Title
Comfort and Health Considerations: Air Movement and Humidity Constraints

Authors
Arens, Edward A
Bauman, Fred
Baughman, A.
et al.

Publication Date
1995-07-01

Comfort and Health Considerations: Air Movement and Humidity Constraints

Final Report - Phase II, Part 1

E. Arens, F. Bauman, A. Baughman, M. Fountain, K. Miura,
T. Xu, H. Zhang, and T. Akimoto
July 1995

Publication number: CEDR-19-95

COMFORT AND HEALTH CONSIDERATIONS: AIR MOVEMENT AND HUMIDITY CONSTRAINTS

Final Report - Phase II, Part 1

Period of Performance:
August 1993 - July 1995

Part of the Coordinated Research Project on
Alternatives to Compressor Cooling in California Transition Climates

Submitted to

California Institute for Energy Efficiency
MOU No. 4904010

Submitted by

E. Arens, F. Bauman, A. Baughman, M. Fountain, K. Miura, T. Xu, H. Zhang, and T. Akimoto
Center for Environmental Design Research
University of California
Berkeley, California

July 1995

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report describes the results of research completed to date during Phases I and II of the project. The report is organized in terms of the major types of work that have taken place. These are:

1) laboratory studies of air movement and comfort.
2) review of the influences of humidity on health, particularly as they impact evaporative cooling and naturally cooled architecture.
3) development of a computer model of the human body sensitive to localized effects of air movement, localized radiant fields, and other environmental influences.
4) assistance with the workshops to create compressor-free house designs.

1. **Laboratory Studies of Air Movement and Comfort** (Subtask D.3)

In Phase I we performed laboratory experiments to define the comfort and acceptability of naturally turbulent air movement under warm conditions. The experimental design was guided by the issues that had been brought into focus by the recently approved ASHRAE Standard 'Thermal Environmental Conditions for Human Occupancy' (Standard 55-92). Edward Arens, Fred Bauman, and Ph.D. student Marc Fountain had been involved with the standard revision over the preceding four years, and the deliberations had revealed a number of gaps in the understanding of how air movement affects cooling and comfort, unknowns that influence how several alternative cooling strategies are evaluated. The proposed standard included strict limits on maximum allowable air movement, which would have prohibited the natural cooling techniques of wind- and fan-driven ventilation, and impacted direct evaporative cooling as well.

To put these issues before the engineering profession, we (Fountain and Arens) published in August 1993 a *ASHRAE Journal* paper describing the new Standard 55 and the uncertainties inherent in its air movement provisions. The paper described the historical reasons for these provisions, including the experimental evidence used in their support.

The laboratory experiments focused on developing information to better represent air-movement cooling in comfort standards. Such information was needed to counter proposed blanket restrictions on air movements above 0.2 m/s in occupied spaces. In order to be influential, it was important that the information be as well-documented as the research underlying the conventional comfort zone.

Our approach was to expose human subjects to types of air movement likely to be experienced in a residence with either open windows, a whole-house fan, a standing fan recirculating room air, or a direct evaporative cooler with a high air flow rate. To this end, we located a type of fan in Japan that produced two modes of windspeed turbulence distribution by software control of its variable speed motor. The power spectra of the fluctuating airstream produced by the two modes represent a range of conditions that might be expected indoors. The fan's mean windspeed could be controlled by the subjects through a remote IR controller. We tested this fan and characterized the flow field created at each power level, including its turbulence intensity, both in isolation and in the spaces in which our our human subjects are tested. We also devised a simple method to monitor the fan setting and velocity distribution during the course of the experiments by monitoring their amperage with an ACR datalogger. Following the tests, we ordered four more to equip the chamber. We are grateful to their manufacturer, the Matsushita Electric Corporation, for donating them to us.

The chamber was reconfigured to allow two 'residentual' settings to be simulated at once, separated by a partition. The velocities on the two sides did not influence each other. Tests were done to determine the preferred air speeds and comfort acceptability limits for both modes of fan operation.

The subjects were tested at two activity levels (or metabolic rates). The first level is directly applicable to the ASHRAE and ISO standards, and represents house or office work (1.2 met, or 70 W/m^2 of body surface area). The second (1 met, or 58.3 W/m^2) is representative of quiet sedentary activity, and is directly comparable to nearly all previous laboratory comfort work. Developing the procedure for producing the higher metabolism in the laboratory was an interesting problem, requiring input from comfort researchers around the country. We tested it in the Exercise Physiology Laboratory at Harmon Gym, and have since seen it adopted in several studies internationally.

We also used an electrically heated thermal manikin to determine the insulation value of the chair and the subjects' clothing under differing wind speeds in the chamber.

During the tests, we monifored the environmental conditions, the subjects' preferred fan settings, and their subjective responses to a range of questions about thermal comfort and windspeed acceptability. We also solicited and assembled their comments. The results were subjected to a variety of satistical tests to describe their responses. They are compared to well-established calculations of predicted response, such as PMV and SET, to detect differences from the standard models.

From the results, a *'zone of likely use'* chart was developed to define acceptable levels of temperature for different levels of air movement. It can be taken as the range of conditions within which the air movement alternative to compressor cooling might be pursued in California. It challenges the most prevalent position toward air movement found in standards, particularly the unqualified implementation of the Fanger draft limit. It provides for considerably higher temperatures than those any of the commonly-used comfort measures would predict, and yet people are comfortable to a similar extent as in the standard comfort zone. Its results are consistent with those of populations studied in field studies in the tropics, and with some other studies done of ceiling fans (plotted in the paper in Appendis A), but this is the first time that these results have been obtained under the same types of experimental conditions as are used in mainstream thermal comfort studies.

For the purposes of this project, we recommend that the setpoints in this chart be used in the computer simulations of the effectiveness of the various cooling strategies that rely on air movement. It will make a very large difference in the estimation of such systems' effectiveness in the various climates across the state.

We have presented these results in January 1995 at a conference in Japan on energy-efficient environmental conditioning. We will present them also at ASHRAE, and hope to see them considered in the formulation of the future ASHRAE Standard 55.

This study is presented in **Appendix A**..

2. Review of Health Effects Related to Humidity in Buildings. (Subtask D.3)

The project also was charged with assessing the health effects of higher levels of humidity as might be found in evaporatively cooled buildings. Recent standards activity has been moving towards mandatory humidity limits justified on health grounds. Such new limits (at the moment they exist only in the form of non-mandatory 'guidance language' in ASHRAE Standard 62, 'Ventilation for Acceptable Indoor Air Quality') could potentially restrict the use of direct evaporative cooling as an alternative cooling strategy. They could also restrict the use of regionally appropriate architecture (ventilative cooling) as ways of saving energy.

We had assembled literature and written a report on this subject in Phase I. In Phase II we continued work on the subject and prepared a two-part paper for the *ASHRAE Transactions*. It organizes the large amount of information related to humidity and health into a building/building systems context. We hope that it will be useful in the current standards deliberation. This paper will be presented at the January 1996 meeting. It is attached in **Appendix B.**

The simplest statement one can make about the various humidity/health effects is that they are inadequately predicted by humidity measured in the building's occupied air space. This parameter (in the form of relative humidity) has however been almost the *only* one being proposed as the basis for humidity limits in ventilation and indoor air quality standards. There are capital resource, health maintenance effectiveness and energy-conservation grounds for making sure that future humidity/health limits be based on humidity variables more relevant to the health effects of concern.

Even if relative humidity were the appropriate parameter, there is little to justify the upper limit suggested in Standard 62 (60%RH). Values of 70% and even 80% RH might be appropriate for most factors, including molds. The critical limit will probably be dictated by the dust mite *Dermatophagoides farinae*, a species more tolerant of low humidities (down to 50% RH) than the species of mite most commonly studied in the past. It has only appeared in the literature in the last few years, and is not well understood. On the other hand, carpet/fabric treatments may be on the way for people who are influenced by this mite.

As a result of our review of health effects, Arens and Ph.D. student Anne Baughman attended numerous humidity-related committee meetings at ASHRAE meetings. These were in the areas of ventilation (TC 2.3), indoor air quality related to Std 62-89 'Ventilation for Acceptable Indoor Air Quality', now in its revision cycle, Environmental Health, and the new Task Group on a comprehensive indoor environmental standard (GPC 10).

We presented our case sufficiently in the proposals for revision of Standard 62, an upper RH limit is applied only to the designed air conditioning capacity of buildings in hot/humid climates. This is a reasonable compromise that deals with moisture processes that are not a problem in dry climates such as California's. If this version of the limit becomes adopted, energy conserving technologies such as direct evaporative cooling and naturally cooled architecture will be able to remain alternatives to compressor-based cooling.

3. Development of Advanced Computer Tools for Comfort Analysis. (Subtask D.3)

We worked together with Professors Shin-ichi Tanabe of Ochanomizu University and Richard de Dear of Macquarie University on developing the original Stolwijk thermophysiological model into a usable tool for designing complex thermal environments. Their visits here in Fall 1993 and Spring 1995 were partially supported by this project. Our collaboration is continuing, with both visitors and a Ochanomizu University Ph.D. student working with us on the model. The work here has involved both programming the model into C++ and experimental work to provide the necessary functions and coefficients for its 16 body parts. We will be developing the model with a user-friendly WINDOWS interface similar to (and compatible with) the one recently developed here for ASHRAE. It will incorporate considerable additional graphics and reporting features.

To link the computer model to empirical air movements studies, we tested the thermal manikin in the wind tunnel. The wind tunnel produces uniform flow across the whole body which , though not particularly typical of real indoor situations, corresponds to the experimental conditions of several major previous experiments. These tests revealed the localized clothing values on different parts of the body, as affected by wind speed and direction. The results are new and necessary for computer modeling in the future.

We also used the manikin to determine the insulation value of padded chairs. This value is significant, around 0.15 clo depending on chair type. It has already allowed researchers to reevaluate the results of field studies where air movement is a significant parameter. It will also be used in computer comfort modeling in the future.

This work is continuing at present. A report and the computer program will be submitted in the Autumn as soon as they are completed.

4. Design Workshop Assistance (Subtask C.2)

A booklet was prepared on Ventilative Cooling for the design workshop (attached in **Appendix C**). Following this, the ventilative cooling problem was assigned to students in an architecture class in spring 1995, resulting in two more student reports analyzing designs amenable to nighttime ventilation through windows. These were incorporated into the workshop materials by Loisos and Ubbelohde.

The workshop will be repeated in the Autumn, and this assistance task is continuing.

ACKNOWLEDGMENTS

The research reported heare was funded primarily by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nore that of any CIEE sponsor. Portions of the laboratory experiments were also supported by the Universitywide Energy Research Group (UERG), University of California, Berkeley.

The authors wish to thank George Brooks, Gretchen Casazza, Anne Friedlander, and Jim Hokanson of the Exercise Physiology Laboratory, Human Biodynamics Department, UCB, for letting us use the respired oxygen apparatus and instructing us on its use. We also are very grateful to Kimberley Allen, Alice Gates, and Nora Watanabe of the Center for Environmental Design Research, who administered the project and helped with the innumerable transactions that it entailed.

APPENDIX A

Air Movement and Thermal Comfort

A study of occupant cooling by personally controlled air movement in a residential setting

Edward Arens
Tengfang Xu
Katsuhiro Miura
Zhang Hui
Marc Fountain
Fred Bauman

ABSTRACT

This study addresses the effectiveness of air movement cooling, an alternative to compressor-based cooling in residences. Subjects in simulated residential settings were exposed to a range of warm temperatures and allowed to adjust air movement to suit their individual preferences, while answering a series of questions about their comfort. Air movement was from the side in two modes of turbulent flow. The air velocities chosen by the subjects, and their subjective responses, are evaluated in the context of existing comfort standards and prediction techniques. A zone is proposed within which personally controlled air movement provides acceptable environments.

1. INTRODUCTION

When air movement cools the human body, it is possible to be comfortable at temperatures above the maximum comfortable temperature for still air. This underlies a number of low-cost energy-conserving measures applicable to the design and operation of buildings in California. In residential buildings, such measures have traditionally been incorporated in the design of the building itself, where building form, room layout, windows, and vents allow the occupant to produce high rates of interior air movement when needed. Throughout the first half of this century, air movement was also promoted by mechanical devices such as whole-house fans, ceiling and room fans, and direct evaporative coolers, which typically produce substantial air movement as they cool.

The introduction of residential air conditioning after WWII led to the displacement of such techniques. Such measures can however still be very effective at conserving the energy now consumed in compressor cooling, especially in climates such as California's. To encourage their reintroduction in common residential practice, some obstacles need to be overcome. One of the major ones is that it is impossible at this time to either design such measures, or assess the comfort they produce, to the levels of certainty expected in heating, ventilating and air conditioning (HVAC) engineering today. This is due in part to our limited current knowledge of how elevated air speeds affect thermal comfort in warm conditions. Because drafts have traditionally been a major cause of HVAC complaints, most of the existing research on air movement has been done under cold-to-neutral conditions that may not be applicable to neutral-to-warm conditions. The relatively few studies of warm conditions in the literature left questions in terms of their implementation in practice. This became clear during the recent revision of ASHRAE Standard 55 [1], in which there was considerable disagreement in the standards committee about how to deal with the concept of cooling by air movement.

Rohles et al. [2] exposed subjects to nine experimental combinations of air temperature and air movement within the ranges of 22.2° to 29.5°C and 0.2 to 0.8 m/s. He found strong relationships between air velocity, air temperature, skin temperature and thermal sensation. Draft discomfort was not observed and Rohles recommended an 'extended' summer comfort zone using 0.8 m/s as the limit for air movement that was incorporated into ASHRAE Standard 55-81. A later study (Rohles et. al. [3]) addressed the question of whether the 0.8 m/s limit was still applicable under the turbulent flow of a ceiling fan. The experimenters found that subjects considered air movement pleasant at levels beyond what had been previously considered reasonable (up to 1 m/s at 29.5°C). These results were closely matched in a study of comfort under both ceiling fans and whole-house fans by Spain [4]. He found that velocities of 0.25 m/s provided comfort to 27.8°C, in ET*), while 1.0 m/s provided comfort to 29.4°C. As with the Rohles studies, higher temperatures were not tested.

The Rohles ceiling fan study was repeated in Arizona by Scheatzle et al. [5] who also extended the test conditions to lower and higher relative humidities. They found the upper limit of acceptability for air motion (as proposed by Rohles) could be raised for lower humidities (to 31°C) but must be lowered for higher humidities. Wu [6] continued the Arizona study for oscillating room fans, and found the acceptable zone to extend as high as 32°C.

Researchers in Japan (Kubo, Isoda, and Yanase [7], and Tanabe and Kimura [8]) have also found similar results in air-movement-cooling studies. Kubo et al. found preferred velocities (the velocity chosen by a subject at a given environmental condition) as follows: at 26°C, 0.6 m/s (for both 50% and 80% RH); at 28°C, 0.66 m/s (30% RH), 0.87 m/s (50%), and 1.02 m/s (80%); and at 30°C, between 1.06 and 1.27 m/s for 30 to 80% RH. At the preferred velocity, the subjects' average thermal sensation was cooler than neutral, and their comfort sensation was positive, on the pleasant side of neutral. Subjects preferred a higher velocity than predicted by the neutral condition for SET* (standard effective temperature) or of PMV (the predicted mean vote). Several air-movement-cooling studies were carried out by Tanabe and Kimura. In preferred velocity tests at 50% RH, they found the preferred velocity at 28°C to be 1.0 m/s, at 29.6°C, 1.2 m/s, and at 31.3°C, 1.6 m/s. They also examined various forms of fluctuating air movements across the range 27-31°C, finding that sine waves (with 10, 30, and 60 second cycles) produced significantly cooler thermal sensations at a given mean velocity than did constant or step-change wind speeds.

2. OBJECTIVES

The study was planned to address the following issues:

- The ability of user-controlled fans to maintain comfort in air temperatures up to 31°C.
- The effect of naturally fluctuating air speeds (as opposed to constant air speeds) on comfort in warm environments, in order to assess the effectiveness of wind through windows.
- The effects of short bursts of activity, typical of a domestic setting, on comfort in warm environments where air movement cooling is available to the occupant. This was to be compared to comfort under sedentary conditions, which has been the basis of all previous studies.
- How to produce an average metabolic rate in the subjects that is the same as that assumed in the ASHRAE comfort standard (1.2 met). This had not been done before in chamber tests.
- The risk that occupants will feel undesirable draft from the air movement in the 24 to 30°C temperature range.
- If the wind bothers the occupants under any of the conditions, to determine the nature of the complaints and their cause.

3. METHODS

3.1 Overall Approach

We decided to test conditions as close as possible to those assumed by ASHRAE Standard 55. The metabolic rates were set to be the same as that of the standard (1.2 met), achieved by a combination of sitting and step-climbing activity. The clothing insulation (0.5 clo) was the same as used in the ASHRAE summer comfort zone, but the incremental insulation of the conventionally padded chair, omitted in the standard, was found to add 0.23 clo to this clothing. Humidity was held as close as possible to 50% throughout. The tests were held in the summer, and the subjects started the tests close to thermal neutrality in order to simulate comfortable continuity, particularly in terms of their skin sweat content, and to counter the possibility of a comfort hysteresis effect in the experiment.

3.2 Test Conditions

The controlled-environment chamber (CEC) used in these experiments is located at the University of California, Berkeley. It is described in detail by Bauman and Arens[9]. It measures 5.5 meters by 5.5 meters by 2.5 meters, and is configured to appear as a realistic residential or office space, to unconfound (at least partially) the psychological experience of being a human subject in a laboratory experiment. It has windows on two sides whose glass temperature can be controlled. In this experiment the glass temperature was held equal to indoor air temperature. A ceiling supply-and-return air distribution system was used to produce a uniform interior temperature with the lowest possible ambient air movement within the occupied zone.

Figure 1 shows the experimental setup. A single partition divided the CEC in half with one subject occupying the south half and another subject occupying the north half of the chamber. Each part was furnished with a cafe-style table, flowers, a mineral water bottle and glass, a wall painting, and a selection of books and magazines, all of which were intended to create a home-like atmosphere. Both parts had views available to the outside. The subject was seated at the table in a padded chair, with armrests, that was selected to represent the range of conventional residential chairs. Manikin tests showed that this chair added an incremental 0.23 clo to the subjects' clothing. The fan is facing the subject approximately 2 meters away.

Figure 2 shows velocity profiles produced by the fan in its fluctuating and constant modes. The observed distribution of velocity is quite uniform within a range of 30 cm (knee height) and 80 cm (neck height for a seated person). Turbulence intensities in this zone average 60% for both fan speed modes. The average velocities produced by the constant speed mode were greater than for the fluctuating mode. Subjects in the constant speed tests had a greater range of mean velocities at their disposal than those in the fluctuating tests, and a greater step change between settings.

A spectral analysis of the air stream at the subject's position gives more detail to the nature of the turbulent fluctuations. *Figure 3* shows the relative density of turbulent frequencies for the the two modes. The constant speed mode has a higher proportion of turbulent eddies cycling in the 1 Hz (one cycle per second) frequency band than is found in the fluctuating speed mode. Superimposed on the fan data are the frequency distributions for natural wind outdoors (ESDU, [10]). The closest fit to the constant-speed fan data is the curve for smooth rural terrain. The closest fit for the fluctuating mode is the curve for quite urban conditions; however the fan distribution is relatively filtered in the frequency range around 1 Hz.

In addition to the frequency distributions for the two fan types, there is also a noticeable pattern in the fluctuating mode of increasing the velocity rapidly from the low to high extreme. This pattern does not occur in the constant speed mode, where velocity changes appears to be random.

3.3 Physical Measurements

A mobile measurement cart was used for collecting physical environmental data during the tests (*Figure 4*). Although developed primarily for field work, the cart incorporates laboratory grade instrumentation and consequently was useful for this series of experiments. See Benton et al. [11] for description of this instrument.

3.4. Survey Instruments

Three approaches were used to elicit subjective responses. The first was a one-time background questionnaire asking demographic and general 'preferred environment' questions (*Figure 5a*). The second was a 'comfort' questionnaire that was used repeatedly during the experiment to obtain current thermal sensation, thermal preference and other votes (*Figure 5b*). Finally, general open-ended comments were solicited from the subjects just before they exited the chamber.

3.5 Experimental protocol

120 subjects were recruited from the local campus community to participate in the experiment. The study was carried out in May-July during warm sunny weather. This was considered advantageous, in that the subjects would be acclimated to summer conditions like those being simulated in the controlled-environment chamber. The subjects were instructed to arrive at the CEC wearing typical summer casual clothes consisting of shoes, socks, underwear, slacks or jeans, and a T-shirt or other light short-sleeved shirt.

The protocol for both constant and fluctuating velocity experiments was as follows. Upon arrival at the laboratory, the subject was assigned to one of the test stations in the chamber and given the background questionnaire to fill out. Since the laboratory chamber had been pre-heated to the test temperature, the subject was asked at the outset to adjust the source of air movement to continually maintain comfort while reading or doing paperwork. The subject was in the chamber for 80 minutes, adjusting the air movement source for comfort as necessary, before the first set of physical measurements was made. During this period the subject performed a physical exercise every 10 minutes. The activity, walking up and down a step 12 times, raised their metabolic rate to 1.2 met (or 70 W/m^2) when averaged over time (*Figure 6*).

After 50 minutes in the chamber, the subjects were asked every 20 minutes to fill out the comfort questionnaire. After the first 80 minutes, he/she was asked to move away from the desk to allow physical measurements to be taken. The measurement cart was positioned where the subject had been sitting, and collected data for five minutes (*Figure 7*). When the measurements were complete, the subject returned to the desk for an exact repeat of the first 80 minutes, but this time without the step-climbing activity. This second period is characterized by a sedentary metabolic rate of 1.0 met (or 58.2 W/m^2). We analyzed only the last questionnaire for each activity level, the one just before the physical measurements were taken. This was done to assure that the subject had come to thermal steady state at the time of sampling.

