

	Period of Day			
	0-6	6-12	12-18	18-24
Clo Value	0.4	0.4	0.4	0.4
Activity level	0.9	1.2	1.2	1.0
Fraction of total time in which comfort achieved	0.99	0.82	0.82	0.99

Daily average = 0.91

Two alternative methods of augmenting ventilation were run through the comfort program: the addition of a windbreak at the end of the block and the addition of a ceiling fan in the unit to create a minimum wind speed of 1 m/s during light wind periods.

Wind Break

	Period of Day			
	0-6	6-12	12-18	18-24
Clo value	0.4	0.4	0.4	0.4
Activity level	0.9	1.2	1.2	1.0
Fraction of total time in which comfort achieved	0.99	0.87	0.87	0.99

Daily average = 0.93

Ceiling Fan

	Period of Day			
	0-6	6-12	12-18	18-24
Clo value	0.4	0.4	0.4	0.4
Activity level	0.9	1.2	1.2	1.0
Fraction of total time in which comfort achieved	0.99	0.98	0.97	0.99

Daily average = 0.98

The ceiling fan proved to be the most effective means of increasing the comfort level, although the 1 m/s velocity modeled here is probably unrealistically high.

CONCLUSION

The comfort-prediction procedure gives building designers useful quantified information on the effectiveness of various design strategies for natural ventilation, with the potential for producing that information instantly on an interactive computer system in the wind tunnel itself. This is a powerful design tool that should result in more successful building designs in the future.

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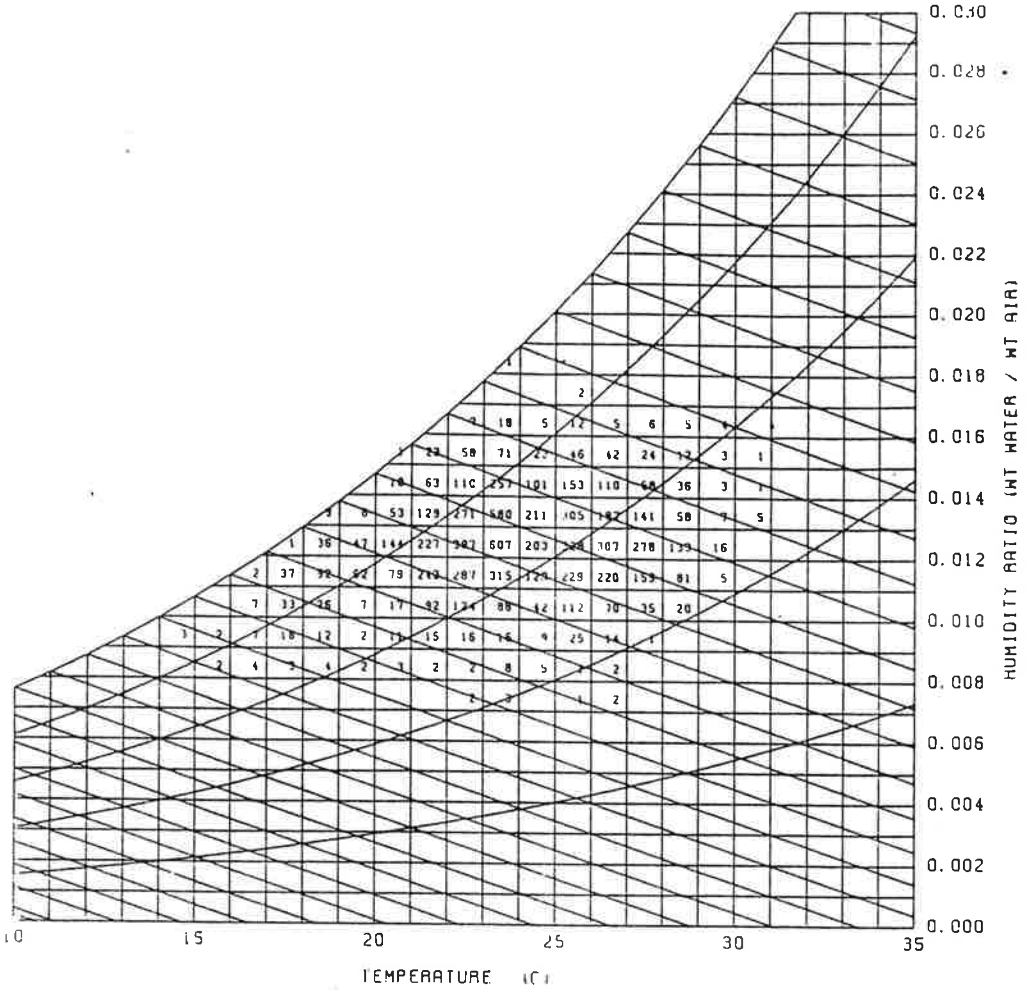