Before leaving, the subjects were asked to write comments, if any, on any aspect of the experiment. The experimental protocol is summarized in *Figure 8*. The matrix of tests is shown in *Table 1*; temperature and fan mode were fixed for any given experiment.

Table 1

Matrix of Tests (each cell indicates the number of subjects tested)

Air Temp	Constant fan mode	Fluctuating fan mode
24 °C		6
25 °C		8
26 °C		12
27 °C	8	12
28 °C	12	13
29 °C	10	14
30 °C	10	11
31 °C	2	3

3.6 Design of the exercise routine

The first half of the tests was designed to equal the metabolic rate assumed in ASHRAE Standard 55, 1.2 Met. This represents a typical metabolic level found in office work, and probably represents an average domestic activity level as well. Since there does not seem to be a standardized approach to creating this particular metabolic rate in people, the following periodic exercise protocol was devised.

The subject's exercise protocol involved getting up from his/her seat once every ten minutes, moving to a nearby 0.2 meter step, and stepping up and down 12 times. The subject then returned to his/her seat. This is roughly equivalent to going up and down a residential flight of stairs every ten minutes, with sedentary spells in between. The metabolic activity generated by this exercise is estimated as follows:

70 kg person x 0.2 m/step x 12 steps = 168 kg·m. Assuming a muscular efficiency of 15%,
168 kg·m ÷ (η = 15%) = 1120 kg·m.
The thermal equivalent of this is: 120 kg·m ÷ 0.00274 W·h/kg·m ≈ 3.05 W·h/(12 step exercise).
At 6 exercises/hour, 6 x 3.05 = 18.3 W.
A sedentary metabolic rate is one Met, equal to 58 W/m^2 of body surface area. At 1.8 m^2 average surface area, one Met equals 104 W. Adding the metabolic rate associated with climbing,
(104 + 18.3) / 104 = 1.18 Met ≈ 1.2 Met

Two additional points might be made. First, the ASHRAE Handbook of Fundamentals [12] suggests subtracting out the mechanical work done from the metabolic heat generated in rising treadmill types of tests. By *not* subtracting it out for the rising steps, we should be accounting for the heat that is subsequently liberated in the body by the down-steps (mechanical work done *on* the body). This is probably the most realistic way to treat the down-steps that are inevitable for climbing stairs in a residential setting. Second, the initial getting up from the chair (and sitting down again) should be equal to one or two steps' worth of exercise.

This turned out to be a very convenient type of exercise for the subjects in the chamber. In a subsequent project, we measured the oxygen consumption of subjects performing the step exercise, and found that the above estimate of metabolic rate was very close when averaged over the 10 minute period. The instantaneous rate ranged between 1.75 to 1.0 met within the period (Bauman, Arens, et al, [13]).

4. RESULTS

4.1. Fan usage

Figures 9a and *9b* show the current draw (in amps) of the two fans being used concurrently. These examples are representative of typical usage found during the experiments. *Figure 9a* presents current draw for a constant fan speed experiment. Note that subject 'b' selected an air velocity at the beginning of the experiment and made no further adjustment of the environment for the remaining 2.5 hours. Subject 'a' ramped the air velocity up at the beginning and made several adjustments during the experiment. *Figure 9b* shows a similar situation for a fluctuating fan mode experiment. Here the fluctuating nature of the fan motor's operation is clearly shown, with the large periodic step change in velocity, occurring every two minutes.

4.2 Physical Environment

Table 2 presents a summary of the physical environmental variables that were measured by the mobile measurement cart for all 120 subjects.

Table 2

Physical Environment Summary

Statistics	Air Temperature 1.1 meters	Air Temperature 0.6 meters	Air Temperature 0.1 meters	Globe Temperature 1.1 meters	Globe Temperature 0.6 meters	Globe Temperature 0.1 meters
	deg. C	deg. C	deg. C	deg. C	deg. C	deg. C
Average	28.3	28.3	28.2	28.4	28.4	28.2
Maximum	32.0	31.8	31.1	32.0	31.8	31.1
Minimum	24.1	24.1	23.7	24.1	24.1	23.8
Std Dev.	1.59	1.58	1.55	1.59	1.58	1.55

Statistics	Air Velocity at 1.1 meters	Air Velocity at 0.6 meters	Air Velocity at 0.1 meters	Average Turbulence Intensity
	m/s	m/s	m/s	percent
Average	1.04	0.68	0.21	44
Maximum	1.62	1.14	0.32	100
Minimum	0.04	0.05	0.04	7
Std Dev.	0.41	0.27	0.06	24

Statistics	Dewpoint Temperature 0.6 meters	Relative Humidity 0.6 meters	Average Air Temperature	Average Operative Temperature
	deg. C	percent	deg. C	deg. C
Average	15.9	47.7	28.3	28.4
Maximum	19.2	54.7	31.6	31.6
Minimum	12.6	37.3	24.0	23.8
Std Dev.	1.6	2.6	1.57	1.57

At head level (1.1m) the maximum air velocity approached 2 m/s while the average of all cases was nearly 1 m/s. The air temperature was intentionally controlled at a level slightly lower than mean radiant temperature in order to smooth occupant-generated heat-load variations in the climate chamber with heating rather than cooling. Relative humidity was controlled around 50% for all tests. Turbulence intensities were typical for indoor conditions, with most ranging between 30% and 60% around an average of 45%.

4.3 Thermal sensation

Appendix A compiles the subjective responses and physical measurements for all subjects, together with the subjects' SET. It is organized by velocity mode, by activity level, and whether the subject is 'bothered by the air movement' (shaded areas). The description of these results follows.

Figure 10a shows the percentage of subjects (at 1.2 met activity) voting in each thermal sensation category in the fluctuating mode experiments. The category 'neutral' includes all thermal sensation votes from 'slightly cool' to 'slightly warm' (truncated at +/- 1.5). Below 27°C, some subjects registered votes below neutral, even though the fans were either off or on the lowest fan speed setting. At 27°C all subjects were in the neutral category while selecting a full range of fan settings. By 28°C, 75% were in the neutral category, with 25% on the warm side. At 29 and 30°C a small majority were neutral, and the subjects voting 'warm' were using fan levels 3 and 4. *Figure 10b* shows results for the constant mode at 1.2 met. Up to 29°C, less than 20% of the subjects found the environment warmer than neutral. At 30°C., however, over 30% percent found the environment more than 'slightly warm' although they were cooling themselves with the fan. At these higher temperatures, the fluctuating speed mode did not cool as many subjects as the constant speed mode. Presumably, this is mostly due to the lower maximum velocity of the fluctuating mode. However, there is evidence from the comments that subjects were more likely to be bothered by the more abrupt breeze changes produced by the fluctuating mode, and therefore turn the fan off or use lower settings even when they were feeling warm.

Figures 10c and 10d present the same data for the sedentary 1.0 met activity. Under these conditions the proportion of neutral responses was much greater, even at the highest temperatures. It is clear that under sedentary conditions, both fans provided more than 80% of the subjects with thermal neutrality.

Figure 11 presents the final physical condition selected by each subject together with his or her simultaneous thermal sensation vote, arranged in the categories described above. The mean velocities associated with each of the four fan speed settings in the constant and fluctuating modes are different, and allow the various settings and modes to be observed separately (e.g., 'c3', 'f4').

4.4 Thermal Preference

Figure 12 presents the subjects' thermal preferences ('I want to be warmer, cooler, no change') in the same format as *Figure 11*. The thermal preference scale inherently produces more 'non-neutral' responses than the thermal sensation scale represented in Figure 5. In offices, even at the neutral temperature, 40 % of a typical population will be outside the 'no change' category, with half preferring conditions to be warmer and half cooler (Schiller, et al., [14]). In comparison, at temperatures above 28°C in this experiment, 44% of all subjects at 1.2 met 'wanted to be cooler' while 6% wanted to be warmer; 22% of all subjects at 1.0 met wanted to be cooler while 4% wanted to be warmer.

4.5 Air Movement Preference

Figure 13 presents the subjects' air movement responses in the same format. The desire for *more* air movement is scattered rather broadly on both axes of the graph. It was expressed more often for the fluctuating mode than the constant mode. A preference for more air movement might suggest that the fan is incapable of providing more air. It might also suggest that the subject set the fan at a level that was the maximum acceptable for other reason (such as noise or distraction), and that this level was insufficient to provide the necessary cooling. These fans provided somewhat lower maximum velocity than in Kubo's and Tanabe's experiments, where higher velocities were selected. The desire for *less* air movement appears on the figure in two general locations: for the lower temperatures in the 1.2 met tests, and for subjects in the highest temperatures at either activity, who were choosing the highest velocity settings.

4.6 Perception of air movement

Roughly 35% of the subjects overall reported that they were 'bothered by the air movement' at least one of the repeated comfort questionnaires. The majority of these reports were concentrated at the higher temperatures, where the fan speed setting was usually either 3 or 4. The 'bothered' comments have a strong tendency to come at the beginning of the experiment, when the metabolic activity is higher. The majority of comments improved as the experiment went on, dramatically so with the constant speed mode. This is significant because initial sensations like 'dry eyes' and 'one side is cold' got better with time rather than worse. The fluctuating mode did not improve as much over time. Comments cited 'surges,' inconsistency,' 'gusts,' 'distraction,' and blowing papers; a small number were favorable saying the wind felt 'natural' or 'like out of doors'.

This picture is supported by the exit comments, listed in *Appendix B*. In these, 18% of the fluctuating and 10% of the constant mode subjects made comments that could be construed as critical of the air movement. This is notable in that the constant experiments were done only at higher temperatures. The highest temperature where favorable comments about fluctuating air flow were recorded was 27.4°C and the lowest temperature where unfavorable comments about fluctuating air flow were recorded was also 27.4 C.

Interestingly, more subjects in the constant mode experiments mentioned thermal asymmetry than the fluctuating mode. The fluctuations might have reduced the subjects' perception of the asymmetry. On the other hand, it may be due to the lower mean velocities provided in the fluctuating mode. There was no significant difference in the air movement preferences between subjects who reported differences in thermal comfort votes for the different parts of their body and those who did not.

Some subjects mentioned controllability of the fan in the constant fan speed mode. One reason given was that there was big difference in average velocity between level 3 and level 4. At the highest temperatures, even the level 4 was not enough and that also contributed to a feeling of lack of controllability.

4.7 Sensations on different body areas

The subjects considered their head area the coolest overall. This might be expected since the head is unclothed, is immersed in the strongest airstream, and has the highest skin thermal sensitivity. There was a difference in perceived temperature between the lower body and upper body, with the lower body being perceived as the warmer, also because the airstream is weaker there. Since thermal environments that produce a cool head and warm feet are generally preferred and sometimes difficult to obtain with a conventional air conditioning, the test conditions might be considered a favorable ventilation arrangement.

The percentage of all subjects in each temperature bin who perceived a side-to-side difference in thermal comfort is shown in *Figure 14a* for the upper body segments and *Figure 14b* for the lower segments. They are grouped into two fan speed levels. Asymmetry can be found at low temperatures at low fan speeds (associated with a perception of draft) and at the highest speeds at high temperatures, both predominantly for the upper body segments.

This raises the question whether the asymmetry in thermal comfort was regarded by the subjects as bothersome. There is also a question whether the response would have been different if people were calling for more or less air movement--i.e., if their asymmetry was due to one of their sides being overheated or overcooled. *Table 3* combines the subjects' votes on air movement preference (want less, no change, more), and whether the air movement bothers them in any way, for those who observed a side-to-side asymmetry in comfort versus those who did not. Interestingly, there is no significant difference for the 'want less' or 'no change' preference categories between the asymmetric and symmetric. However, those calling for more air movement were more prone to be voting that they are bothered by the air movement when they felt thermally symmetrical. These are primarily people experiencing the fluctuating mode: the reduction in asymmetry may be due to lower mean velocities provided by the fan in that mode.

Table 3

Effects of Comfort Asymmetry on Air Movement Perception and Preference

Upper Part of Body

	Asymmetric		Symmetric		Subtotal	Grand Total
Air Movement Preference	bothered	not bothered	bothered	not bothered		
• want less air movement	44%	3%	44%	8%	100%	36
• no change	7%	16%	12%	64%	100%	164
• want more air movement	12%	18%	38%	32%	100%	34

Lower Part of Body

	Asymmetric		Symmetric		Subtotal	Grand Total
Air Movement Preference	bothered	not bothered	bothered	not bothered		
• want less air movement	17%	0%	72%	11%	100%	36
• no change	2%	7%	18%	73%	100%	164
• want more air movement	6%	12%	44%	38%	100%	34

5. ANALYSIS

5.1 Comparison with computer comfort model results

The indices TSENS (Gagge et al. [15]) and PMV (ISO [16]) have scale values equal to the thermal sensation scale used on the comfort questionnaires. The indices were computed for each subject's exposure and compared to the votes measured by the questionnaires. 9.2% of this experiment's observations were outside the neutral band of +/-1.5 thermal sensation. In comparison, TSENS predicted 0.4%, and PMV 9.7%.

The experimental results were also compared to the comfort zone extension shown in Figure 3 of ASHRAE Standard 55 92. Since the boundaries of the comfort zone also represent the +/- 1.5 thermal sensation boundaries, one can compare the percentage of points falling outside the boundaries of the comfort zone with the percentage of people who voted uncomfortable. The curves in ASHRAE's Figure 3 are started from 26° ET* to make the warm boundary of the summer comfort zone, and from 23 ° ET* to make the cold boundary. In both the 1.2 met and 1.0 met tests, 4% of total subjects were to the outside of the cold boundary of the comfort zone, and the rest (38% and 47% respectively) were outside the warm boundary. If one includes on top of this the limit of 0.8 m/s recommended by the Standard 55 as the maximum for sedentary activity, the percent of subjects outside the comfort zone climbs to 68% at 1.2 met, and 75% at 1.0 met. The Standard 55 comfort zone overestimates the discomfort reported by these subjects.

5.2 Comparison with the draft limit.

Figures 11, 12, and 13 show the velocities chosen by the subjects under various temperatures, including those covered by the draft limit (Fanger et al. [17]) that has been incorporated into ASHRAE 55-92. This limit, labeled 'PD' is shown for comparison on the figures (velocities above the line exceed the limit of 15% uncomfortable due to draft). Clearly, the velocities chosen by the subjects exceed the allowable limits in the great majority of cases, including cases where they register being cool. The draft limit is however designed only to protect the most draft-sensitive 15% of the population, and in this experiment the number of subjects choosing velocities below the limit does approximate 15%.

5.3 Analysis of thermal sensation

A linear regression of thermal sensation as a function of air temperature found a slope (for 1.2 met) of one scale value of thermal sensation to 3.5°C. in air temperature. At 1.0 met, one scale value spanned over 6°C. A typical value for this slope found in most field and laboratory studies of thermal comfort near the center of the comfort zone (without the subject having control of air movement) is 3°C per scale unit. The flatter slopes observed in this study show that people can widen their comfort zone with air movement that is under their control. The neutral temperature of the regression was 25.5°C for 1.2 met activity, and 27.5°C for 1.0 met.

5.4 Significant differences between groups

Tests were done to determine whether significant differences existed between groups and categories in the experiments. T-tests were used for continuous variables such as measured air velocity and thermal sensation votes, and Mann-Whitney's test was used for the category variables such as thermal and air movement preference, fan setting, present feeling, and air movement acceptability. The groups that yielded significant differences were gender, metabolic activity level, and whether a constant speed or fluctuating fan was used. *Table 4* shows the groups, the parameter that separated the groups, which group yielded the higher parameter value, and the significance level.

HVAC engineers commonly note that females feel drafts and complain about them more often than males. The data from *Table 4* suggest in addition that females require less air movement to be comfortably cooled at elevated temperatures. Both the air movement preference responses and the measured values of preferred air velocity support this assertion. Higher metabolic activity as might be expected produced the desire for lower temperature and increased air movement.

Table 4
Significant differences between groups

Group	Significant measured variable	Group that had the higher value of the significant variable	Significance level (to better than)
Gender	Preferred air velocity	Males (higher velocity)	10%
Gender	Air movement preference	Males (want more velocity)	5%
Met	Air movement acceptability	1.2 met (less vote accept'l)	5%
Met	Thermal sensation	1.2 met (feel warmer)	1%
Met	Thermal preference	1.2 (want to be cooler)	1%
Met	Present feeling	1.2 met (feel warmer than comfortable)	2%
Met	Fan setting	1.2 (fan setting higher)	10%
Met	Measured air velocity	1.2 (air velocity higher)	10%
Const/Fl	Measured air velocity	Constant (higher mean velocity)	5%
Const/Fl	Air movement preference	Fluctuating (want more air movement)	5%

The division for the constant versus fluctuating fan is also not straightforward. The subjects with the constant speed mode chose higher velocities that those with the fluctuating mode, which may simply result from the fluctuating fan's lower top speed limiting the velocity available. This interpretation is supported by the observation that people who were using fluctuating fans stated a preference for more air movement more often than those who were using constant speed fans, and also felt warmer. On the other hand, this effect could have occurred because the velocity fluctuations were irritating to subjects, causing them to limit for non-thermal reasons the amount of airflow that they need to remain comfortable. This interpretation is supported by the larger number of subjects who commented about the fluctuating air flow in both the comfort survey and the exit survey. There is another fluctuation mechanism that might warrant further investigation. Fanger et al. [17] suggested that fluctuating fans provide greater cooling than constant speed fans, especially if the frequencies peak in the 1 Hz range. This effect has been corroborated by Ring et al. [18] by simulating the effect of depth of thermoreceptors on transient warmth and cold perception. Because the cold receptors are closer to the surface, they are stimulated to report cooling at higher frequencies (around 1or 2 Hz) than the deeper warm receptors (around 0.2 Hz). The constant speed mode of the fans in this experiment produce turbulence peaking between 0.7 and 1 Hz, and in theory should therefore cool better at a given speed than the fluctuating mode that peaks around 0.2 or 0.3 Hz. It may not be possible to find this effect in this data set because of the confounding effect of the fan modes' differing wind speeds.

5.5 The zone of likely use

A 'zone of likely use' (*Figure 15*) is proposed for locally controlled air movement in a residential setting. The concept is intended to define the conditions within which fans or naturally-produced air movement will cause a substantial fraction of occupants to be sufficiently comfortable that one could reasonably expect them to rely on air-movement cooling rather than resort to air conditioning. It may have applicability to the design of task-ambient air conditioning as well.

Figure 15 includes for comparison two air movement recommendations drawn from existing literature on thermal comfort, Scheatzle et al. [5], and Fountain et al. [19]. The zone from Scheatzle is very close to the ZLU at the warm side, but the ZLU extends one degree to the left on the cold side, since we observed subjects using fans throughout that region. The Schaetzle zone is quite similar to the others by Rohles and Wu (not shown). The PS ('percent satisfied' index) from Fountain, representing 85% satisfied below the curve, cuts across the left third of the ZLU. The velocities referred to by the PS index are for air jets that are more local on the body than the air movement produced by the fans in this experiment or by the ceiling fans in Schaetzle's. They may therefore be expected to have lower acceptable maximums than those in this experiment, where the moving air covered larger parts of the body. Taken together, these studies support the zone's boundaries.

6. CONCLUSIONS

In conclusion, it is possible to maintain comfortable conditions in a residential setting up to 31°C if air velocity of 1 m/s is available over the upper body. The zone within which substantial numbers of subjects were comfortable was put into a 'zone of likely use' for fans, which matched the findings of previous studies that included ceiling fans and oscillating fans. Although males tended to want more air velocity than females, the zone applies to both genders. The zone should apply for time spans of at least three hours, the duration of these tests.

Because the fans provided a lower maximum air velocity over a somewhat more confined body area than the fans used by Kubo et al. and Tanabe et al., there is a higher percentage of subjects voting warm and preferring more air movement than reported from their studies. In this respect these tests are conservative. They are also conservative for residences because they forced the subjects to be in a fixed orientation relative to the air flow throughout the test. The freedom to move one's position would clearly have alleviated some of the discomfort symptoms reported. This may not be a conservative assumption for offices, however.

The fluctuating fan produced significantly more 'bothered responses both in the surveys and in the exit comments. Distraction, disturbed hair, and eye irritation were noted, the latter presumably due to shortened eye-film breakup time. Given that the 'constant' speed mode in fact fluctuated to a similar extent as the 'fluctuating' mode but with less abrupt swings from extreme to extreme, it appears that the nature of the fluctuation is important. This supports findings by Tanabe and Kimura [6]. Fluctuating fan controllers might best provide smoother sinusoidal transitions.

The effects of metabolic rate are noticeable in the results, with higher cooling rates demanded of the fans at 1.2 met versus 1.0 met. An exercise method was devised to simulate the 1.2 met rate of Standard 55. This procedure, based on an assumption of 15% muscular efficiency, was supported by limited respired oxygen measurements. It simulates the realistic effect of climbing a flight of stairs, or of getting up and moving about, and is practical to administer in the laboratory.

The study supports the finding of Tanabe et al. and Kubo et al. that calculated SET* predicts values higher than 26° for temperature-velocity combinations that are being selected by the subjects and rated as thermally neutral. Tanabe suggested the predicted values might be lowered the correct amount by adjusting the minimum skin wettedness parameter from 0.06 to 0.03 to represent the drying effect of air movement. We intend to investigate this suggestion with these data.

ACKNOWLEDGEMENTS

The authors would like to thank Adil Sharag-Eldin for the spectral analysis of the fan, and Richard de Dear and Takashi Akimoto for their assistance with the experiment and paper. The work was supported by CIEE, a research unit of the University of California. Publication of research results does not imply CIEE endorsement or agreement with these findings, nor that of any CIEE sponsor.

REFERENCES

[1]ASHRAE. 1992, *Standard 55-92: Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

[2]Rohles, F., Woods, J., and Nevins, R., 1974. "The effects of air movement and temperature on the thermal sensations of sedentary man." *ASHRAE Transactions*, Vol. 80, Pt. 1, pp. 101-119.

[3]Rohles, F., Konz, S., and Jones, B., 1983. "Ceiling fans as extenders of the summer comfort envelope." *ASHRAE Transactions*, Vol. 89, Pt. 1, pp. 245-263.

[4]Spain, R.S., 1984. "Energy savings in buildings using fans and allowing floating temperatures in rooms," Ph.D. dissertation, Department of Architecture, Texas A&M University.

[5]Schaetzle, D., Wu, H., and Yellot, J. 1989. "Extending the summer comfort envelope with ceiling fans in hot, arid climates." *ASHRAE Transactions*, Vol. 95 Pt. 1.

[6]Wu, H. 1989. "The use of oscillating fans to extend the summer comfort envelope in hot arid climates," *Proceeding of the Second ASHRAE Far East Conference on Air Conditioning in Hot Climates*, Kuala Lumpur, Malaysia, 20 pp.

[7]Kubo, H., Isoda, N., and Yanase, T., 1992. "The effects of preferred air velocity on the human body in muggy conditions," *Journal of Architecture, Planning, Environmental Engineering; (Transactions of the AIJ)*, No. 442.

[8]Tanabe, S. and Kimura, K. 1994. "Effects of air temperature, humidity, and air movement on thermal comfort under hot and humid conditions," *ASHRAE Transactions*, Vol. 100 Pt. 2, 16 pp.

[9]Bauman, F. and Arens, E. 1988. "The development of a controlled environment chamber for physical and subjective assessment of human comfort in office environments," *Proceedings: International Symposium on Advanced Comfort Systems for the Work Environment*, May 1-3, Troy, New York, Rensselaer Polytechnic Institute

[10]Engineering Science Data Units, 1985. "Characteristics of atmospheric turbulence near the ground," ESDU International Ltd. Item No. 85020, London.

[11]Benton, C.C., Bauman, F.S., and Fountain M.E., 1991. "A field measurement system for the study of thermal comfort," *ASHRAE Transactions*, Vol. 96 Pt. 1.

[12]ASHRAE. 1989, *Handbook of Fundamentals*. Atlanta: American Society of Heating, Refrigeration, and Air-Conditioning Engineers

[13]Bauman, F., Arens, E., Akimoto T., Miura, K., and Xu, T. In press. "The impact of relative humidity standards on energy efficient cooling strategies in California," Final Report for CIEE Exploratory Project, Center for Environmental Design Research, University of California, Berkeley.

[14]Schiller, G.E., Arens, E.A., Benton, C.C., Bauman, F.S., Fountain, M.E., and Doherty, T.J., 1988. "A field study of thermal environments and comfort in office buildings," *ASHRAE Transactions*, Vol. 94 Pt. 2.

[15]Gagge, A.P., Fobelets, A., and Berglund, L., 1986. "A standard predictive index of human response to the thermal environment," *ASHRAE Transactions*, Vol. 92, Pt. 2.

[16]ISO. 1984. *Standard 7730*, "Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort." Switzerland

[17]Fanger, P.O., Melikov, A., Hanzawa, H., and Ring J., 1988. "Air turbulence and sensation of draught," *Energy and Buildings*, Vol. 12, pp. 21-39.

[18]Ring, J.W., de Dear, R., and Melikov, A., 1993. "Human thermal sensation: frequency response to sinusoidal stimuli at the surface of the skin," *Energy and Buildings*, Vol. 20, pp. 159-165.
[19]Fountain, M.E., Arens, E., deDear, R., Bauman, F., and Miura, K., 1994. "Locally controlled air movement preferences in warm isothermal environments," *ASHRAE Transactions*, Vol. 100 Pt. 2, 14 pp.

Appendix A: Summary of Survey Responses

Organized by Velocity Mode, Activity Level, and Whether the Subject is 'Bothered by the Air Movement' (Shaded Areas)

High Activity, Constant Fan Mode

Subject ID No.	Bothered by Wind	Air Movement Preference	Fan Level	Air Temp	SET	Thermal Sensation	Thermal Preference	Head	L-upper	R-upper	L-lower	R-lower
	1=yes 2=no	1-want less 2-no change 3-want more	1=low 4=high	°C	°C	cold-hot (-3,3)	1-want warmer 2-no change 3-want cooler	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold
49	1	1	4	30.7	28.4	2.0	3	2	2	2	2	2
50	1	1	4	30.6	28.3	0.0	2	1	2	1	2	1
56	1	1	4	27.6	25.3	1.0	3	2	1	1	2	2
57	1	1	3	27.1	25.2	1.0	3	2	3	2	1	1
83	1	1	4	29.0	26.8	1.5	3	3	2	2	2	2
101	1	1	4	30.0	27.7	1.5	3	2	1	2	1	2
110	1	1	4	28.2	25.9	0.2	3	1	1	1	1	1
111	1	1	2	29.2	27.5	0.0	2	1	1	1	1	1
114	1	1	3	26.6	24.5	0.5	3	2	2	2	2	2
53	1	2	2	28.0	26.8	0.1	2	1	1	1	2	2
55	1	2	3	28.4	26.5	0.0	2	1	1	1	1	1
59	1	2	3	27.2	25.3	0.0	3	1	1	2	2	2
60	1	2	2	27.0	26.0	-0.5	2	1	1	3	1	1
62	1	2	3	27.7	26.2	-0.1	2	1	1	1	1	1
94	1	2	4	29.9	27.2	1.0	3	2	1	1	2	2
96	1	2	4	29.7	27.3	0.8	3	1	1	1	2	2
97	1	2	3	29.8	27.7	1.0	2	1	1	1	2	2
108	1	2	2	28.7	27.4	0.6	2	1	1	1	2	2
61	1	3	3	28.2	26.2	1.1	3	1	1	2	2	2
90	1	3	1	28.2	28.3	0.7	2	1	1	1	1	1

112	1	3	4	29.0	26.3	1.0	2	1	1	1	1	1
91	2	1	4	27.4	25.2	0.0	2	1	1	2	1	1
98	2	1	3	29.8	27.8	1.0	3	1	1	1	1	1
51	2	2	2	30.2	29.0	1.0	3	2	1	2	2	2
52	2	2	3	30.7	28.7	0.5	2	1	1	1	2	2
54	2	2	4	27.9	25.6	0.3	2	1	1	1	2	2
58	2	2	3	26.9	25.1	1.0	2	1	1	1	1	1
79	2	2	3	28.9	27.2	0.0	2	1	2	1	1	1
81	2	2	4	29.0	26.9	1.0	1	1	1	1	2	2
82	2	2	4	28.6	26.3	1.0	2	1	1	1	1	2
89	2	2	3	27.8	25.9	0.5	2	1	1	1	1	1
95	2	2	2	29.1	27.5	1.0	3	2	2	1	1	1
99	2	2	2	29.5	28.2	2.0	3	2	2	2	2	2
100	2	2	4	29.8	27.4	2.0	3	2	1	1	2	2
102	2	2	4	30.3	27.9	1.0	3	2	2	1	2	1
106	2	2	4	29.1	26.7	0.5	3	1	1	2	2	2
109	2	2	4	28.0	25.7	1.5	3	1	1	2	1	2
113	2	2	2	27.7	26.4	0.0	2	1	1	1	1	1
115	2	2	2	27.5	26.1	0.5	2	1	1	1	2	2
116	2	2	2	27.1	25.9	1.0	2	2	1	1	1	1
105	2	3	2	29.1	27.8	1.0	3	1	1	1	2	2
107	2	3	4	29.2	26.9	1.5	3	2	2	2	2	2
117	2	3	3	26.8	24.9	0.2	2	1	1	1	1	1

Low Activity with Constant Fan Mode

Subject ID No.	Bothered by Wind	Air Movement Preference	Fan Level	Air Temp	SET	Thermal Sensation	Thermal Preference	Head	L-upper	R-upper	L-lower	R-lower
	1=yes 2=no	1-want less 2-no change 3-want more	1=low 4=high	°C	°C	cold-hot (-3,3)	1-want warmer 2-no change 3-want cooler	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold
82	1	1	3	28.6	26.0	0.0	2	1	1	1	1	1
83	1	1	4	29.0	26.0	1.0	3	2	1	3	1	1
91	1	1	4	28.2	25.2	-0.2	2	1	3	1	1	1
57	1	2	1	26.7	25.7	-1.0	2	1	1	1	1	1
59	1	2	3	27.1	24.4	-0.5	2	1	1	1	1	1
81	1	2	3	29.3	26.7	1.0	3	1	1	1	2	2
90	1	2	1	28.1	27.0	0.0	2	1	1	1	2	2
96	1	2	4	29.6	26.6	0.0	2	1	1	1	1	1
95	1	3	2	30.2	27.7	0.0	2	1	1	1	1	1
56	2	1	3	28.3	25.6	0.0	2	2	1	1	2	2
114	2	1	1	26.9	25.7	-2.0	2	1	1	1	2	2
49	2	2	3	30.9	28.3	1.0	3	2	2	2	2	2
50	2	2	4	30.6	27.5	0.5	3	1	2	1	2	2
52	2	2	3	30.4	27.6	0.0	3	2	1	1	2	2
53	2	2	2	28.0	26.0	0.0	2	1	1	1	1	1
54	2	2	0	28.0	28.6	-	3	1	1	1	1	1
55	2	2	3	27.9	25.3	0.0	2	1	1	1	1	1
58	2	2	3	26.7	24.2	0.0	2	1	1	1	1	1
60	2	2	2	27.2	25.2	0.0	2	1	1	1	1	1
61	2	2	3	27.9	25.2	0.0	2	1	1	1	1	2
62	2	2	3	27.6	25.0	-1.0	2	1	1	1	1	1
79	2	2	4	29.0	26.0	-1.0	2	1	1	1	1	1
89	2	2	3	28.1	25.3	1.0	3	2	1	1	1	1
94	2	2	4	30.1	26.7	2.0	2	1	1	1	1	1
97	2	2	3	29.5	26.8	0.0	2	1	1	1	1	1

98	2	2	3	30.0	27.2	-0.5	2	1	1	1	1	1
99	2	2	2	29.8	27.7	0.0	2	1	1	1	2	2
100	2	2	4	29.8	26.8	1.0	3	2	1	1	1	1
101	2	2	4	29.7	26.6	0.0	3	1	1	1	1	1
102	2	2	4	29.7	26.7	0.0	2	1	2	1	1	1
105	2	2	3	29.1	26.4	0.0	2	1	1	1	1	1
106	2	2	4	28.9	25.8	0.0	2	1	1	1	1	1
107	2	2	4	28.6	25.7	1.6	3	2	2	2	2	2
108	2	2	2	29.0	26.9	0.0	2	1	1	1	1	1
109	2	2	4	27.8	24.7	-1.0	2	1	3	1	1	3
110	2	2	2	27.8	25.8	-1.0	2	1	1	1	1	1
111	2	2	1	28.5	27.2	-1.0	2	1	1	1	1	1
112	2	2	4	28.9	25.6	0.0	2	1	1	1	1	1
113	2	2	1	27.2	26.1	0.0	2	1	1	1	1	1
115	2	2	2	27.5	25.5	0.0	2	1	1	1	1	1
116	2	2	2	26.8	24.7	-1.0	2	1	1	1	1	1
117	2	2	2	27.1	25.0	0.0	2	1	1	1	1	1
51	-	1	3	30.3	27.7	0.6	3	1	1	2	2	2

High Activity with Fluctuating Fan Mode

Subject ID No.	Bothered by Wind	Air Movement Preference	Fan Level	Air Temp	SET	Thermal Sensation	Thermal Preference	Head	L-upper	R-upper	L-lower	R-lower
	1=yes 2=no	1-want less 2-no change 3-want more	1=low 4=high	°C	°C	cold-hot (-3,3)	1-want warmer 2-no change 3-want cooler	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold
9	1	1	0	26.9	27.9	-0.2	1	1	1	1	1	1
12	1	1	3	27.4	26.1	1.0	3	2	2	2	2	2
23	1	1	4	30.3	28.4	0.5	2	1	1	1	1	1
35	1	1	4	28.9	26.9	1.2	2	1	2	1	2	2

38	1	1	3	28.8	27.7	1.5	3	2	2	2	2	2
40	1	1	4	29.3	27.2	0.5	2	2	1	1	1	1
63	1	1	1	26.1	25.5	1.5	2	1	1	1	1	1
66	1	1	4	26.4	24.6	1.5	3	1	1	2	1	2
70	1	1	1	25.6	25.3	1.0	3	2	1	1	2,3	-
73	1	1	1	24.8	24.3	-1.0	1	3	3	1	1	1
76	1	1	3	24.8	23.9	-0.5	2	1	1	3	1	3
88	1	1	0	25.4	26.2	0.0	2	1	1	3	1	1
1	1	2	3	26.6	25.3	1.0	3	1	1	1	2	2
19	1	2	4	29.3	27.3	1.2	3	1	1	2	2	2
22	1	2	4	30.4	28.2	1.0	3	1	2	2	1	1
26	1	2	3	30.3	28.9	1.0	3	1	2	2	1	2
34	1	2	4	29.1	26.9	1.5	3	1	1	2	1	1
37	1	2	4	29.3	27.5	2.4	3	2	2	2	2	2
46	1	2	4	28.3	26.7	0.7	2	1	1	1	2	2
77	1	2	1	25.5	25.0	-1.5	1	1	3	1	1	1
87	1	2	1	25.4	24.8	-2.0	1	1	3	1	1	1
118	1	2	3	26.3	25.1	-2.0	1	1	3	1	3	1
119	1	2	3	26.2	25.0	1.5	2	1	1	3	1	1
25	1	3	4	30.2	28.3	1.5	3	2	2	2	2	2
27	1	3	4	30.3	28.6	3.0	3	2	2	2	2	2
30	1	3	4	27.9	25.9	1.5	3	2	2	1	2	1
31	1	3	3	28.1	26.7	0.9	3	2	1	1	1	2
32	1	3	4	28.1	26.2	1.2	3	2	2	2	2	2
39	1	3	4	28.6	26.6	2.3	3	2	2	2	2	2
45	1	3	4	28.1	26.2	2.1	3	2	1	1	2	2
103	1	3	3	30.0	28.6	1.0	2	1	1	1	2	2
104	2	1	4	29.8	27.9	1.0	3	1	1	1	2	2
2	2	2	2	27.0	26.1	0.0	2	1	1	1	1	1
3	2	2	2	27.0	26.0	0.0	2	1	1	1	1	1
4	2	2	1	27.1	26.5	0.0	2	1	1	1	2	1
5	2	2	3	26.5	25.4	0.9	3	2	1	2	1	2
7	2	2	4	26.4	24.6	0.0	2	1	1	1	1	1

8	2	2	0	26.7	27.6	0.0	2	1	1	1	1	1
10	2	2	2	26.8	26.1	-0.9	2	2	1	3	1	1
11	2	2	4	27.4	25.4	0.5	2	1	1	1	1	1
15	2	2	1	27.8	27.4	0.0	2	1	1	1	1	1
16	2	2	3	26.4	25.1	0.8	2	1	1	1	1	1
17	2	2	3	29.0	27.6	0.1	2	1	1	1	1	1
18	2	2	4	29.1	27.1	0.1	2	3	1	1	3	1
20	2	2	3	29.5	28.1	1.0	3	2	1	1	2	2
24	2	2	4	30.3	28.4	1.0	3	1	1	2	2	2
29	2	2	3	27.9	26.6	1.0	3	1	1	2	2	2
33	2	2	1	27.7	27.1	0.0	2	1	2	2	1	1
36	2	2	1	29.3	28.5	0.3	2	1	1	1	1	1
41	2	2	3	29.4	28.0	1.0	2	1	3	1	2	2
42	2	2	4	29.3	27.3	0.5	3	1	1	1	2	2
44	2	2	3	27.5	26.2	0.2	3	1	1	1	2	2
47	2	2	3	28.9	27.4	0.3	2	1	3	1	1	2
48	2	2	4	27.9	26.1	1.0	3	2	2	1	1	1
64	2	2	3	26.2	24.9	0.5	1	3	3	3	1	1
65	2	2	3	25.6	24.4	0.0	2	1	1	1	1	1
67	2	2	1	26.1	25.4	-0.7	2	1	1	1	1	1
68	2	2	1	25.5	25.0	-0.5	2	1	1	1	1	1
69	2	2	3	25.7	24.4	1.0	2	1	1	1	2	2
71	2	2	3	26.8	25.4	0.3	2	1	1	1	1	1
72	2	2	3	26.4	25.2	0.0	2	1	1	1	1	1
74	2	2	2	24.8	24.1	-1.0	2	1	1	3	1	1
78	2	2	3	25.4	24.2	1.2	2	2	2	1	1	1
84	2	2	2	25.0	24.1	0.2	2	1	1	1	1	1
85	2	2	4	24.1	22.4	0.2	2	3	1	1	3	3
86	2	2	3	24.4	23.4	0.0	2	1	2	1	2	1
92	2	2	4	28.0	26.0	0.0	2	1	1	1	1	1
6	2	3	4	27.0	25.2	1.0	2	1	1	1	2	2
13	2	3	4	31.1	29.0	1.7	3	2	2	2	2	2
14	2	3	4	31.6	29.3	2.0	3	2	2	2	2	2

21	2	3	3	30.1	28.8	0.5	2	1	2	1	1	1
43	2	3	3	28.4	27.0	0.3	2	1	1	1	2	1
75	2	3	2	25.8	24.9	1.0	2	1	1	2	1	2
80	2	3	3	29.2	27.9	1.5	2	1	2	2	2	2
93	2	3	2	27.9	26.7	0.7	3	1	1	2	1	1
28	2	-	4	30.0	28.0	1.8	3	2	1	2	2	2

Low Activity with Fluctuating Fan Mode

Subject ID No.	Bothered by Wind	Air Movement Preference	Fan Level	Air Temp	SET	Thermal Sensation	Thermal Preference	Head	L-upper	R-upper	L-lower	R-lower
	1=yes 2=no	1-want less 2-no change 3-want more	1=low 4=high	°C	°C	cold-hot (-3,3)	1-want warmer 2-no change 3-want cooler	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold	1=comft 2=warm 3=cold
5	1	1	4	27.0	24.2	0.2	3	1	1	1	2	2
12	1	1	3	27.1	25.0	-1.0	2	1	1	3	1	1
26	1	1	4	30.7	27.9	-1.0	2	1	3	1	3	1
33	1	1	1	27.7	26.0	-1.0	2	1	3	1	1	1
34	1	1	4	28.8	26.0	1.9	3	1	2	2	2	2
38	1	1	3	28.7	26.6	0.5	3	1	1	2	2	2
40	1	1	3	28.7	26.6	0.2	2	1	3	1	1	1
66	1	1	4	26.1	23.5	1.0	3	1	1	2	1	2
6	1	2	4	26.3	23.8	0.0	2	1	1	1	2	2
17	1	2	3	29.8	27.5	0.7	2	1	1	1	1	1
37	1	2	3	27.7	25.9	1.5	3	1	2	1	2	2
46	1	2	3	27.8	25.6	-0.6	2	1	1	3	1	1
70	1	2	-	24.9	23.8	0.0	2	1	1	1	1	1
77	1	2	1	23.7	22.2	-2.0	1	1	3	1	3	1
87	1	2	1	24.2	22.6	-1.0	2	1	3	1	1	1

30	1	3	3	26.8	24.9	-0.2	2	1	1	3	1	1
31	1	3	3	28.0	25.8	1.0	2	2	1	1	1	1
32	1	3	4	27.7	25.1	1.1	3	2	2	2	2	2
45	1	3	4	28.5	25.6	2.0	3	2	1	2	2	2
76	1	3	0	24.9	25.4	0.5	2	1	2	2	2	2
29	1	Only want less fluctuation	3	28.0	25.8	0.4	2	1	1	1	1	2
1	2	2	3	27.7	25.5	0.0	2	1	1	1	1	1
2	2	2	2	27.9	26.1	0.0	2	1	1	1	1	1
3	2	2	2	25.2	23.3	0.0	2	1	1	1	1	1
7	2	2	4	26.7	24.1	0.0	2	1	1	1	1	1
8	2	2	0	27.0	27.6	-1.0	2	1	1	1	3	3
9	2	2	0	27.1	27.7	0.0	2	1	1	1	1	1
10	2	2	2	26.9	25.2	-1.2	2	1	3	3	1	1
11	2	2	1	27.4	25.8	-0.5	2	1	1	1	1	1
13	2	2	4	28.5	25.9	-0.2	2	1	1	1	1	1
14	2	2	4	28.8	26.1	0.0	2	1	1	1	1	1
15	2	2	1	30.2	28.3	0.0	2	1	1	1	1	1
16	2	2	3	28.6	26.6	0.9	3	1	1	1	1	1
18	2	2	4	29.1	26.4	0.0	2	1	3	1	3	1
19	2	2	4	29.4	26.7	-0.4	2	1	1	1	1	1
21	2	2	4	31.0	28.2	0.9	3	1	2	1	1	1
22	2	2	3	29.9	27.7	0.0	-	1	1	1	1	1
23	2	2	3	29.7	27.7	0.2	2	1	1	1	1	1
24	2	2	4	30.0	27.3	0.5	3	1	1	1	2	2
25	2	2	4	29.8	27.2	1.5	3	1	2	1	2	2
35	2	2	3	29.1	26.7	0.5	2	1	1	1	1	1
36	2	2	3	28.8	26.5	0.1	2	1	1	1	1	1
41	2	2	0	28.5	29.2	0.0	2	1	1	1	2	2
42	2	2	4	29.5	26.9	0.1	2	1	1	1	1	1
43	2	2	3	27.9	25.7	-0.4	2	1	1	1	1	1
44	2	2	3	28.7	26.5	0.0	2	1	1	1	1	1
47	2	2	3	27.9	25.7	0.2	2	1	1	2	1	2