Figure 1. Number of hours in coincident temperature and humidity bins for the Honolulu Test Reference Year

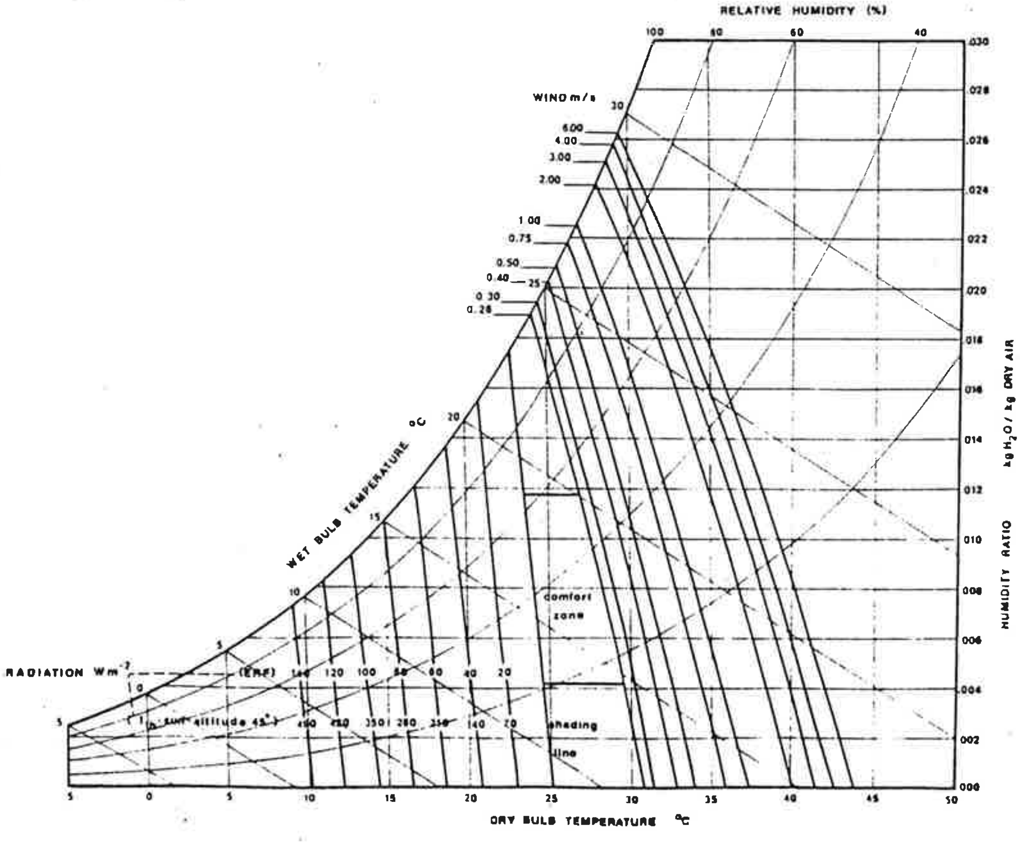

Figure 2. Bioclimatic chart showing lines of equal comfort under various combinations of climate. Lines correspond to ASHRAE Comfort Standard 55-81 for activity level of 1.3 met and 0.4 clo.