48	2	2	2	28.3	26.4	-1.1	2	1	1	1	3	3
63	2	2	1	25.9	24.4	1.4	2	1	1	1	1	1
64	2	2	2	25.9	24.2	-0.3	1	1	1	3	3	3
65	2	2	3	25.8	23.6	-0.8	2	1	1	1	1	1
67	2	2	1	25.2	23.9	-1.0	2	1	1	3	1	1
68	2	2	0	26.1	26.6	0.0	2	1	1	1	1	1
69	2	2	2	26.1	24.3	-1.0	2	1	1	1	1	1
71	2	2	3	26.6	24.6	0.0	2	1	1	1	1	1
72	2	2	1	27.0	25.4	0.1	2	1	1	1	1	1
73	2	2	0	24.5	25.1	-0.2	1	3	1	1	1	1
74	2	2	1	25.2	23.8	0.0	2	1	1	1	1	1
78	2	2	0	24.7	25.3	0.0	2	1	1	1	1	1
80	2	2	3	29.5	27.1	0.0	2	1	1	1	2	2
84	2	2	0	24.7	25.1	0.1	2	2	1	1	1	1
85	2	2	1	24.5	22.9	0.0	2	1	1	1	1	1
86	2	2	2	24.3	22.8	0.0	2	1	2	1	1	1
88	2	2	0	24.0	24.4	0.0	2	1	1	1	1	1
92	2	2	4	28.2	25.5	0.0	2	2	2	1	1	1
93	2	2	0	27.5	28.1	0.1	2	1	1	1	1	1
103	2	2	3	29.7	27.5	0.2	2	1	1	1	1	1
104	2	2	4	29.9	27.1	0.0	2	1	1	1	1	1
118	2	2	1	26.1	24.6	0.0	2	1	1	1	1	1
20	2	3	3	31.3	29.1	1.0	3	2	2	2	2	2
27	2	3	4	30.7	28.1	2.0	3	2	2	2	2	2
28	2	3	4	30.2	27.3	0.5	3	1	2	2	2	2
39	2	3	4	29.1	26.4	2.1	2	1	2	1	2	1
75	2	3	1	23.7	22.2	-1.0	1	1	3	1	3	1
119	2	3	2	25.8	24.1	2.2	2	1	2	1	1	1
4	4	2	0	27.2	28.0	0.3	-	1	1	1	2	2

Appendix B: Comments from the Exit Survey

1. Comments from Subjects Using Constant Fan Speed Setting

Subject #	Comment
#49	The air movement is very much as it would be in my house because I don't have air conditioning (hot & sticky) but the air feels stale - very dead. I would like opened windows. Controlling the rate of air movement is not enough to feel comfortable. There was a strong urge to more the fan closer and in a different position. It was hard to feel really comfortable because you have to stay in the same position. The partitions make me feel confined & unable to see around me.
51	As an architecture student, I can appreciate the study of air movement and temperature control. I applaud the fact that you are studying the many dimensions of thermal comfort.
52	I got slightly confused by the remote control. It would be nice if we could contact the researcher if something went wrong or we have questions (without leaving the station).
53	Chair was positioned too far away from the table. The exercises seemed pointless, and at first were too frequent - they were annoying. But I guess you had your reasons for them.
54	The room is kind of stuffy and humid though not unreasonable.
55	I think the table should be closer for maximum comfort and the chair should have a head rest. I don't like how the fan only blows on one side of me. My left eye was dried.
56	I felt the room was really warm- the fan helped but not as much as I needed. The exercise area was not by the fan so I got really hot doing the 'step-ups'.
57	I much prefer to sit with my feet up. Could you provide a little bow or stool for feet? I enjoyed having the newspaper to read and water to drink.
58	The setting, comfortable chair , pleasant water color and flowering plant all greatly added to my sense of comfort. I understand that the researcher was controlling the thermal environment. My thermal comfort was really at an optimum level in this setting. However, my left leg & left arm seemed stiff. I would have enjoyed more and prolonged opportunities for exercise. Exercise helps me to concentrate better and to sit at one place for extended periods of time. In sum, although the room and my body temperatures were extremely comfortable, my body got stiff after sitting in one place for a long time.

59	For the first hour, I was a little bit warmer than I would like to be. However, as time passed I grew accustomed to the temperature and it became quite comfortable. Having long hair, the air flow tended to cause a little irritation but the rest of my body welcomed it. Overall a very comfortable experience.
60	The experiment was a relaxing an quiet experience. I have never before had a fan blowing directly in one direction, though. Usually it rotates.
61	It was very hard for me to be able to tell how different parts of my body were feeling due to the blowing air. My left side was warm and started to perspire so then I got the chills. This was my only problem. Thanks.
62	I am interested in learning more about why these experiments are being conducted, what is being looked for, where the results are going- basically the who, what, where, why about this experiment. It would be good to have some final information flyer about the goals and results of the experiment. (possibly one posted outside)
79	I felt that when the temperature was too warm or too cool, I was unable to fully concentrate on whatever tasks I was doing (i.e. listening to music reading textbook). It made me feel distracted and frustrated when this was the case. However once I adjusted the fan to a perfect speed all this distraction and frustration went away. It is truly amazing how something so seemingly trivial, thermal comfort, can really have such a big impact on pursuing and accomplishing the important tasks that we must all undergo everyday.
81	I am curious as to why the exercise wasn't more rigorous, since a more rigorous exercise seems like it would affect comfort more. I like the idea of controlling the fan because it allowed me to interact with my environment just as I would if I was at home. If the experiment was video taped, then maybe you could have also analyzed body movement shifting and the restlessness as a result of being comfortable or not.
83	The environment should be more colorful. Please reduce the noise of the fan.
91	The experiment was more elaborate than I expected. I never realized this much energy was being focused on the study of comfort. I think it might have been better if the fan had a more continuous setting speed. There seems to be a big difference between level 3 and 4. A fan that can be "dimmed" like some lights would have been helpful.
94	The chair wasn't super-comfortable. No other comments really- I hope you get useful information from the study.
96	I didn't like the position of the fan. I rather have the fan behind me , so all parts of the body are equally fanned. I think it is more comfortable if there were more air flow or I could open a window.

102	Lamp was very hot! The room temperature was also much too high.
106	Perhaps the fan could have been stronger. I had it on high the whole time so maybe I would have liked to be a little cooler. It is not easy to know what the optimum level is when my available conditions were maxed out. Actually, I was very comfortable the whole time.
107	The room was very hot the entire time and it made it difficult to get comfortable . Also the chair was too loose and the desk was positioned too far away. I wish the fan had higher settings.
109	I hope this type of experiment will benefit society. I want to thank you for letting me participating in your experiment.
113	Using the remote control to adjust the fan was comfortable the whole time.
114	2.5 hr's sitting was a hell of a lot longer than I thought it would feel. Maybe you should bring in a couple of TV's & get some more interesting magazines.
116	I didn't care about the space table, or sitting facing the wall. It was very comfortable since there wasn't any noise, and the room temperature was slightly warm (I prefer warmer temperature). However, when I turned the fan on at 3:40, I began to get a little bit cooler, but still it was comfortable.
117	The experiment forced me to take some time for myself for the first time in a long, long time. If truly, want to see how I relax, you should here included a TV because that was what I usually like to help me relax. By the way, I think that the lamp above the table is killing your plant. The remote control for the fan looks neat.

2. Comments from Subjects Using Fluctuating Fan Speed Setting

Subject #	Comment
#1	At first, it was hot. I spent a lot of time adjusting the fan. After 1 or 1$^{1}/_{2}$ hour, I became acclimatized and felt comfortable. The ticking of the timer is annoying. It made me a bit warmer, I think.
#4	In first 30 min., my thermal sensation was not stable. Once I felt that the thermal sensation of my body was stable, I would prefer the velocity level 1 or 2, for the first experimental case with activity and level 0 or 1 for the second case. The control of room temperature is very important. Pleasant. I could see moving leaves through window. Direction of the fan should be toward the subject.
#7	The room temp. was fine. Air movement was O.K. Nothing uncomfortable.
#10	Nice atmosphere. Flowers and picture and water is appreciated.

#11	The fan does a satisfactory job in simulating natural breeze as air movement varies from time to time. The constant air movement of most fans annoys me.
#12	I noticed I felt cooler after the sun had set. The amount of sun light in the room might have affected my thermal preference. The fan was too loud on the level 4. So I never placed it on 4. The surroundings were pleasing and the cool colors were comforting.
#13	I maintained the fan on the level 4 throughout the experiment. In the first half of the experiment with the exercise, I felt much warmer when sitting at the chair. The moment when the fan was breezing at a low speed were the most noticeable and the most uncomfortable.
#15	I was comfortable overall, if anything, slightly warm. Fan on high was too much for reading paper work.
#16	Air was a little warm and heavy. maybe more humidity than I am accustomed to have. Overall, it was not at all remarkable one way or another.
#17	The experiment was relaxing and enjoyable.
#21	The environment was rather humid. But maybe it's suppose to be that way.
#22	I might have switched from 4 to 3 on the fan because the sun set and I usually like warmth in preparation for the cooler night. The surroundings were very attractive and thoughtful. My enjoyment of participating in this experiment has largely to do with the pleasant surroundings.
#23	I feel, if I had kept my shoes on, I would have remained very warm the entire experiment. But taking off my shoes allowed my temperature to decrease and myself to be much more comfortable and relaxed. I enjoyed the ability to read my book peacefully.
#24	Today was a hot day. I think that, if I had been wearing shoes, then my whole body would have been comfortable. (By the end of the experiment, only my legs were too warm.)
#29	Question 3 should have more choices.- Since air velocity changes, "less" and "more" are not well referenced. Question 5 should have 5 or 7 point scale rather than 3.
#30	I found that the level of air movement was a major factor in my comfort with a great difference between two side near the fan and the side away from the fan. I could not seem to find a comfortable fan level later in the experiment. The lighting in the room could be better.

#32	I just want to explain that even if the temperature and humidity and rate of air movement were all perfect, I would not be comfortable during this experiment. I would feel stifled and inhibited psychologically. I would want to get up, jump around, do exercise, open windows, sing, dance, stretch, play, to feel free to move my body when I feel like it, not when somebody tells me to. I hardly noticed any problem with physical cold or warmth. But I was very aware of the restrictions on my activity and the sterile, empty, stuffy state of the room I was in. I'm used to living in a more dirty, messy, noisy, chaotic environment. And I'm used to moving around a lot.
#34	I noticed that the chair level was too high for me, resulting in the chair cutting into my thigh - I compensate somewhat by propping my feet in chair cross bar and tilting back on chair, but ultimately, some strain on posture/spine. Ideally, I would have adjusted a lamp above (tilted it) to cut down on light glare + perhaps 60 watt bulb or less, given other lighting in the room. I.E.: I consider posture strain + light glare to diminish comfort and increase distractibility. Chair position on carpet is too far from the table for maximum comfort, especially for reading material. Flower on table, painting on wall great to enhance environmental tolerance as well as view of nature + light outside. Quiet of room was a plus. Instructions to drink water 'sparingly'. Does that mean it's bad to consume 16.9 oz within $2^1/_2$ hours? I've read of a 90 min. concentration cycle in people.- I notice that it is good to take a mental or physical break -felt the need to stop reading at 90 minutes + soft focus \ nonmental activity. I've noticed that 15 min. before experiment is over (1215), that my mouth is dry - wondering if the air is too dry? I also feel tired - perhaps I'm "reading"-I got up at 5-6 am. My eyelid on left (fanside) is somewhat dry also left nostril!
#36	At times the room seemed to get somewhat "muggy" or humid.
#37	The uncomfortable heat
#38	The warm room made me sleepy. It was more tolerable toward the end - it seemed less humid.
#40	More comfortable chair would be nice.
#43	My feet were constantly a little hot. I would have taken my shoes off if I were able. Flowers were a nice touch. I didn't alter the fan speed at all. Is that necessary or desired?
#44	I would have liked to be able to move my chair forward a few inches for a more comfortable reading position.

#45	Not knowing, exactly what effects are being studied, it seemed as though the changes in the environment were minor and/or subtle to the point of barely noticing any change. The step exercise didn't seem to increase my body temperature if that was its intention.
#46	Sometimes I think it is difficult to determine the comfort at the moment asked. The comfort or lack thereof is noticed more when it comes up and is not focused. Perhaps you could have some ongoing questions with time? The constant change in the fan speed was distracting sometimes. My butt(sorry) was hot.
#47	It is a little warm today. The main difficulty I had (beside the uncomfortable heat) was the varying speeds of the fan. The bursts of air were nice in that they were similar to a natural breeze, but hard to concentrate with, especially in the beginning. Both the heat and this became less a problem as I became acclimated. Not a bad experience. Everything is well arranged.
#48	The environment here reminds me of some libraries. It is quiet here.
#50	I think I became more and more comfortable. - My body seemed to adjust the to the climate. At first my contact lenses bothered me because of the strong air on #4, but on #3 it was fine. But after walking on the step, I needed to back it on #4. The surprising thing was - my eyes were not bothered. I think I became a little tired of the air always coming from the same side. - but not so much. It was OK. But for the most part, I was comfortable. Oh, my feet were pretty warm throughout. I would have liked to have them colder. I felt a little humid.
64	I was getting sleepy more than halfway through the experiment. The fan was okay at the beginning when it was warmer But it became cooler as time progressed. The breeze reminded me of open air.
65	I became increasingly more comfortable as the afternoon progressed- I was uncomfortably warm only for the exercises. The oscillation of the fan became less bothersome as time passed.
67	The environment is nice and quiet. However, the chair is not very comfortable for 2 and a half hours.
70	The importance of psychological factors within controlled environments is of extreme urgency in determining the efficacy of man-made comfort. Your questionnaire needs to address such issues. The architectural presence an office space needs to look into how such environments affect human behavior and habitation. If comfortable environment are to be manifested they should incorporate a holistic architectural conception of construction and dwelling.

73	In the beginning I was a little cold but I liked the air currents. After I turned off the fan I was more comfortable and didn't really miss the air currents that much. However, I still think I would have liked to have been warm the whole time.
75	The room wasn't uncomfortable (temperature). But it could have used more circulation. An open window would have been nice, It was a bit stuffy.
76	When I first walked into the room, I thought it was very stuffy and warm and little air movement. As I sat down and started to cool down, the fan felt nice and comforting. However as the experiment progressed I became less comfortable as I started to feel colder. It could be lack of exercise towards the end. I turned off the fan but was still cold.
78	When I was too warm I liked the automatic variation in air movement because it felt like I was outside. But I was also glad I could turn it off when I cooled down to perfect temperature.
80	The fan seemed to periodically blow wind more strongly and then less so. --------- Shouldn't the air flow be consistent?
84	The fluctuating fan is very nice and cooled perfectly when it was needed.
92	The mild physical activity is a good idea. I may have fallen asleep if I did not engage in the activity! Although the environment was quite comfortable. I usually prefer a slightly cooler environment(in the 70's F range) so that I don't become too comfortable and fall asleep.
103	I became more relaxed and comfortable as the time went on. I think it might have something to do with the fact that it was becoming darker outside and the environment became more relaxing.
118	I tend to like feeling cool rather than hot - I would rather be slightly cool than slightly warm. I also like a good amount of air circulation- without it I tend to feel warmer.
119	It was fairly easy to adjust the fan to my desired level. The temperature and air did provide a good level of comfort and enabled me to relax.

LIST OF FIGURES

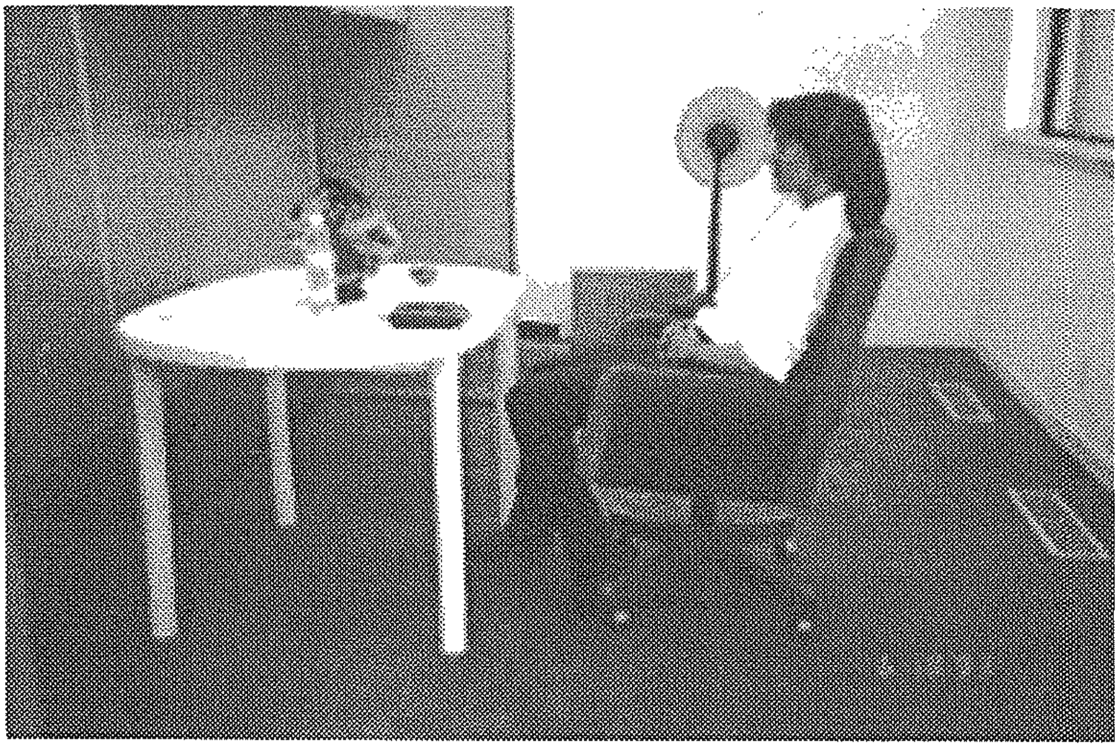


Figure 1a. Experiment setup, with subject and fan

Figure 1b. Chamber configuration

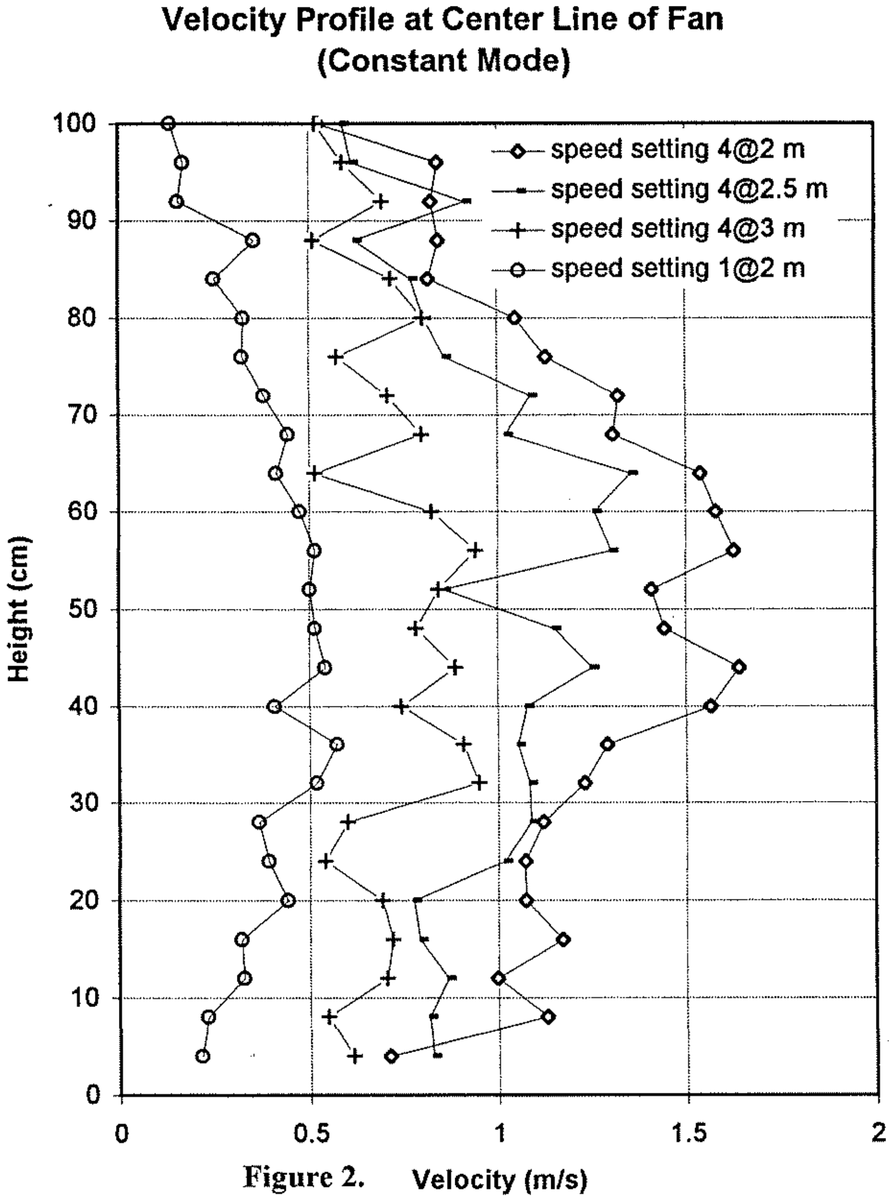
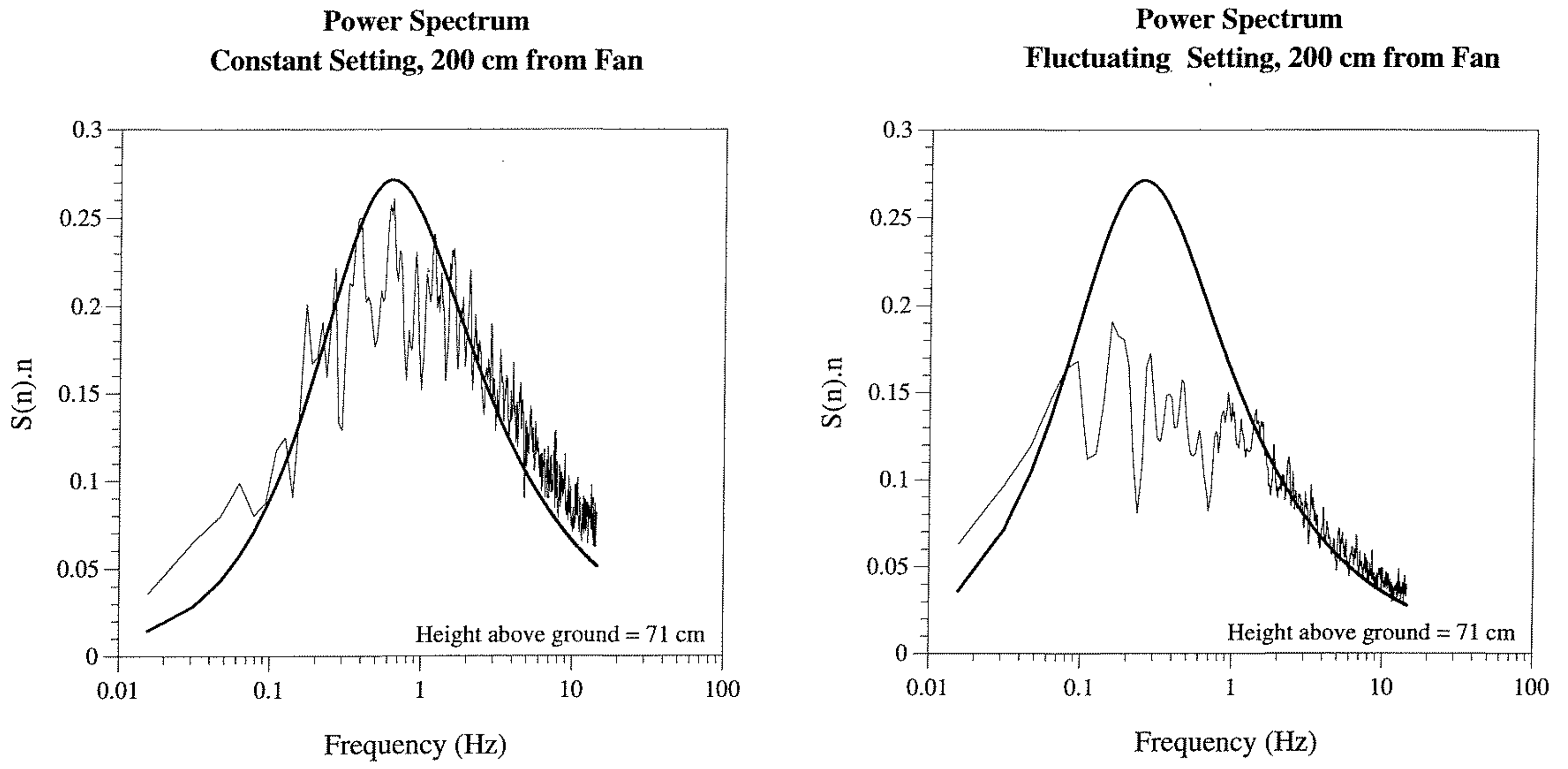

Velocity Profile at Center Line of Fan
(Constant Mode)
Height (cm)
0
10
20
30
40
50
60
70
80
90
100
Velocity (m/s)
0
0.5
1
1.5
2
speed setting 4@2 m
speed setting 4@2.5 m
speed setting 4@3 m
speed setting 1@2 m

Figure 2.