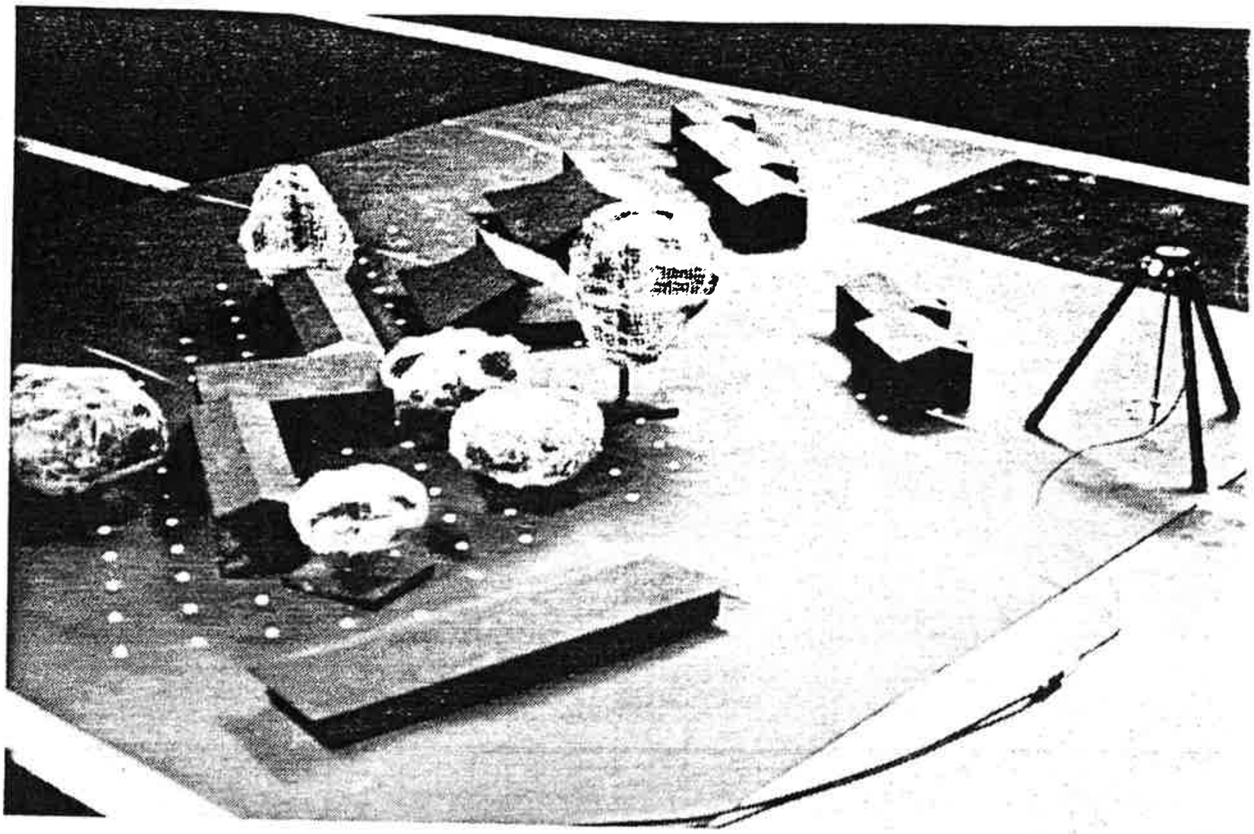

Figure 3. Site model in the wind tunnel

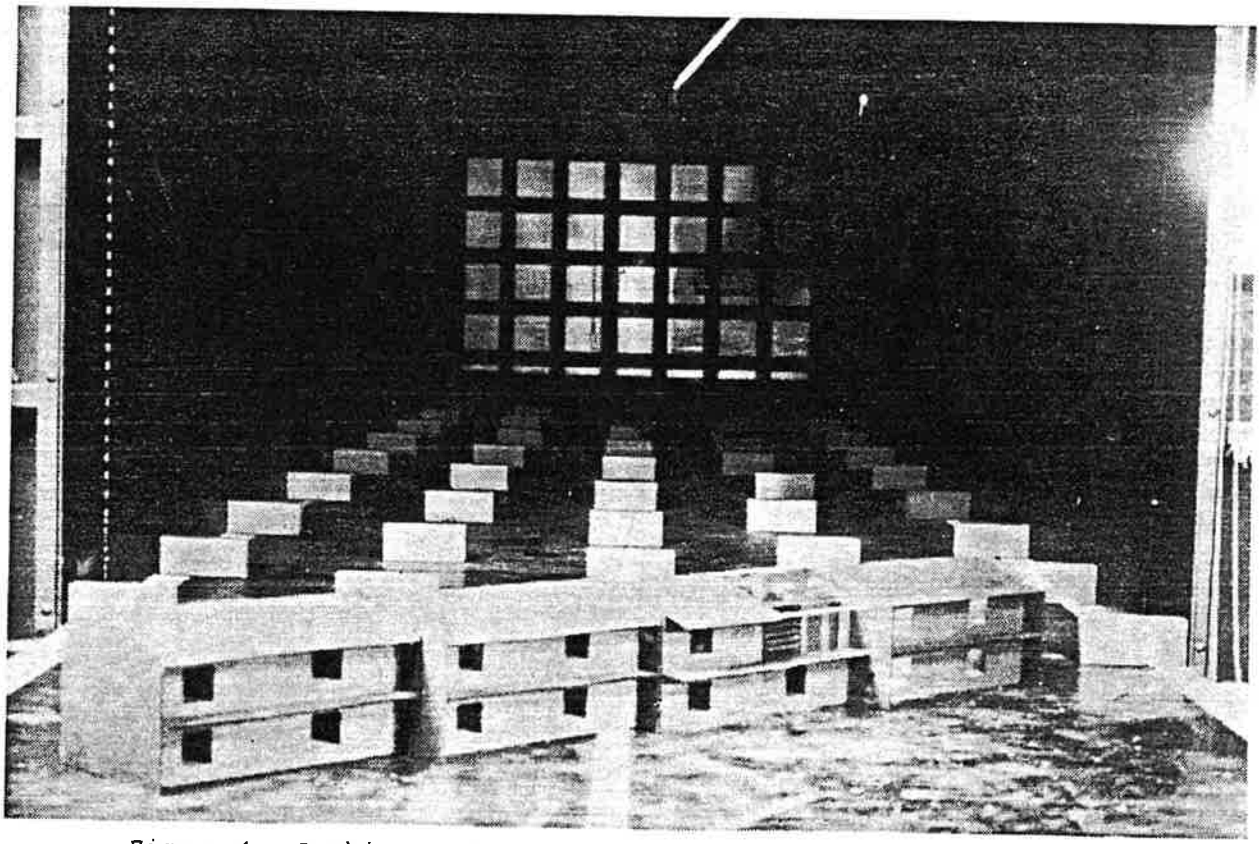

Figure 4. Looking upstream at a row of staggered housing units in the wind tunnel, with detailed upstairs unit third from left.