Power Spectrum
Constant Setting, 200 cm from Fan

Power Spectrum
Fluctuating Setting, 200 cm from Fan

Figure 3.

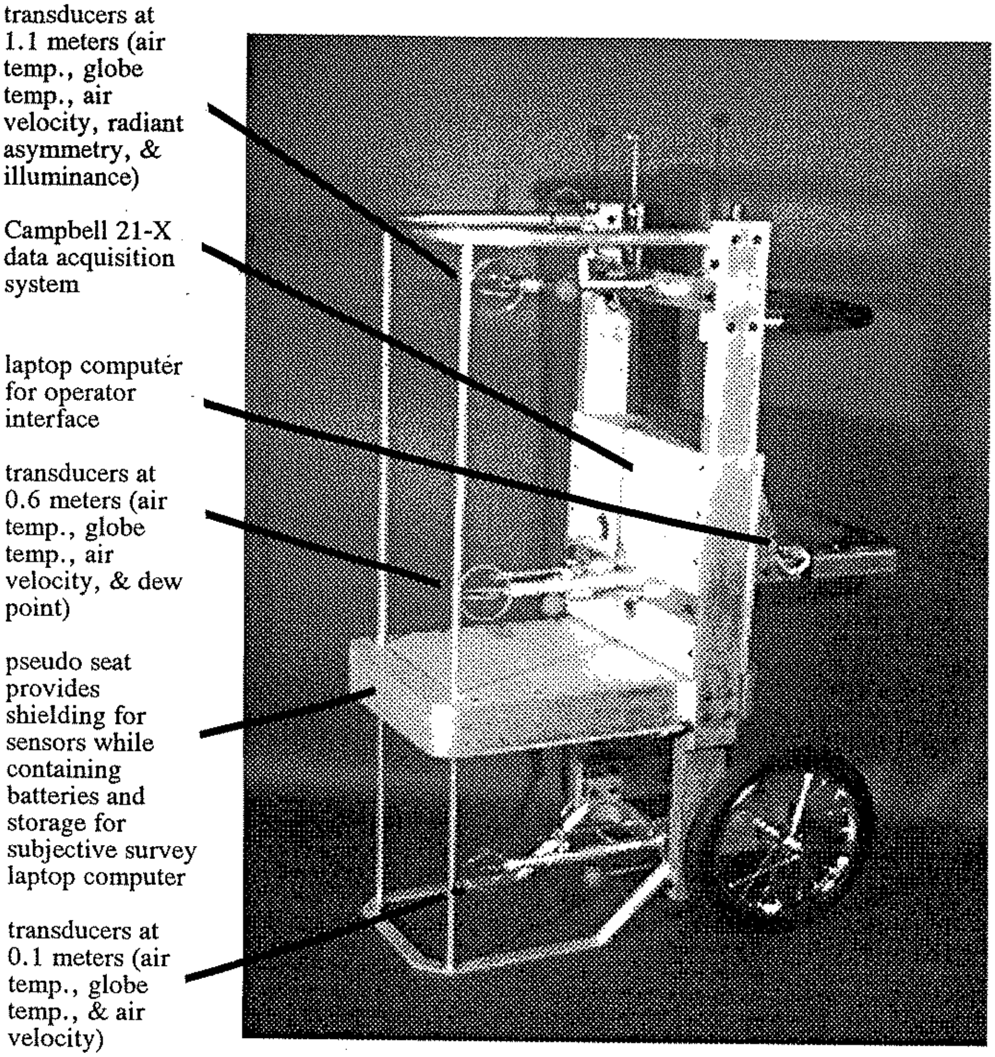


Figure 4. Mobile measurement cart

Comfort Study ————Background Survey

Please fill out both pages of survey completely. If you have any question about the form, please feel free to ask the researcher.

Background Characteristics

1. Name: ____________________
2. Date: ____________________
3. Phone number: ____________________
4. Home zip code: ____________________
5. How long have you lived in the Bay Area? ____________________
6. On the average, how many hours per day do you spend inside your home on working days? ____________________
7. On the average, how many hours per day do you spend inside your home on weekends or non working days? ____________________
8. What is your approximate height? _____ Feet _____ Inches
9. What is your approximate weight? _____ Pounds
10. What is your age? _____ Years
11. Your sex?
    1 ☐ Male
    2 ☐ Female
12. Your ethnic background?
    1 ☐ Asian American
    2 ☐ Black
    3 ☐ Caucasian
    4 ☐ Hispanic
    5 ☐ Other (please specify: ____________________)
13. Is English your primary language?
    1 ☐ Yes
    2 ☐ No
14. How many cigarettes do you smoke per day? ________ Cigarettes
15. How many cups of caffeinated beverages do you drink per day? _____ Cups per day
16. How many hours do you exercise per week? _____ Hours

Figure 5a.

Comfort Study————Questionnaire

1. Please write down the time: ____________________
2. Please check (☒) the box that best describes your present **Thermal Preference**:
    ☐ I want to be warmer
    ☐ I want no change
    ☐ I want to be cooler
3. Please check (☒) the box that best describes your present **Air Movement Preference**:
    ☐ I want less air movement
    ☐ I want no change
    ☐ I want more air movement
4. Please tick (✓) the scale below in the place that best presents your **Overall Thermal Sensation** at this moment:

-3	-2	-1	0	+1	+2	+3
COLD	COOL	SLIGHTLY COOL	NEUTRAL	SLIGHTLY WARM	WARM	HOT

5. Please check (☒) one box that best describes your **Present Feeling** in each of the five different parts of your body shown on the following figure:

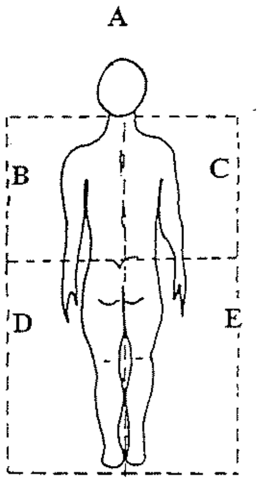
(A) Head
☐ comfortable
☐ warmer than comfortable
☐ cooler than comfortable

(B) Left upper part
☐ comfortable
☐ warmer than comfortable
☐ cooler than comfortable

(C) Right upper part
☐ comfortable
☐ warmer than comfortable
☐ cooler than comfortable

(D) Left lower part
☐ comfortable
☐ warmer than comfortable
☐ cooler than comfortable

(E) Right lower part
☐ comfortable
☐ warmer than comfortable
☐ cooler than comfortable



6. Does the present rate of air movement bother you in any way?
    1. ☐ Yes
    2. ☐ No

If yes, how? (please don't include any influence of fan noise in your response)
____
____

Figure 5b.

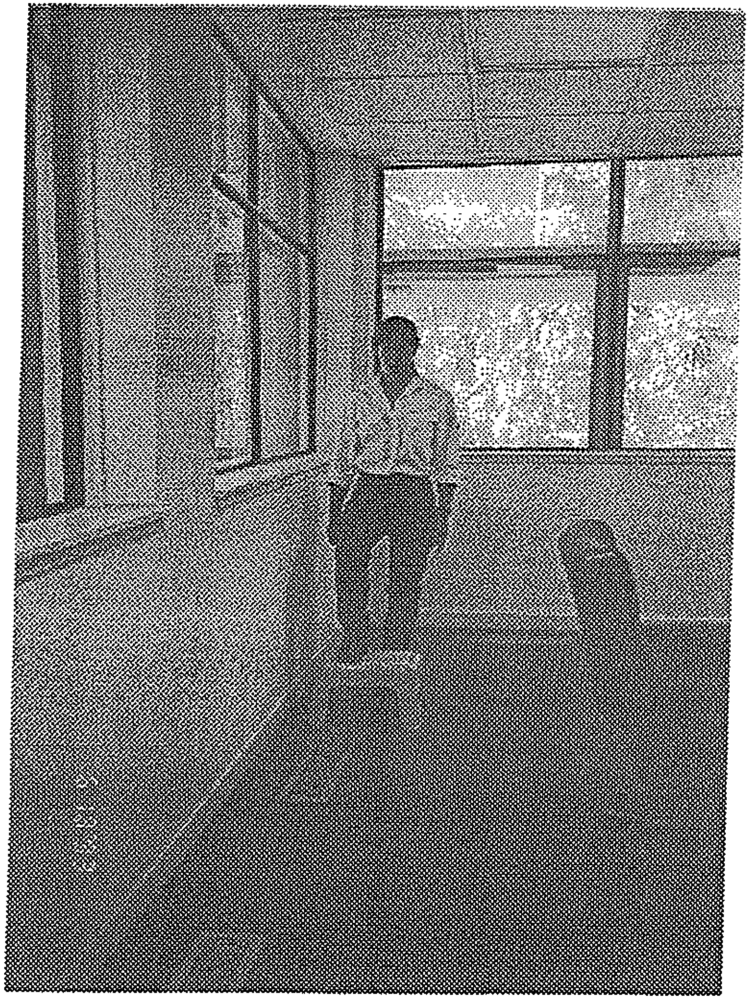


Figure 6. Subject performing step exercise

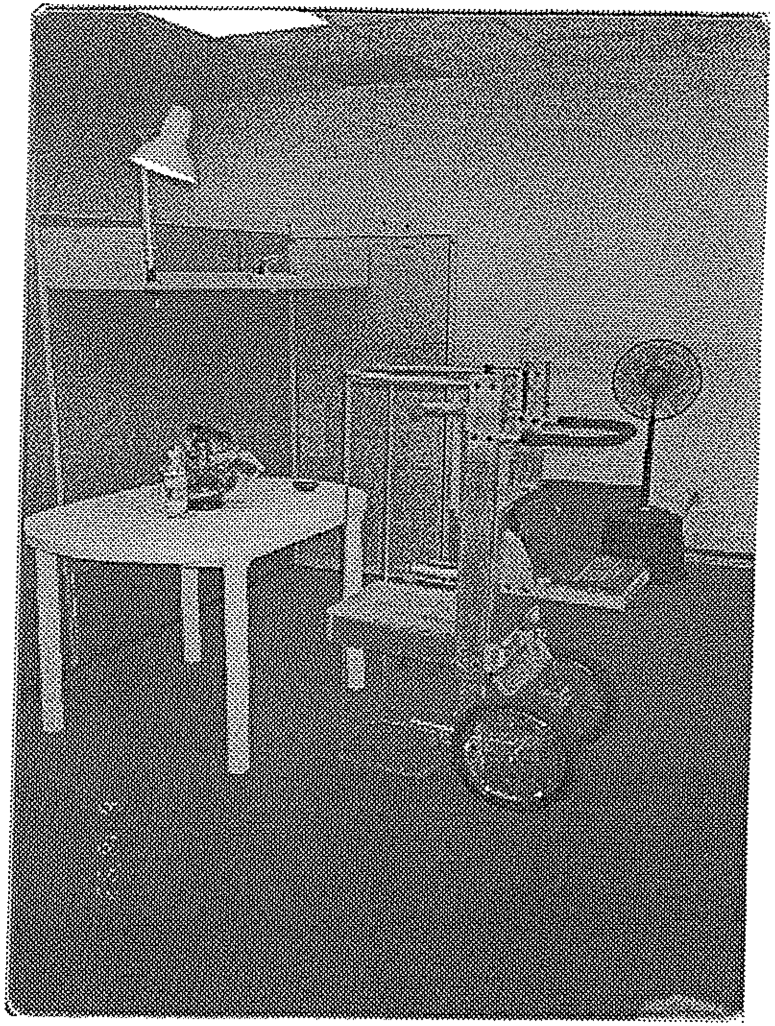


Figure 7. Physical measurement at 80 and 160 minutes

Experimental Record

Alternatives to Compressive Cooling

Date: _______ Time: 10:00am 1:30pm 7:00pm SP/OA Temp: __________

Subject(No.2): ______________________ Researcher: ______________

Actual Time	Time	Survey Cart	Fan Level (0-4)	Activity (H/L)	Note
	0	Coming-in		H	Oral temp
	20 min	1st Activity		H	
	30 min	2nd Activity		H	
	40 min	3rd Activity		H	
	50 min	Survey 4th Activity		H	
	60 min	5th Activity		H	
	70 min	Survey		H	
	80 min	Cart		H	
	85 min			L	
	135 min	Survey		L	
	155 min	Survey		L	
	160 min	Cart		L	Oral temp
					Water consumption

Figure 8.

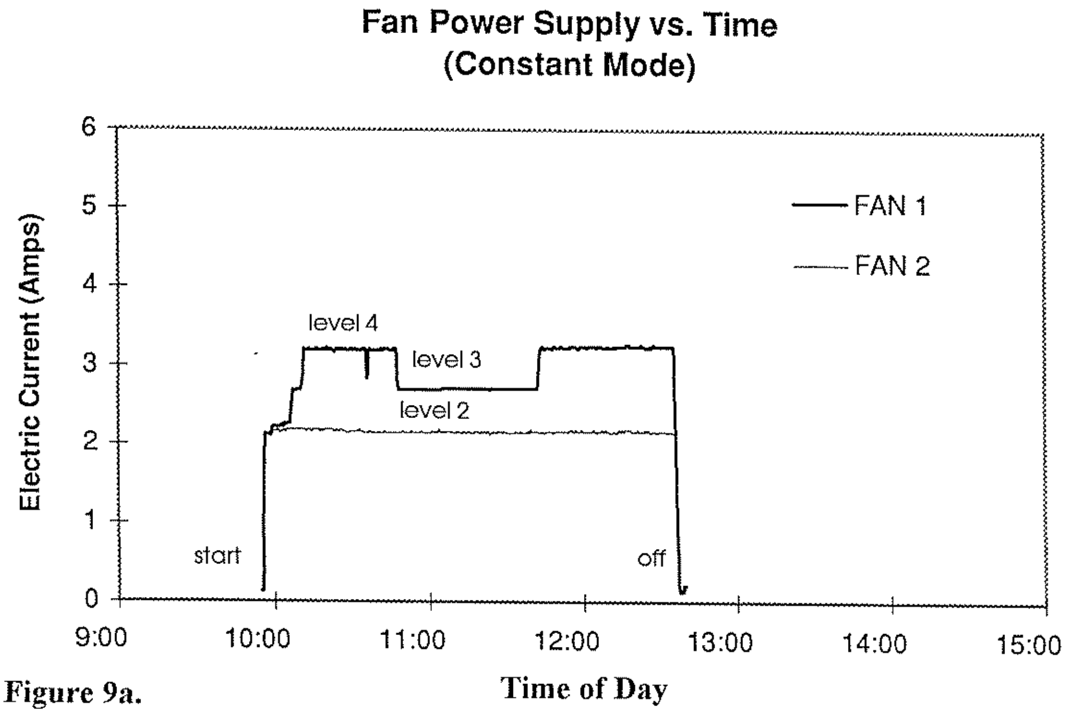


Figure 9a.

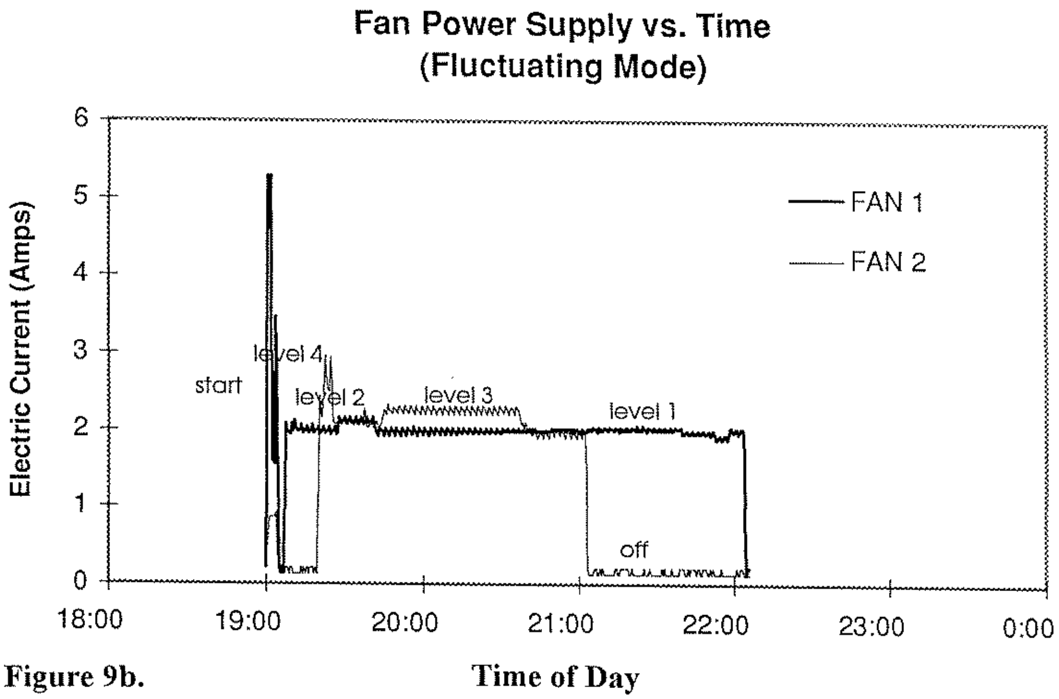


Figure 9b.

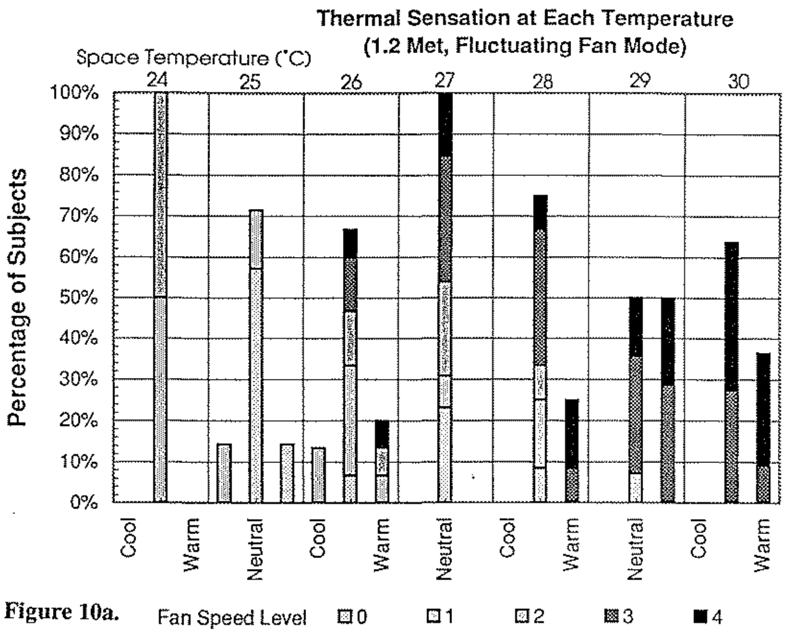


Figure 10a.

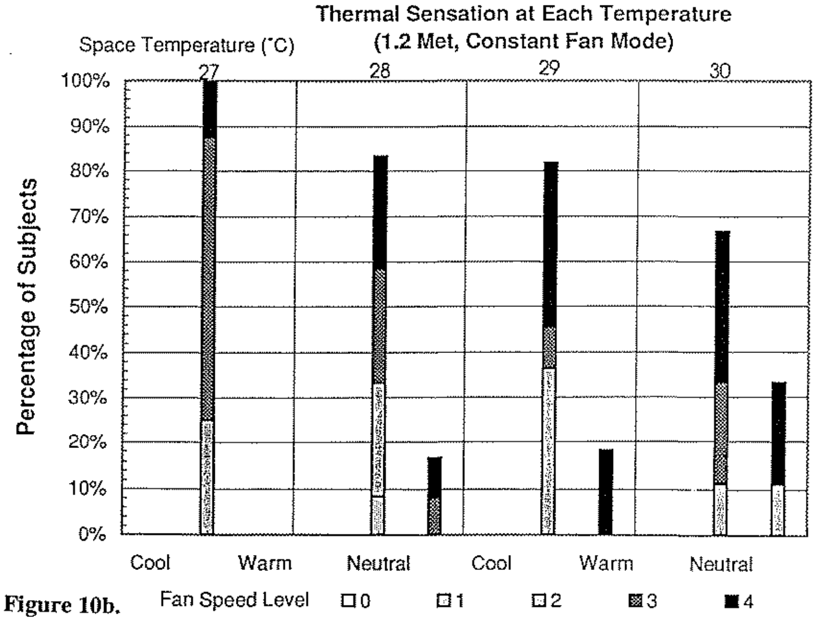


Figure 10b.

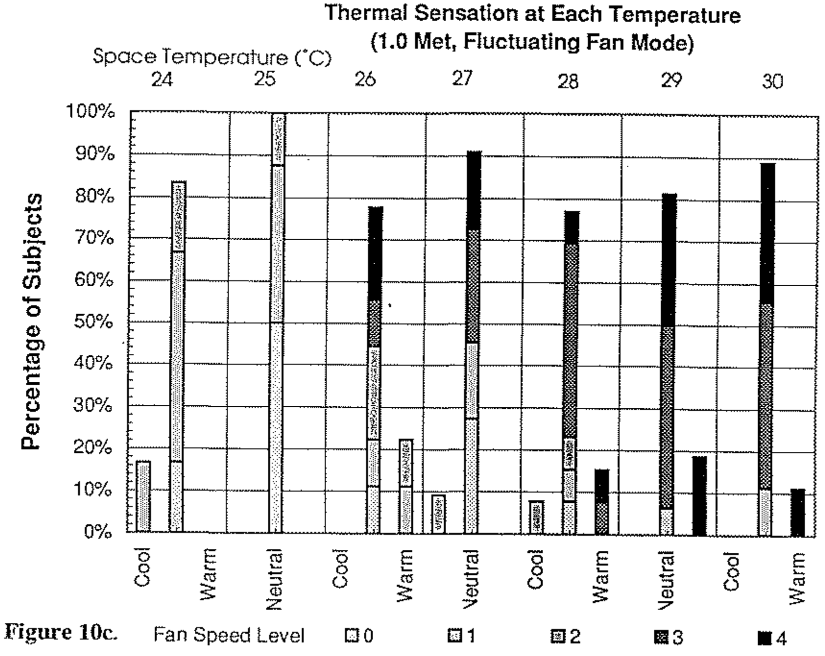


Figure 10c.

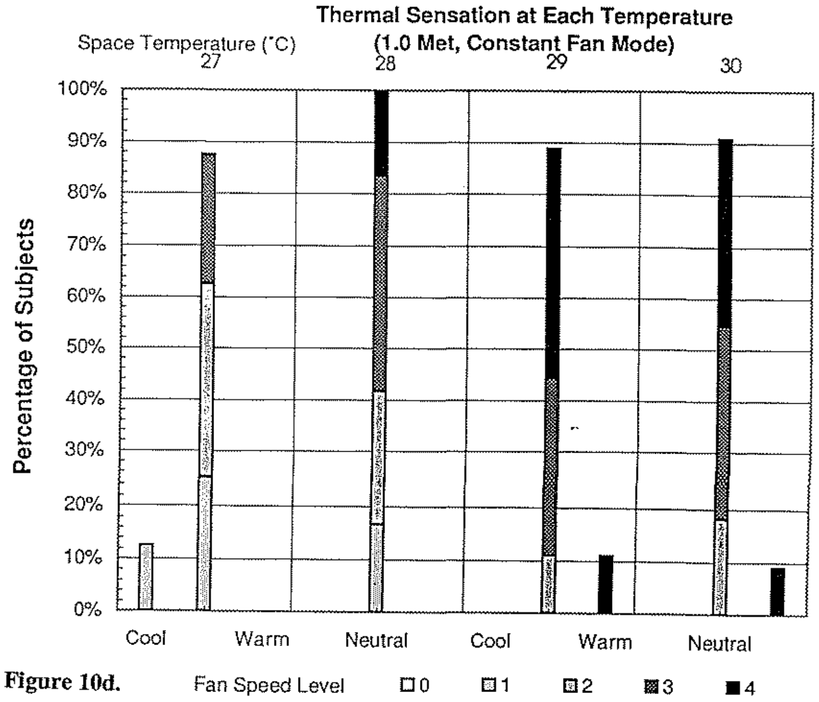
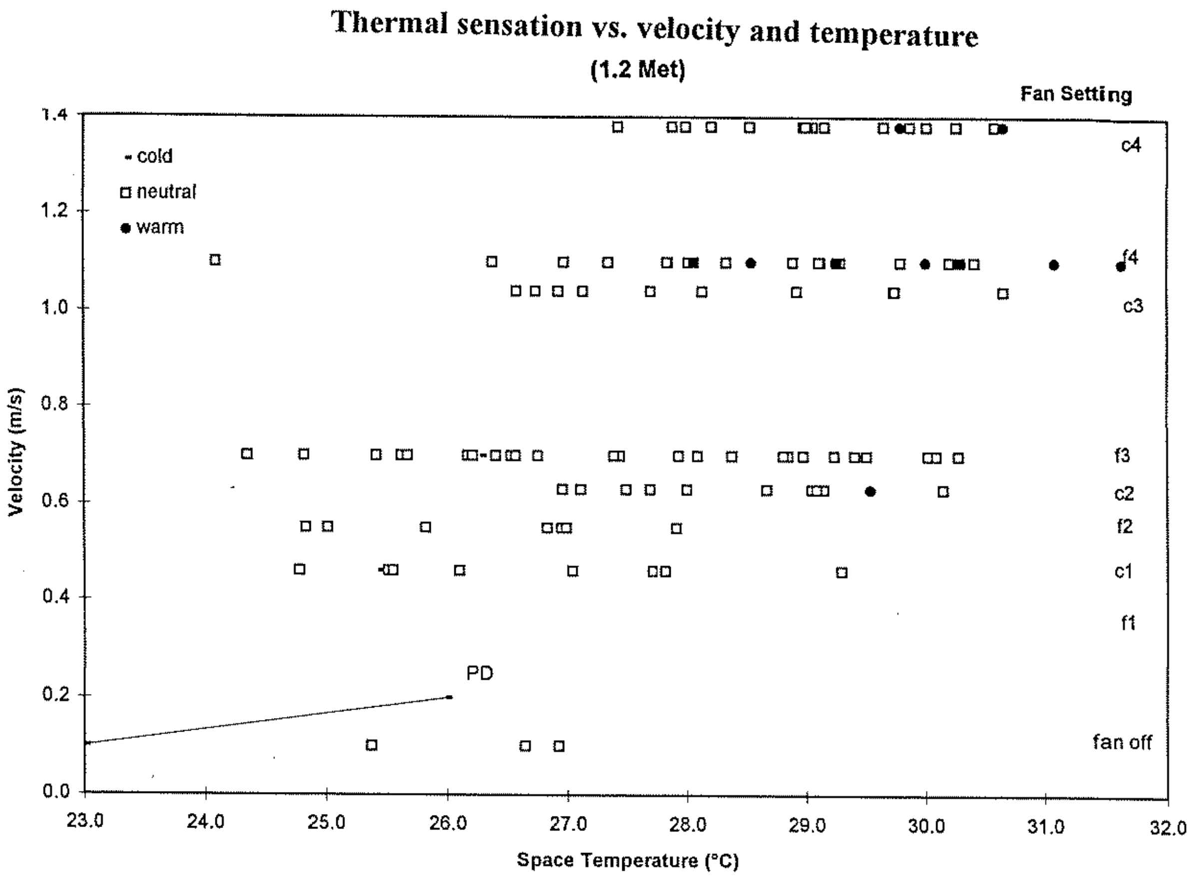


Figure 10d.


Thermal sensation vs. velocity and temperature
(1.2 Met)
Fan Setting
- cold
□ neutral
● warm
Velocity (m/s)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
c4
f4
c3
f3
c2
f2
c1
f1
fan off
PD
23.0
24.0
25.0
26.0
27.0
28.0
29.0
30.0
31.0
32.0
Space Temperature (°C)

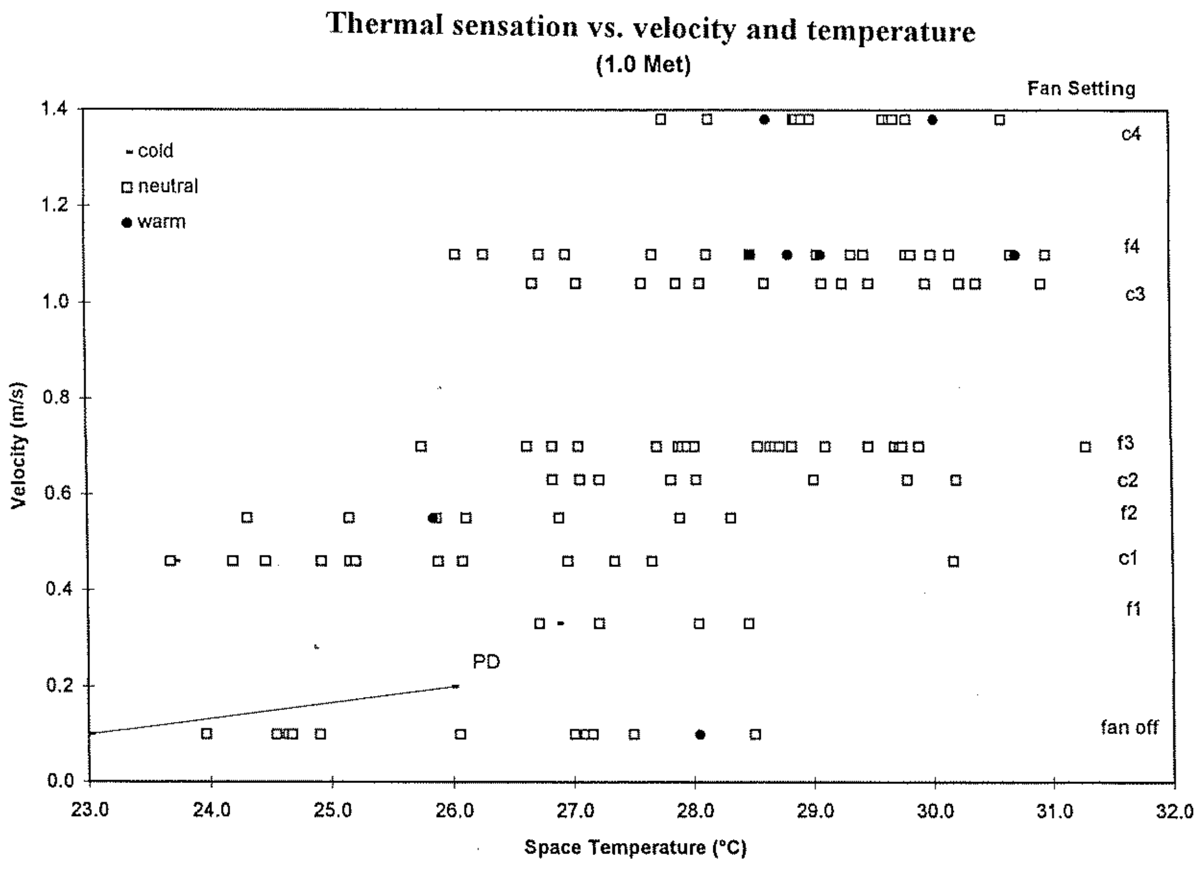
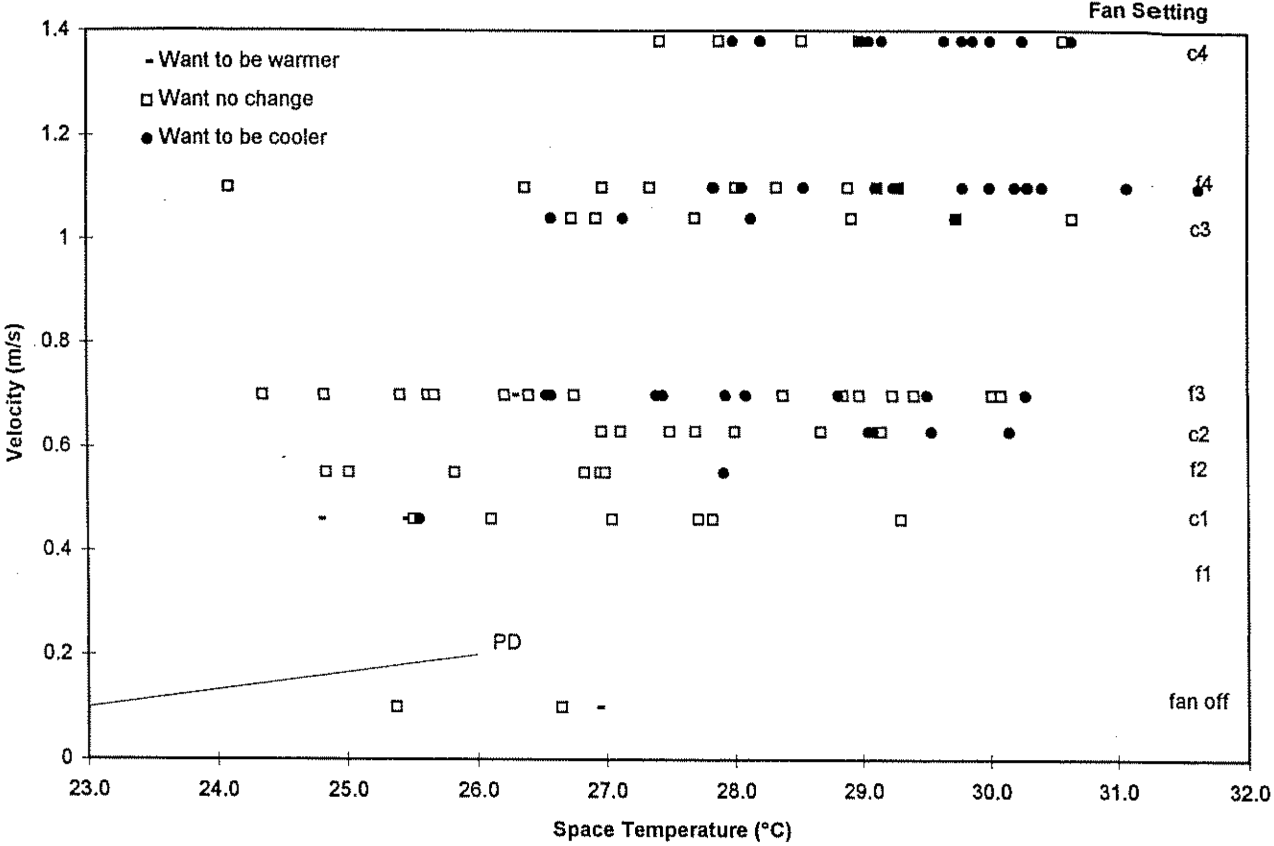

Thermal sensation vs. velocity and temperature
(1.0 Met)
Fan Setting
- cold
□ neutral
● warm
Velocity (m/s)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
c4
f4
c3
f3
c2
f2
c1
f1
fan off
PD
23.0
24.0
25.0
26.0
27.0
28.0
29.0
30.0
31.0
32.0
Space Temperature (°C)

Figure 11.

Thermal preference vs. velocity and temperature
(1.2 Met)



Thermal preference vs. velocity and temperature
(1.0 Met)

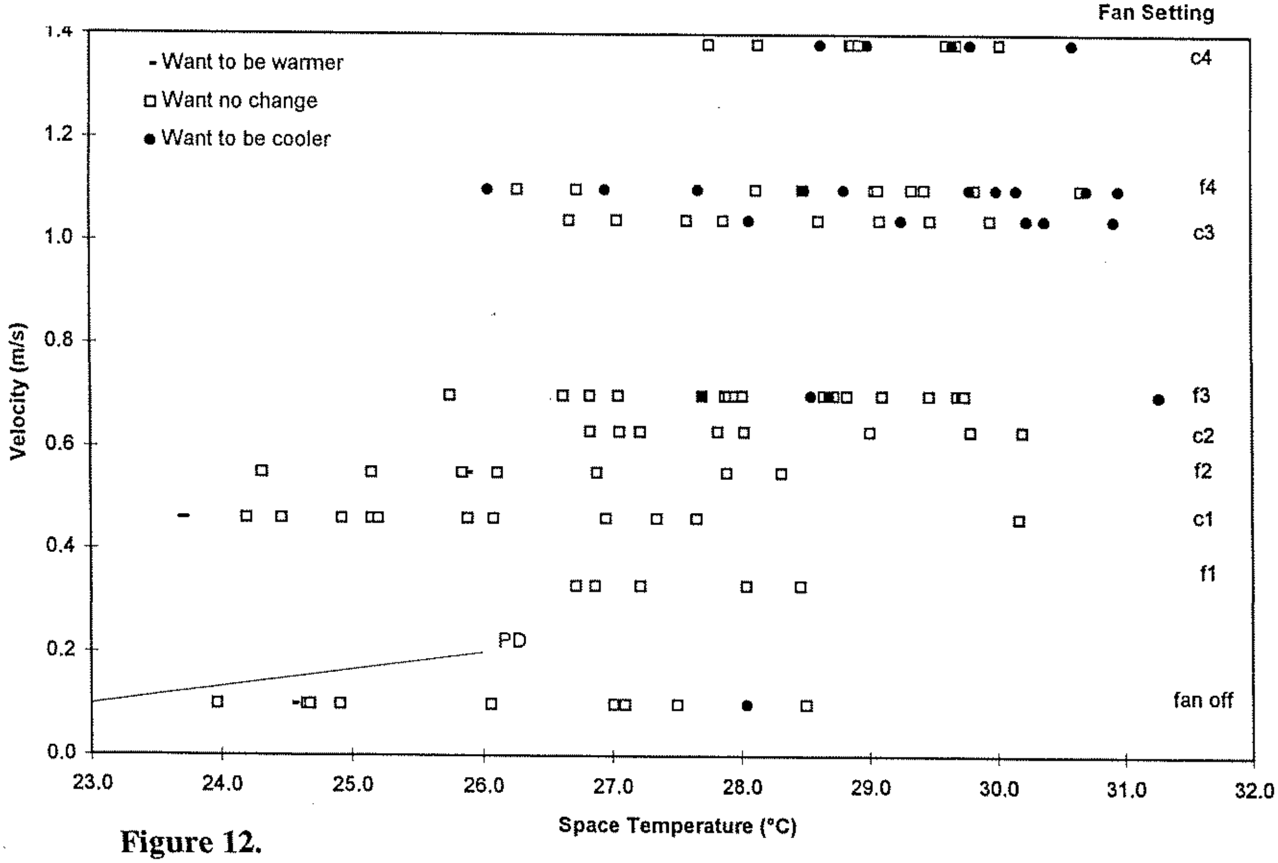
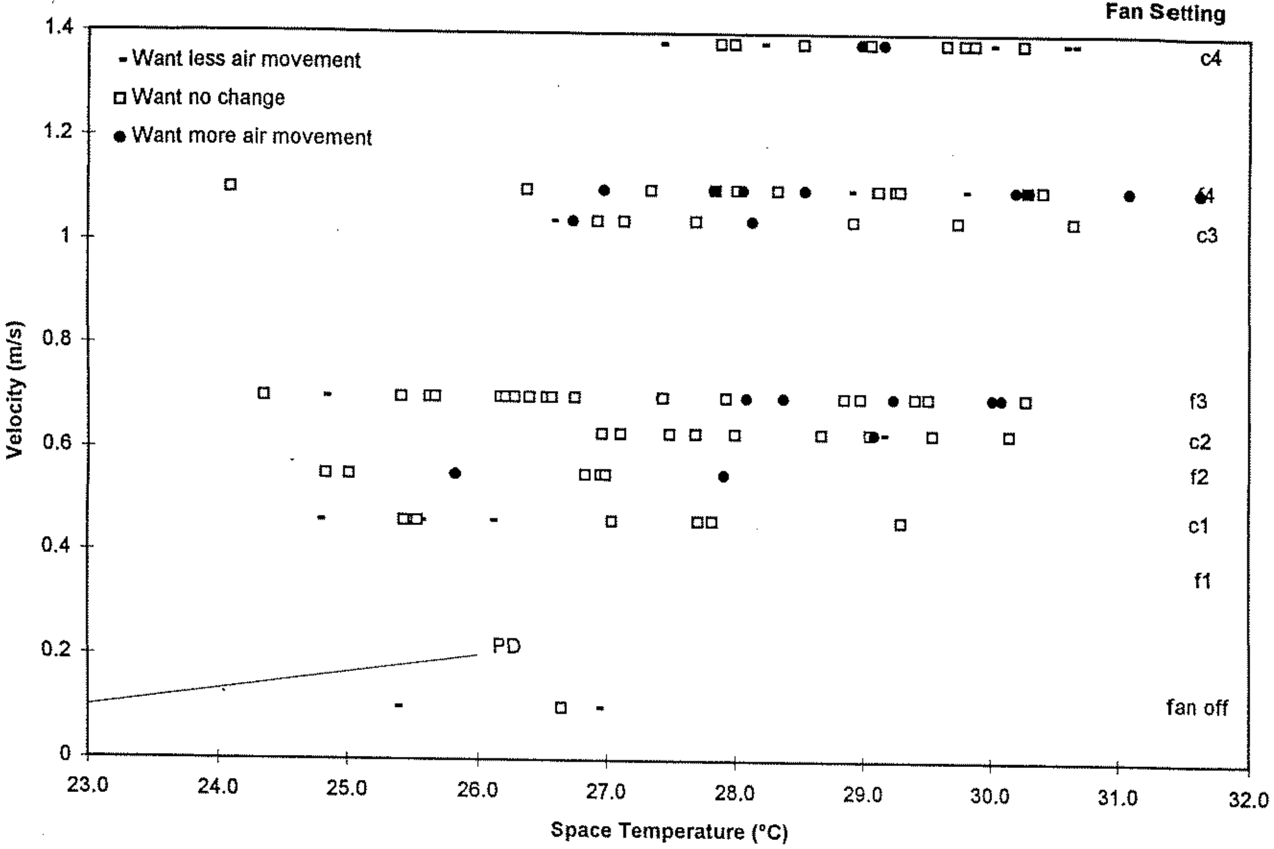


Figure 12.