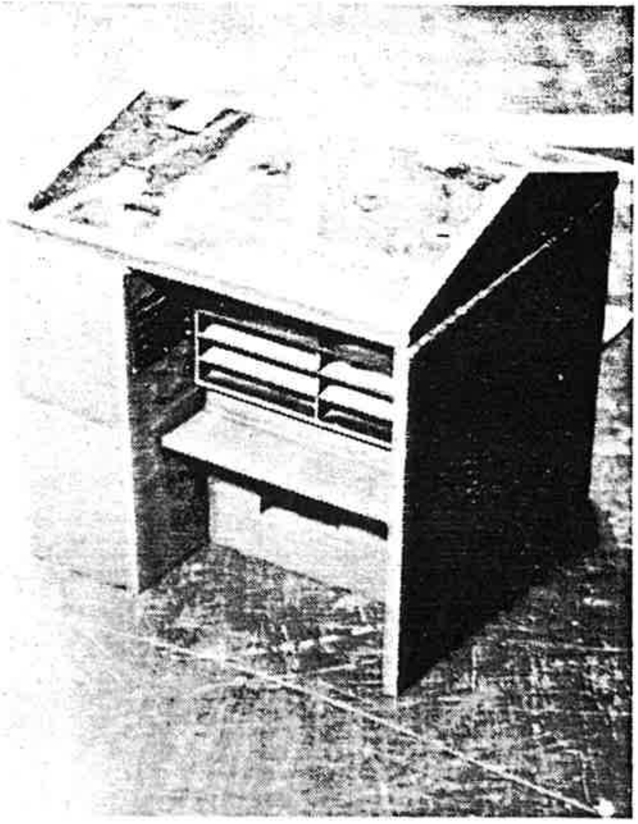

Figure 5. Building model: rear exterior of detailed upstairs unit

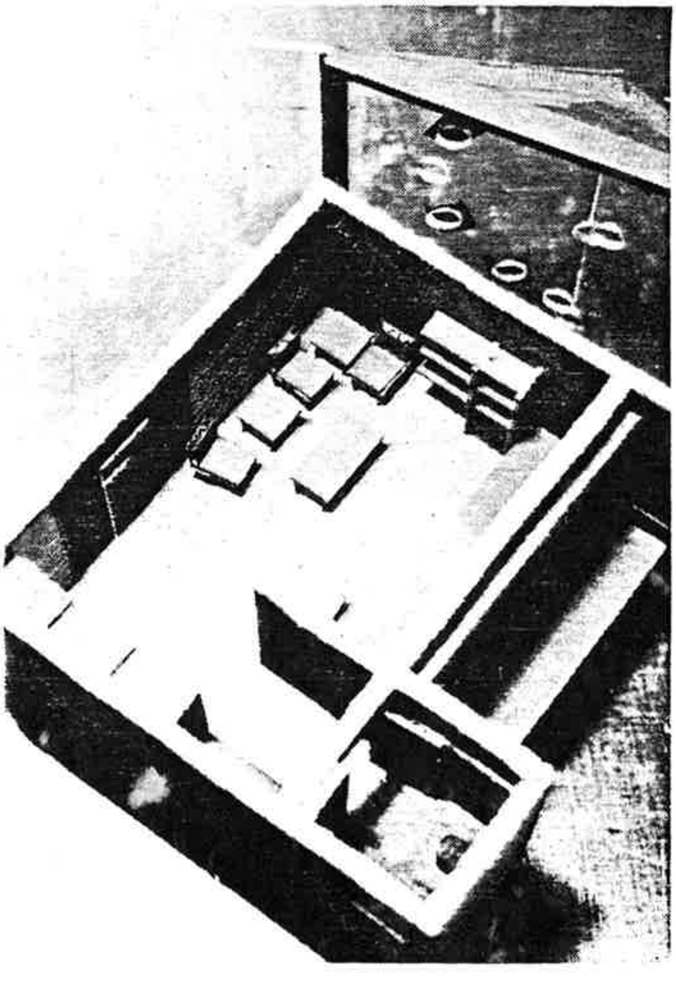

Figure 6. Building model: interior