Air movement preference vs. velocity and temperature
(1.2 Met)



Air movement preference vs. velocity and temperature
(1.0 Met)

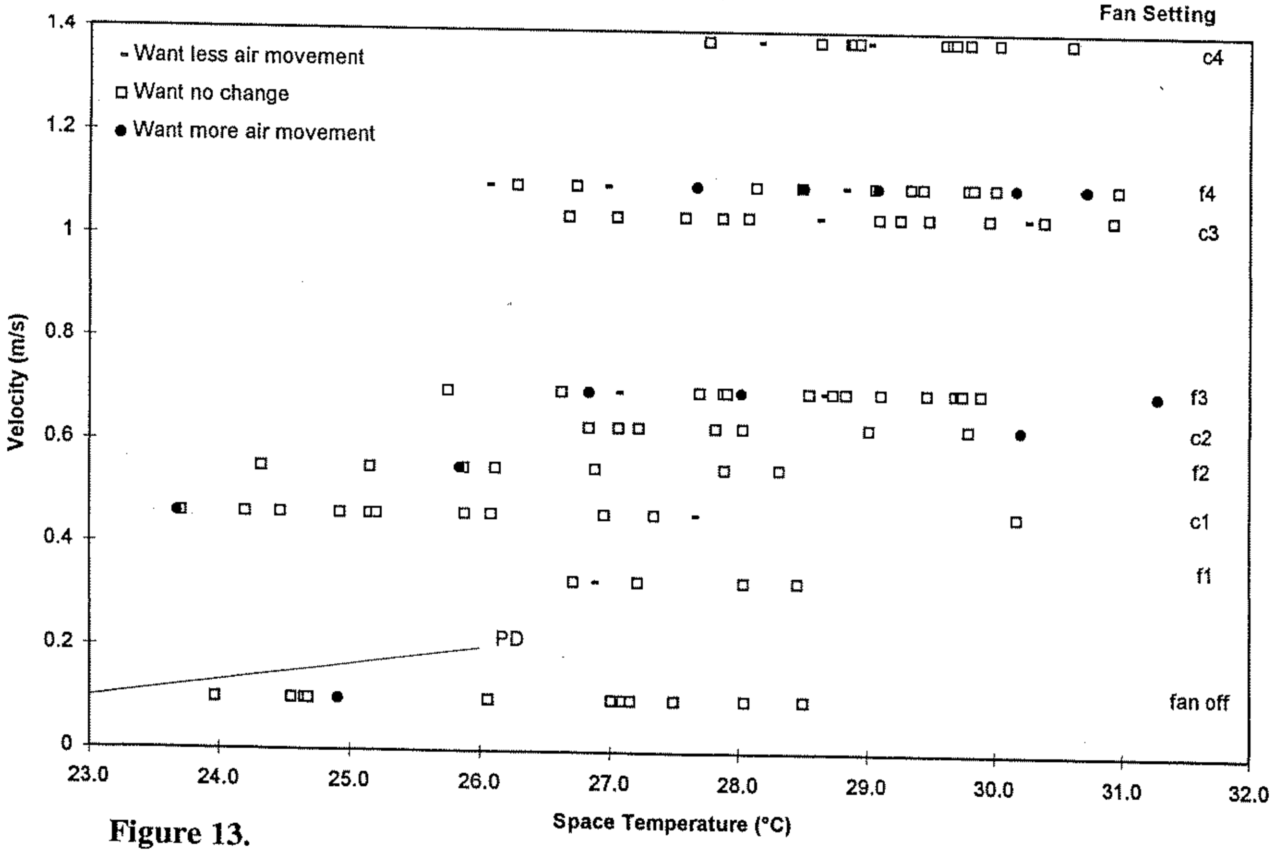


Figure 13.

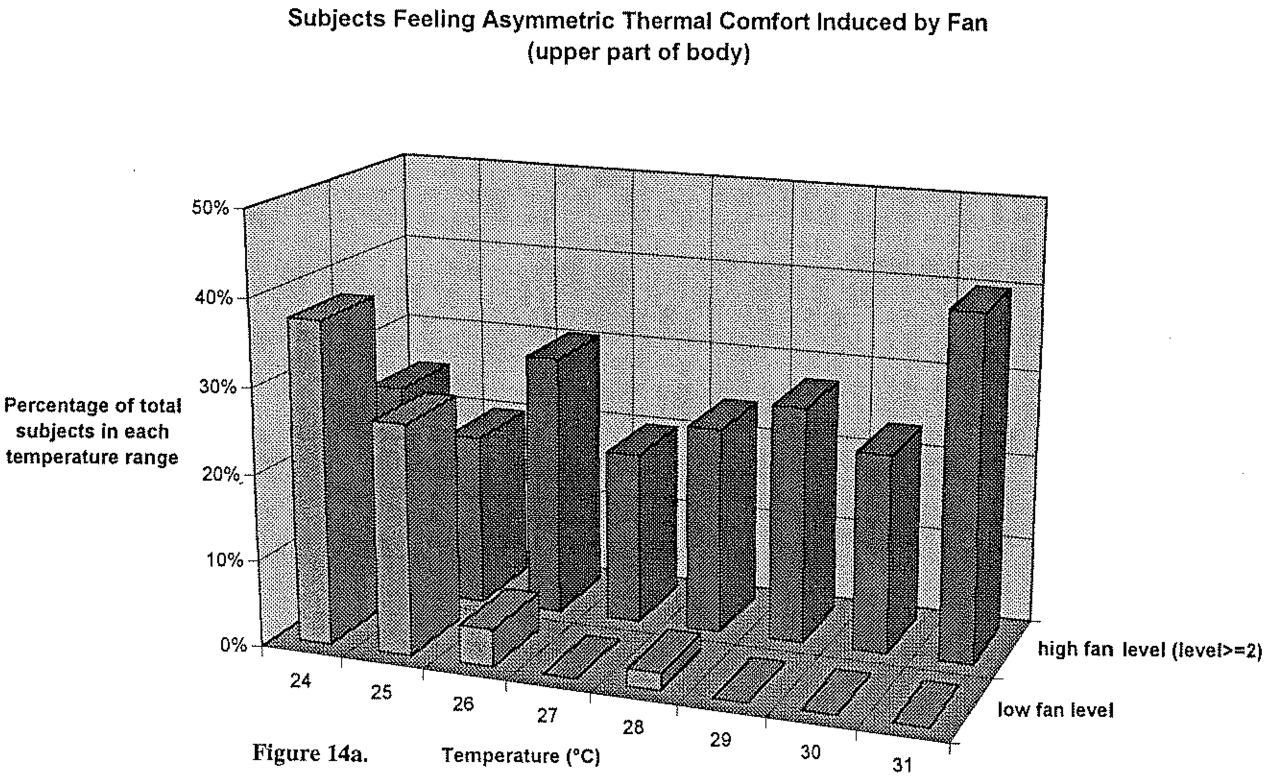


Figure 14a.

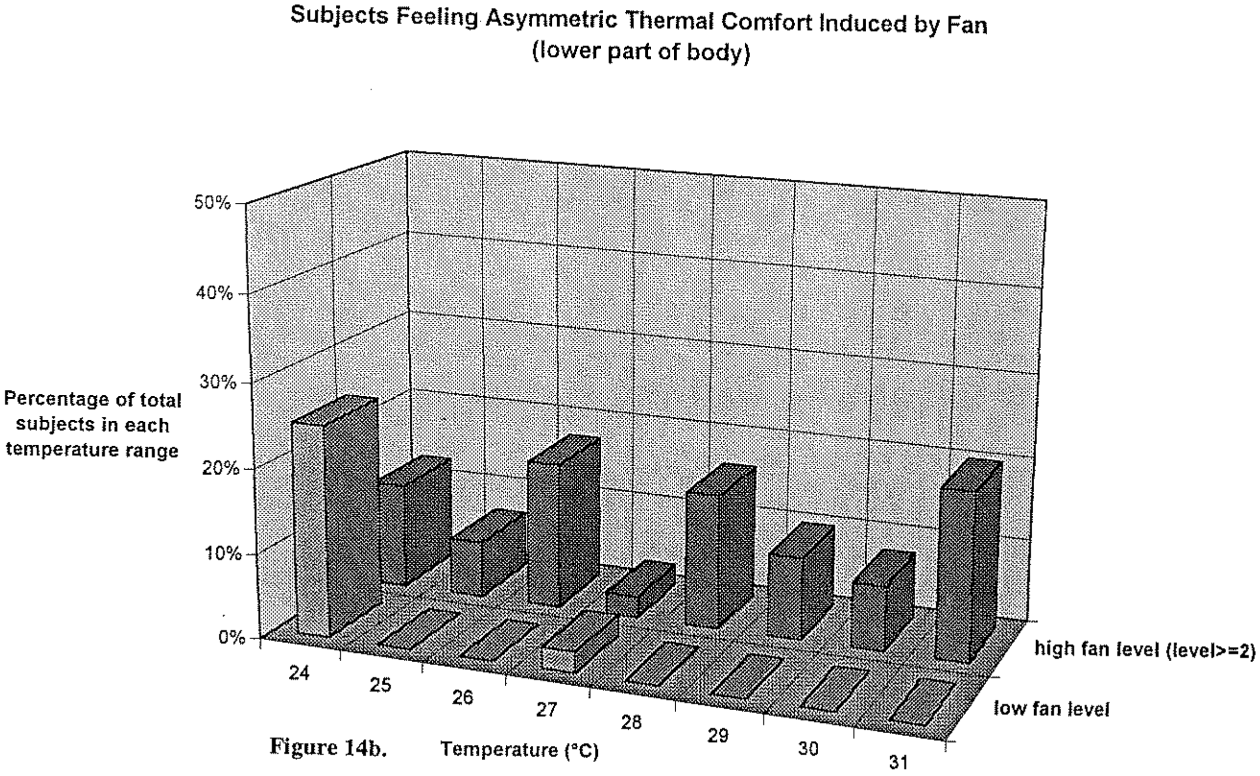
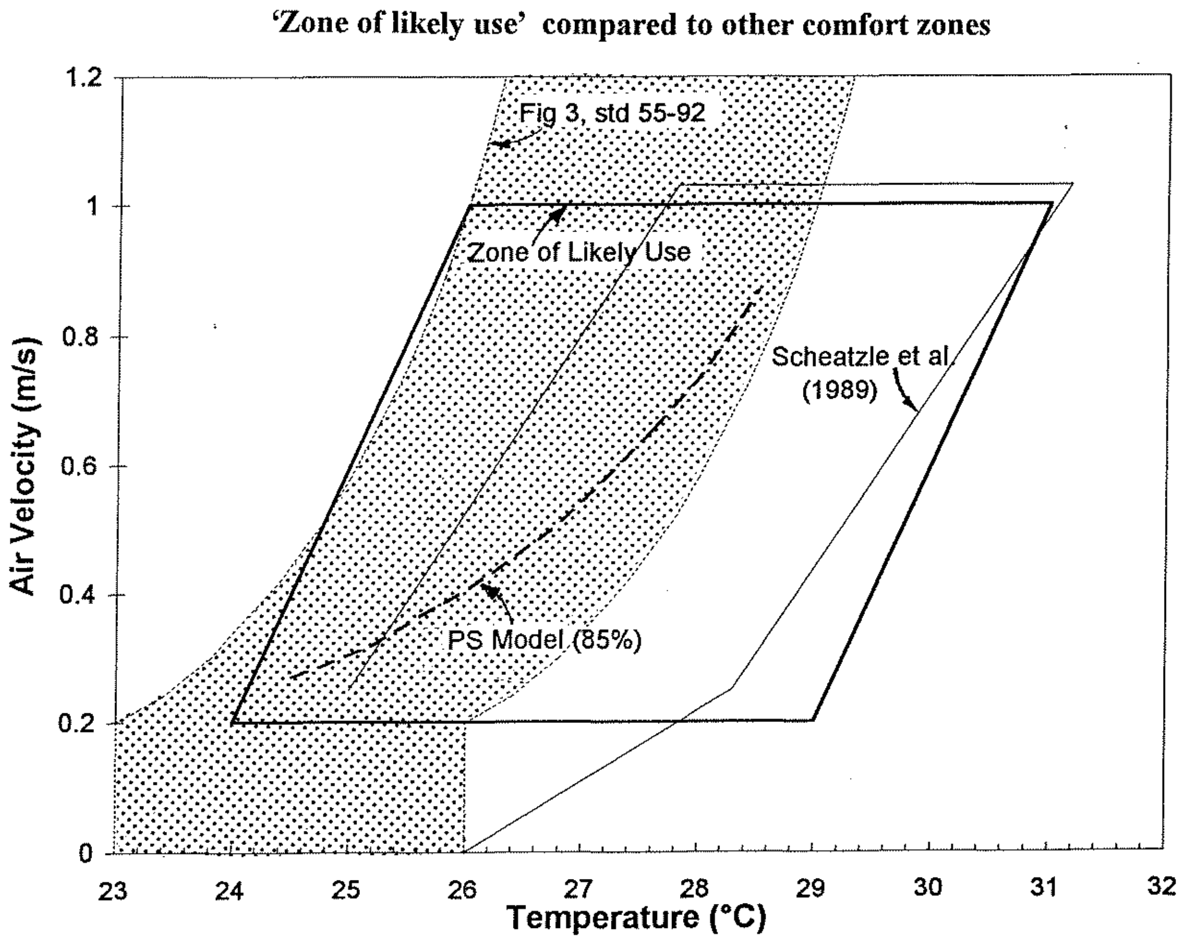


Figure 14b.



'Zone of likely use' compared to other comfort zones
Fig 3, std 55-92
Zone of Likely Use
Scheatzle et al (1989)
PS Model (85%)
Air Velocity (m/s)
1.2
1
0.8
0.6
0.4
0.2
0
23
24
25
26
27
28
29
30
31
32
Temperature (°C)

Figure 15.

APPENDIX B

Indoor Humidity and Health

INDOOR HUMIDITY AND HUMAN HEALTH

PART I

LITERATURE REVIEW OF HEALTH EFFECTS OF HUMIDITY-INFLUENCED INDOOR POLLUTANTS

Anne Baughman and Edward Arens
Center for Environmental Design Research
University of California, Berkeley

ABSTRACT

Standards for indoor thermal conditions and ventilation include upper limits for relative humidity that are typically in the range of 60 to 80% RH. Although the reasons for the limits are often not explicitly stated, it is generally known that they were set out of concern for the health effects that might occur should the humidity become too high. The primary health effects of high humidity are caused by the growth and spread of biotic agents, although humidity interactions with non-biotic pollutants, such as formaldehyde, may also cause adverse effects. This literature review identifies the most important health issues associated with high humidities and presents humidity requirements, typical contamination sites within buildings, and remediation measures for each pollutant. Part II: *Buildings and their Systems* addresses the physical causes of moisture-related problems in buildings.

INTRODUCTION

Standards for indoor thermal conditions and for ventilation have traditionally put upper limits on the amount of humidity permissible in interior spaces because of concern for the health effects that might occur should the humidity become too high. Such limits are found in past versions of ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy), ASHRAE Standard 62 (Ventilation for Acceptable Indoor Air Quality), and in most international standards. The values set for the upper limits have typically ranged from 60 to 80% RH, although boundaries of absolute humidity have also been used. To date the relationship of high humidity to the full spectrum of air quality issues and to the relevant characteristics of building envelopes and conditioning systems has not yet been addressed in a comprehensive manner. This situation affects our ability to set rational standards and building specifications.

Human health is not affected by high levels of humidity *per se*. Known health effects related to high humidity are primarily caused by the growth and spread of biotic agents under elevated humidities, although humidity interactions with non-biotic pollutants, such as formaldehyde, may also cause adverse effects. Existing limits appear to be based on engineering experience with such humidity problems in buildings.

The position of any upper humidity limit has very large economic significance, particularly in hot-arid parts of the country where evaporative cooling is an energy-conserving option. In the West, it affects the need for billions of dollars of new peak electrical generating capacity that could be offset by non-compressor-based cooling. It also directly affects a substantial fraction of the cooling load in hot-humid climates. Under such economic imperatives, it is desirable to examine the position of any upper humidity limit with care. Ideally, one would be able to assess the health risks against the economic benefits for any given humidity limit. At present, there is insufficient information on this subject to even begin such an analysis.

This review of the literature identifies a number of health-related agents that are affected by indoor humidity. All of them affect human health primarily through their inhalation from the air, although some of them have lesser effects through the skin. Biological agents require appropriate conditions in the building for their germination, growth, release to the air, and transport to the human host. Airborne levels of non-biological pollutants, such as formaldehyde and ozone, may also be affected by humidity through influences on offgassing and surface reaction rates. Finally, the occupants' susceptibility to these agents may also be a function of humidity, although this appears to be a problem primarily at low humidities, when respiratory ailments result from dry mucous membranes (Green, 1985). The health implications of low humidities are not addressed in this paper. Part II of this paper *Buildings and their Systems* addresses the relationships of the environments within buildings and conditioning systems to the growth of biological pollutants.

OVERVIEW OF HUMIDITY RELATED HEALTH CONCERNS

The primary influences of humidity on health are through biological pollutants. The following outline describes the health issues most commonly associated with biological pollutants:

<u>Infectious disease (pathogens)</u>
  bacteria (e.g., *Streptococcus, Legionella*)
  viruses (e.g., common cold, flu)
  fungi (e.g., *Aspergillus fumigatus*)

<u>Allergic reactions (e.g. asthma, rhinitis)</u>
  dust mites (dried body parts and fecal excreta)
  fungi

<u>Non-allergic immunologic reactions (e.g., hypersensitivity pneumonitis)</u>
  fungi
  bacteria

<u>Myctoxicosis</u>
  fungi

Infectious disease can occur when viable pathogenic organisms enter (usually through inhalation) and colonize in the body of a susceptible host. The most commonly found pathogens are bacteria or viruses, although fungal pathogens, such as *Aspergillus fumigatus* also exist (Flannigan, 1992). Most pathogens are transmitted through human to human contact when droplet nuclei form as a result of sneezing or coughing and are subsequently inhaled by a human receptor. A few pathogens, most notably the bacterium *Legionella*, can colonize abundantly within moist environments outside the human body and become airborne given proper conditions.

Non-infectious health conditions related to biological pollutants include allergic, immunologic and toxic responses. The primary source of these adverse health effects are the byproducts of organisms rather than the viable organism itself. The term *allergy* is used specifically to refer to illnesses that take place as a result of the formation of IgE antibodies in affected persons. All human beings have some IgE antibodies, but only a fraction of the population responds readily to allergen exposure and produces enough IgE antibodies to cause an allergic reaction. Once the antibodies form, the person becomes sensitized and re-exposure to the allergen can then trigger larger immune reactions resulting in allergic symptoms. This IgE mediated reaction develops in 20-30% of the people in the United States (Seltzer, 1995). The allergic diseases with well-documented links to indoor air quality include allergic rhinitis (rhino conjunctivitis), primarily affecting the nasal area, and allergic asthma and bronchopulmonary aspergillosis (ABPA), both of which affect the lower airways and alveoli. The major portion of patients suffering from asthma are allergic to dust mites, mold, and/or animal dander. The estimated overall prevalence of asthma and rhinitis may be as high as 20% the population (Berglund et al., 1992) and according to the American Lung Association the number of people with reported asthma in the U.S. has greatly increased in recent years, with a 49% increase since 1982.

Non-allergic immunologic responses, characterized by recurrent flu-like symptoms (e.g., hypersensitivity pneumonitis, farmer's lung and humidifier fever), seem to be unrelated to the IgE antibody. They occur as a result of repeated pollutant exposures which trigger other antibody-dependent mechanisms as well as cellular immune responses. Although there seems to be no genetic predisposition, only a fraction of those exposed develop overt symptoms (Burge, 1988).

Mycotoxins are produced by fungi and can lead to respiratory irritation, interference with pulmonary macrophage cells, and/or higher risks of cancer (Flannigan and Miller, unpublished). Many fungi also produce volatile organic compounds that may be respiratory irritants, and have been suggested as a contributing factor to sick building type symptoms in microbially contaminated buildings (Bjurman, 1993; Sorenson, 1989).

Non-biological pollutants such as formaldehyde, ozone, oxides of nitrogen, and sulfur affect humans primarily through chemical irritation of the mucous membranes. Formaldehyde is released into the indoor air from building materials in ways that are dependent on atmospheric humidity. Surface reactions, and consequently the amount and toxicity of ozone and NO_X and SO_X in the air, may be influenced by humidity levels. The extent to which humidity increases or decreases the health impacts of these pollutants, however, is relatively small compared to other environmental factors, such as air change rates and outdoor pollutant levels. For example, the use of direct evaporative cooling leads to a rise in indoor humidity levels, which may reduce ozone by increasing surface reactions. However, this effect is relatively insignificant compared to the increased influx of outdoor air which tends to increase indoor ozone concentrations to levels near that of the outdoor air (Stock and Venso, 1993).