of detailed upstairs unit

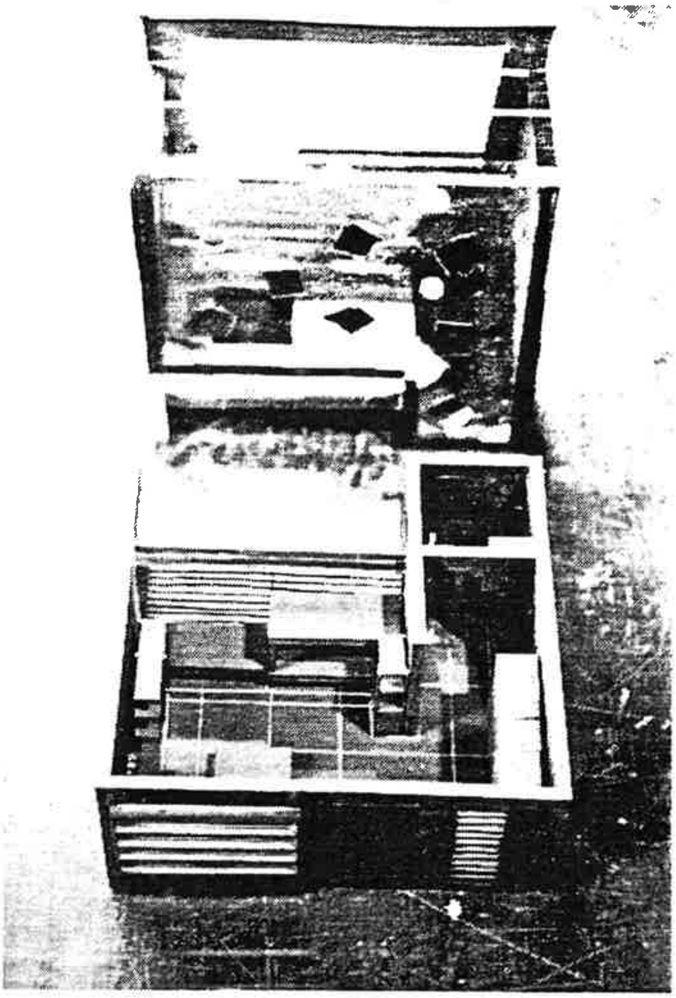

Figure 7. Building model: interior of detailed downstairs unit

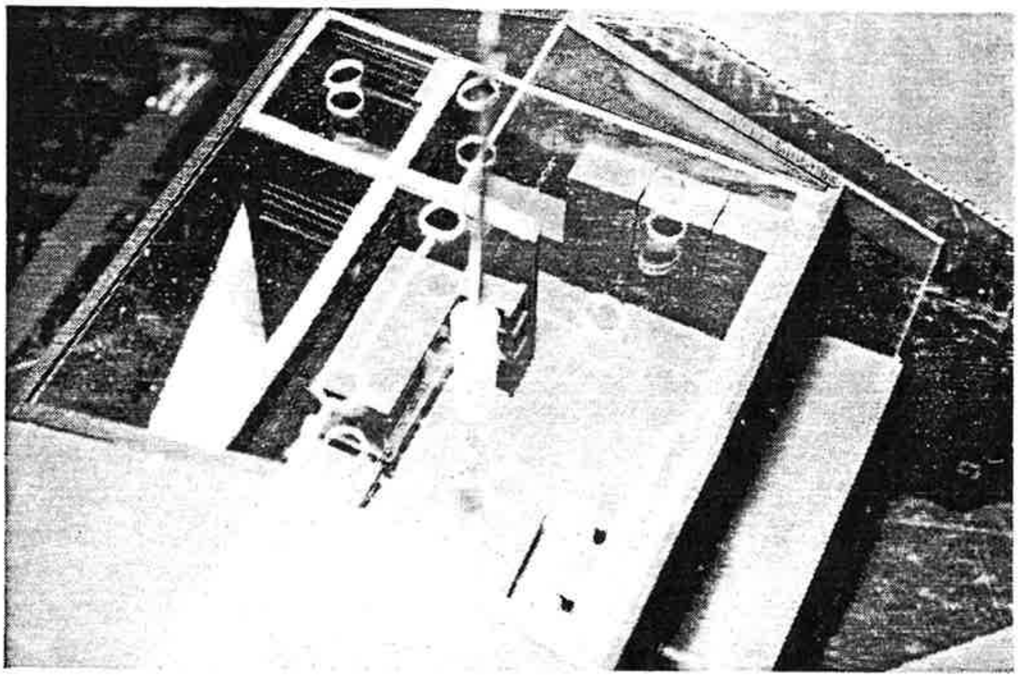

Figure 8. Anemometer probe in the model

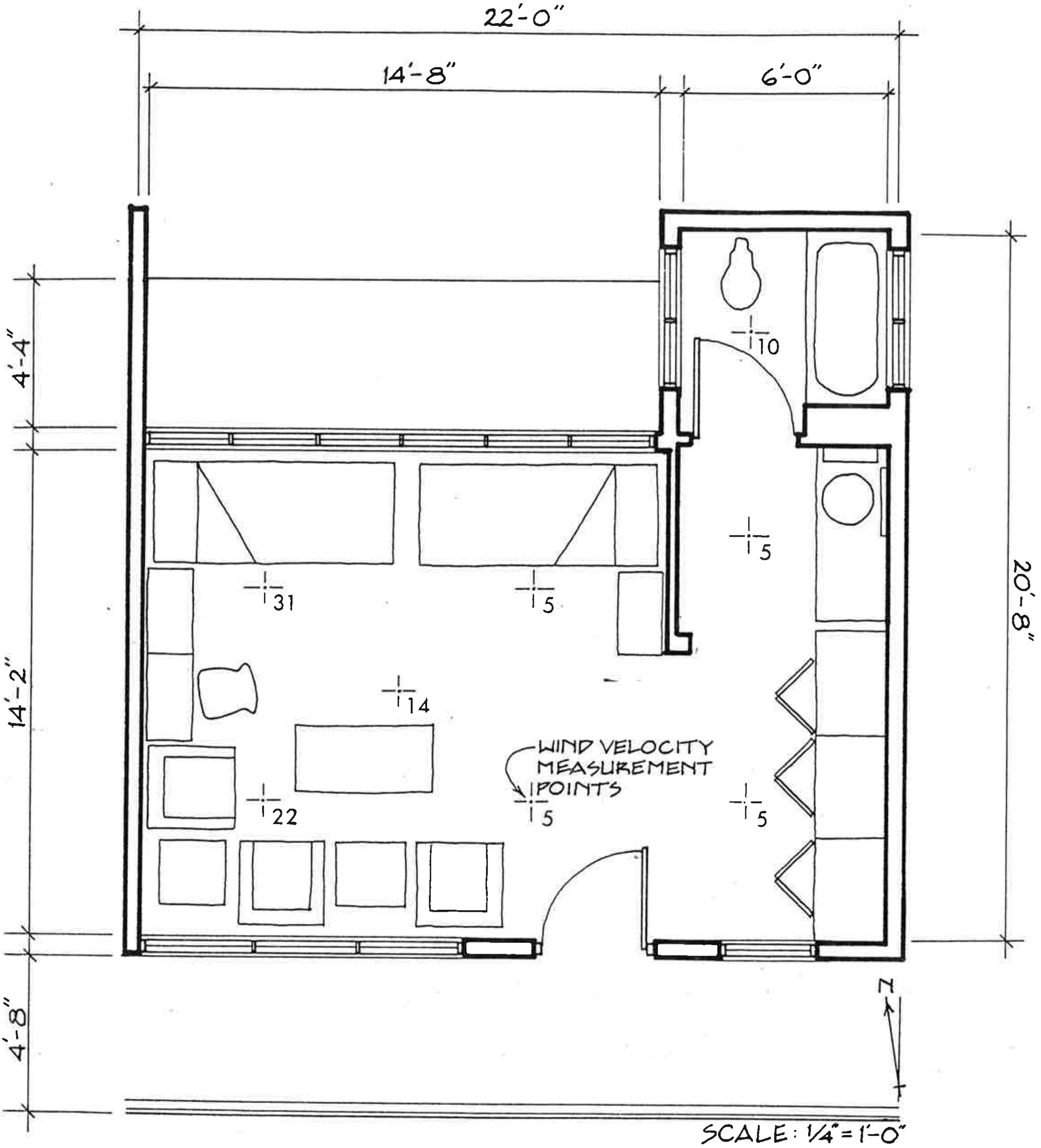

Figure 9. An example configuration of the test unit with velocity ratios (in percent) measured for an east wind