DUST MITES

Introduction

Mites are considered one of the most important allergens in house dust particularly in regions with high humidities and temperate climates. The most common genus of mites found in house dust within North America and Europe is *Dermatophagoides* of which there are two species, *D. pteronyssinus* and *D. farinae.* It is estimated that 10% of the population within the U.S. is allergic to house dust and 70% of these people are specifically allergic to mite allergens (Bates et al., 1993). The actual allergen is not the mites themselves, which are approximately 1/3 mm in length at maturity, but the dried fragments of their body parts and fecal excreta. These by-products are initially 10 to 50 μm in diameter but break down into smaller fragments that become airborne when dust is disturbed. According to one study more than half of the weight of mite allergens within a home were found to be less than 5 μm in length (Reed and Swanson, 1986). These particles are the primary health concern since they can be inhaled into the lower airways of the lungs and if quantities are significant IgE antibodies can form, leading to allergic reactions in the susceptible portion of the population.

A number of studies have demonstrated a high prevalence of sensitization to mite allergens among patients with asthma and nonspecific respiratory symptoms (Voorhorst, 1964; Korsgaard, 1983; Platts-Mills, 1989; Smith et al., 1985; Arlian et al., 1992). In most of these studies the patients were referred to the researchers by clinics and compared with control subjects randomly selected from the same or a similar population base. Sensitization to mite allergens was demonstrated by a positive skin prick test. The study of Danish homes by Voorhorst in 1964 was the first to establish a definitive link between the presence of mite allergens and respiratory symptoms. Korsgaard (1983) confirmed this finding when he found significantly higher concentrations of dust mites in the homes of 25 asthmatic patients compared to 75 randomly selected homes. Arlian et al. (1992) conducted a five year study of 252 homes inhabited by dust-mite sensitive people in eight different regions of the U.S. They found that 83% of the homes had average mite densities greater than the estimated sensitivity threshold of 100 mites/gm of dust.

Studies in the literature also provide evidence to support a connection between damp housing and sensitivity to dust mites and childhood respiratory symptoms. For example, Murray et al. (1985) studied 774 homes inhabited by children with respiratory symptoms in British Columbia and found that over 90% of these children lived in areas defined as "humid" (i.e. indoor humidity estimated to be 50% or greater for four or more months out of the year). In addition, there was a significant difference in the number of mite-sensitive children in the "humid" areas (skin prick test positive for *D. farinae* in 31% and *D. pteronyssinus* in 40%) as compared to those living in areas defined as "dry", with an indoor RH of 50% or higher for no more than 2 months per year (skin prick test positive for *D. farinae* and *D. pteronyssinus* in 3% and 2% respectively). Verhoeff et al. (1995) conducted a study which included 259 children with chronic respiratory symptoms and 257 control children. There were more cases of mite and mold sensitization in the children with respiratory symptoms. These children were also slightly more likely to have been living in homes where mold or damp was reported or observed than were the controls.

Along with respiratory symptoms, high levels of dust mite allergens have also been correlated with atopic dermatitis (AD), characterized by itchy, irritated skin (Harving et al., 1990; August, P.J., 1984). In general, these studies suggest that those susceptible to mites (i.e. those likely to form IgE antibodies) are also likely to develop skin sensitization if exposed to high concentration of mite allergens. For example, Colloff (1992) examined the density of dust mite populations in mattresses in the homes of 23 people with AD who were mite-sensitive and found that counts were significantly higher then in the mattresses of the non-atopic control group. Colloff also cites a number of references that link atopic dermatitis to high dust mite exposure including IgE anytibody responses to mite allergens amongst patients with AD and marked clinical improvement following intensive eradication of mite allergens.

The regional diversity of mite studies in the literature suggest that mites occur indoors all over the world from arctic Greenland to tropic Africa (Anderson and Korsgaard, 1986). The study by Arlian et al. (1992) included eight different geographic regions within the U.S. They found that *D. pteronyssinus* and *D. farinae* were by far the most common species with *D. pteronyssinus* predominating in humid regions with moderate climates, and *D. farinae* predominating in areas with prolonged periods of dry weather. This finding was supported by Lang and Mulla (1977) who examined mite populations in four different climate zones of southern California and found significant numbers of *D. pteronyssinus* and *D. farinae* in 14 of 15 of the coastal homes and in 9 of 15 of the inland valley homes. *D. pteronyssinus* was the predominate species in the coastal region, while *D. farinae* predominating in the inland regions.

Mites are relatively sparse in regions with low outdoor humidity such as at high elevations and in desert areas (Brundrett, 1990; Murray et al., 1985; Lang and Mulla, 1977). However, if the indoor humidity is allowed to rise due to internal sources such as direct evaporative cooling, mite populations, particularly *D. farinae*, can become significant even when outdoor humidities are low. For example, O'Rourke (1993) evaluated 190 evaporatively cooled homes in Tucson, AZ, and detected mites within more than half of the homes, with *D. farinae* being the overwhelmingly predominant species (greater than 98% of all mites recovered).

Environmental Requirements

Mites contain about 70 -75% water by weight and must maintain this in order to reproduce (Arlian, 1992). Their primary source of water is ambient water vapor which they are able to extract directly from unsaturated air by means of a hygroscopic salt solution in the supracoxal gland (Fernandez-Caldas et al., 1994). The amount of water gained through ingestion of moist food is relatively small. Laboratory studies of *D. pteronyssinus* suggest that optimal conditions for growth and development occur between 70-80% RH at 25°C, with acceptable ranges of 55%-80% RH and 17-32°C (Anderson and Korsgaard, 1986). The upper humidity limit is constrained by the possibility of mold growth, particularly above 88%, which can inhibit mite development (Brundrett, 1990).

Arlian (1992) performed laboratory studies of both *D. farinae* and *D. pteronyssinus* and found that the critical equilibrium humidity (CEH) for fasting mites, defined as the lowest RH at which mites are able to maintain their water balance, was 73% and 70% RH at 25 °C for *D. pteronyssinus* and *D farinae* respectively. The CEH was found to be influenced by temperature and ranged from 55% at 15°C to 75% at 35°C for *D. farinae*. According to Arlian, this temperature relationship, together with the fact that feeding mites do gain small amounts of water from food, may explain why significant populations of mites are found in environments with relative humidities below 70%. Survival of mites for prolonged periods at lower humidities may also be explained in part by the crystallization of salts within the supracoxal gland, which may slow down the rate of dehydration (Fernandez-Caldes et al., 1994).

Under optimal conditions mites live for three months with three different larval stages. The survival of active adult mites (both male and female) is limited to 4-11 days at humidities below 50% RH at 25°C (Arlian et al., 1982). The protonymph, however, which is one of the dormant larval forms, can survive for months at low humidities and then evolve to the more active forms when optimal conditions return (Arlian, 1992). This observation is supported by the field study by Lang and Mulla (1978) in which the different stages of mite development were quantified. In this study a higher number of protonymphs were found when the RH fell below critical levels (50% -65% RH). These protonymphs are particularly difficult to remove with normal vacuuming since they can bury themselves within surfaces (Arlian, 1992).

As one might expect, most of mite allergens are formed by adults during their active phase. Thus, for a given number of mites, the highest levels of allergens found in the environment usually correspond to optimal humidity conditions. Arlian (1992) examined the effect of RH on mite metabolism for a range of RH's between 22% and 95%, and observed that feeding rates, and consequently the amount of fecal matter produced, increased with increasing RH. The effect was particularly significant between 75% to 85% RH, for which there was a fivefold increase in the weight of food consumed for both *D. pteronyssinus* and *D farinae*. Below the CEH, Arlian found that mites fed sparingly and produced little fecal matter. These results suggest that significant reductions in the level of mite allergens, which consist primarily of metabolic byproducts, may occur if RH is reduced below the CEH. For more detailed information on the mite life cycle and metabolism see Arlian, 1992.

Laboratory studies suggest that temperatures within the range typically found in occupied spaces have little direct effect on the length of the mite's life cycle and that mites are able to survive extreme temperature conditions for limited periods. For example, under laboratory conditions over half of *D. pteronyssinus* survive after 12 days when continuously exposed to 34°C and 75% RH while at 2°C and 75% RH, 64% of *D. farinae* adults survive after 72 hours (Lang and Mulla, 1977). Mites are also able to reproduce at temperatures as low as 17°C, albeit more slowly than at 25°C (Murray and Zuk, 1979).

Mites subsist primarily on shed human and animal skin scales. It is believed that the mites cannot digest lipids within the skin scales themselves and require the aid of xerophilic fungi, of the genus *Aspergillus,* to dissolve the lipids for them (Flannigan, 1992; Hart and Whitehead, 1990, Platts-Mills, 1989). This suggests that conditions for mite survival must also be suitable for these fungi.

Absolute vs. relative humidity

Some researchers have suggested that absolute humidity rather than relative humidity is the limiting factor controlling mite metabolism (Korsgaard, 1983; Platts-Mills et al., 1987b). However, the predominant evidence from laboratory studies and field work suggests that relative humidity is the controlling factor. Mites have a high surface-to-volume ratio and are poikilothermal (i.e. their body temperature is identical to that of the surrounding environment) (Anderson and Korsgaard, 1986). Since there is no temperature gradient between the mite and the surrounding environment, the relative difference between the air vapor pressure and the mite's internal saturation vapor pressure is proportional to the relative humidity rather than absolute humidity. Arlian (1992) has demonstrated that the driving force for the uptake of water from unsaturated air is the number of water molecules impinging on the mite's uptake surface. Arlian also performed laboratory studies which suggest that mites are able to maintain a water balance at 20°C and 79% RH, but die at 27°C and 56% RH (i.e. the same absolute humidity).

Field studies: Residential

Field studies within homes generally support the laboratory findings that indoor relative humidity is the most significant environmental condition associated with high mite populations and allergen concentrations. However, it is not clear from these studies what specific level of humidity is critical. Significant concentrations of mites and allergens have been found at indoor humidities as low as 40% RH (O'Rourke, 1993), but more often at indoor humidities above 50% RH. For example, in a study of homes in Vancouver Murray and Zuk (1979) detected significant numbers of mites only when the RH was greater than 50% for at least part of every day during the month of collection. Smith et al. (1985) also found a direct correlation between mite population and indoor RH in a study of 20 homes of mite-sensitive children, with mite populations peaking at RH of 50% or greater. Hart and Whitehead (1990) evaluated 30 homes in the UK and found that mite populations were most strongly correlated with indoor RH and that bedrooms with humidities above 64% RH contained significantly more mites in mattresses than those with humidities below this level.

Regional studies suggest that dust samples from different homes within the same region can exhibit wide differences in mite concentration due to differences in indoor humidity alone. For example, Lintner and Brame (1993) evaluated 424 homes across the U.S. and found that the greatest variations in mite population occurred as a result of differences in the indoor relative humidity between homes rather than regional climatic differences. Korsgaard (1983) conducted a four-season study of 50 Danish apartments, all within the same region, and found that seasonal variation in dust mite populations in mattresses correlated with the indoor humidity, while homes with the lowest indoor humidities did not contain detectable levels of mite populations.

Long-term studies suggest that seasonal trends in mite populations correlate with seasonal variations in indoor humidity. For example, in a nineteen-month study of six homes in southern California, Lang and Mulla (1978) found seasonal differences in species composition, with *D pteronyssinus* more abundant in July-Nov. and *D. farinae* more abundant Aug.-Dec. Both species were found to be less prevalent from late spring to July. Although monthly population fluctuations correlated with indoor relative humidity, the population increases lagged 1-2 months behind the time that conditions first became favorable, while population declines correlated directly to the time that relative humidity levels fell below critical levels (47-50% RH for *D. farinae* and 60-65% RH for *D pteronyssinus*). Arlian et al. (1982) also found significant seasonal fluctuations in the two-year study of 19 homes in Ohio, with highest densities of mites occurring during the humid summer months and lowest densities occurring during the drier late heating season. In the study by Korsgaard (1983), those apartments that had low absolute indoor humidities in the winter did not contain noticeable concentrations of mites in the summer and autumn despite the fact that the humidity conditions increased to levels that were high enough to support peak populations. This suggests that, in this case, winter conditions may have been severe and long enough to kill off even the dormant protonymph, assuming other remediation steps were not taken.

Based on a number of field studies it is also apparent that allergen levels correlate with seasonal variations and that changes in allergen levels lag behind both increases and decreases in indoor RH. Lintner and Brame (1993) studied 424 homes across the U.S. and found a distinct seasonal fluctuation of mite allergens for both *D. pteronyssinus* and *D. farinae* species, with the *D. pteronyssinus* allergens peaking in July and the *D. farinae* allergens peaking in September. In a study by Friedman et al. (1992) of homes in the upper Connecticut River Valley, there was a marked seasonal increase in total *D. pteronyssinus* allergens from June to September. . In a one-year study of 12 homes in central Virginia, Platts-Mills et al. (1987a) found that increases in both mite population and allergen levels lagged approximately one month behind increases in indoor humidity and that several months passed before a fall in allergen levels was detected after a drop in indoor humidity.

In all of the field studies cited, the highest concentrations of mites were found in mattresses, thick carpeting, and/or heavily used fabric-upholstered furniture. This suggests that mites thrive best within microenvironments that contain a source of food (shed skin scales) and have a relatively high and consistent moisture level. For example, bedding is a common site for mites because there is an ample supply of food and the humidity within an occupied bed is higher than that within the air of the surrounding space. This is also true of upholstered furniture, with permeable fabric that can absorb and retain the moisture given off by an occupant. Field studies have found less variation over time in the number of mites within bedding as compared to other sites (Smith et al., 1985). Murray and Zuk (1979) also found significant numbers of mites in mattress dust during the winter even when indoor RH fell below 50%.

Carpeting can also be a localized site of increased humidity and consequently may be an important reservoir for allergen in both homes and schools. Studies conducted in schools have demonstrated that carpets contain high levels of a variety of allergens including pollen, cat and dog dander and mite and mold allergens (Fernandez-Caldas et al., 1994). This may be the primary source of exposure for young children who generally live closer to the floor and do not have high exposures in bedding since they usually sleep on plastic covered mattresses. Arlian (1992) studied the micro-environment of a carpeted floor and found that the relative humidity within the carpeting was 9.6% higher than that of the ambient air 1-2 meters above the floor. This was attributed to the decreased temperature of the floor, (3.7°C lower on average than the ambient air) which drove the relative humidity up. In this study, Arlian also found that long-pile carpeting contained significantly more mites than short pile carpets and tile or wooden floors (i.e. short-pile carpets did not contain significantly more mites than floors without carpets). This finding is also supported by a study by O'Rourke (1993) in which house mites were found four times more frequently in homes with wall to wall carpets than in homes with other floor types.

Field Studies: Office Buildings

The few studies of mite populations that have been conducted within commercial buildings have shown that mite levels are generally low (Menzies et al., 1992). In a study of office buildings in the mid-Atlantic states, Hung et al. (1992) found moderate-to-high levels of mite allergens within carpeting and chairs of one of the five buildings studied. In a study of buildings in New England area by Friendman et al. (1992), very low population levels of dust mites were found within the carpets of workplaces . The observation of low mite levels within commercial buildings may not be surprising since these buildings tend to be less humid than residences due to the frequent use of air conditioning and fewer internal sources of moisture (e.g. cooking, showering, etc.). In addition, commercial buildings do not usually contain bedding and thick carpeting, the most common sites for mites in residences. It has also been suggested that mites tend to be more common on ground floors than upper stories and are rare in hotels (Reed and Swanson, 1986).

Remediation

The strong correlation between indoor relative humidity and dust mite population has led to recommendations to reduce indoor humidity. However, exactly where upper limit should lie is not obvious. Most of the field studies suggest that when indoor humidity is kept below 50% RH, mite populations do not grow to significant levels. Laboratory studies, on the other hand, in which the microenvironment of the mite is in equilibrium with the surrounding air, suggest that mite population growth and metabolism (related to the amount of allergen produced) can be significantly reduced if relative humidity is kept below 70% RH at 25°C (Arlian, 1992).

One reason for the discrepancy between field and laboratory studies may be the difference in relative humidity between the mite's microhabitat, which can be considered to be within a few millimeters of the horizontal surfaces on which they lie, and that of the surrounding air due to differences in temperature as well as the ability of certain types of surfaces to retain moisture. The humidity measurements for the field studies cited were taken from the air within the core of the room, which may not correlate with the RH within the microenvironments from which the mite samples were taken. The time frame of the RH measurements was also not indicated for most of these field studies - instantaneous measurements taken at the time of sampling may not be representative of long-term conditions. In addition, seasonal changes in indoor humidity have a significant effect on mite populations and allergen levels as suggested by the long-term field studies; however the specific time constraints have not yet been resolved.

There are a number of effective remedial methods directed at reducing allergens and mites within their microhabitat in addition to control of relative humidity. These include specialized vacuuming procedures, removal of high pile carpeting and heavily used upholstered furniture, regular hot water cleaning of bedding, covering mattresses and pillows with vinyl casing, and application of acaricides (Htut, 1994). For example in a study of laundry procedures, McDonald and Tovey (1992) found that all mites were killed by water at 55°C or higher. In a study by Platts-Mills et al. (1989), a tenfold or greater reduction in mite-allergen levels was achieved in many houses by hot washing all bedding at least every 10 days, and removing carpets and upholstered furniture. Wickman et al. (1994a), found a significant decrease in mite allergens levels on mattress surfaces six months after they had been encased with a semipermeable polyurethane cover. Based on the observed seasonal effects for temperate climates, it seems that late winter and early spring are the best times to clean mattresses and carpets aggressively to kill the few mites that survived the winter. Theoretically, this should reduce the chances of having a large infestation in the summer months.

Vacuuming is effective only if central vacuuming systems, HEPA filters, or systems that entrain dust in a liquid medium are used. Conventional vacuuming does not help to reduce mite populations and allergens within carpets, and can actually aggravate the problem. Allergens particles in the size range of the greatest health significance ($< 2\ \mu m$) easily pass through the filter bags of conventional vacuums, causing a significant increase in the concentration of airborne allergens during and shortly after vacuuming (Kalra et al., 1990). In a two year study of mites in 19 homes in Ohio, Arlian et al. (1982) found no significant correlation between the number of mites and the frequency or thoroughness of cleaning, amount of dust, or age of furnishings or dwelling. Arlian (1992) suggested that the ineffectiveness of cleaning may also be related to the difficulty in removing larval forms of mites adhering to surfaces.

Acaricides are now available which have been specially designed to eliminate mites from carpeting. One such product uses benzyl benzoate as the active ingredient. It is formulated as a moist powder with a wax to bind mite fragments and excrement so that they can be vacuumed. It is designed to be reapplied every six to eight months. Results from a number of studies suggested that this product has been successful in reducing mite populations (Htut, 1994). Benzyl benzoate was initially marketed in Europe and has been approved for use in all states in the U.S. except California (Center Laboratories, 1994). Fungicides, such as natamycin, kill the fungi required by mites to digest lipids in the skin scales and have also been used with some success (Flannigan, 1992; Platts-Mills et al., 1987b, Htut, 1994) however, in one study in which a double-blind, placebo-controlled method was used, no significant improvement was observed (Reiser, et al. 1990). Other surface treatments which have been used include liquid nitrogen, benzyl benzoate in combination with tannic acid, and benzoic acid (Htut, 1994).

Other possible methods of reducing mite levels include the use of electric blankets, which can reduce the local humidity within bedding (Hart and Whitehead, 1990) and dehumidification/air conditioning (Lintner and Brame, 1993). According to a study by de Boer and van der Geest (1990), a reduction in dust mite populations of 19-84% can be achieved by heating the mattresses with electric blankets when the beds are not being slept on. In a field study by Cabrera et al. (1995), dust mite allergens were reduced by more than 50% with the use of a dehumidifier.

Improved ventilation systems within homes can also help to reduce mite levels by counteracting internal sources of humidity, such as cooking and showering in climates where outdoor humidity is not the major source of moisture. Wickman et al. (1991) suggest that house dust mite infestation used to be rare in Stockholm, however, mite sensitive children are now frequently observed which may indicate an increased infestation rate. The authors attribute this to a reduction in the ventilation rate resulting from energy conservation programs. In a follow-up study, Wickman et al. 91994b) looked at the concentration of dust mites in seventy homes in Stockholm belonging to two major house types: those with crawl-space basements and those with concrete floor slabs and determined that the highest risk factors for allergen concentration exceeding the median were unimproved natural ventilation (i.e. no mechanical exhaust), concrete floor slabs and condensation on windows. In a study of Danish homes, Harving et al. (1994) found that decreases indoor humidity through the use of use of supply and exhaust ventilation systems significantly reduced dust mite levels.

FUNGI

Introduction

Fungi (via airborne fungal spores, fragments of hyphal mat, and metabolic byproducts) have been linked to a number of adverse health effects, including allergic reactions, hypersensitivity pneumonitis, mycotoxicosis and pathogenic disease. In general, however, fewer people are allergic to fungi than to dust mites and animal dander (Flannigan et al., 1991). Beaumont et al. (1985) demonstrated that many more respiratory patients with suspected allergies react to animal dander (34%) and house dust (44%) than to molds (3%). The most common genera known to cause asthma and rhinitis include *Alternaria, Aspergillus, Cladosporium* and *Penicillium* (Flannigan and Miller, unpublished). A few genera, such as *Aspergillus* (*A. niger* and *A. fumigatus*), *Histoplasma and Cryptococcus,* are pathogenic and can infect the lungs, ears or eyes in susceptible hosts; however, reported cases are relatively rare (Gravesen, 1979; Flannigan, 1992; Miller, 1992). Metabolic gases produced by fungi contain volatile organic compounds (VOC's) that are responsible for the mildew odor. These VOC's may be a contributing factor of sick building type symptoms including eye, nose and throat irritation, headache and fatigue (Bjurman, 1993). In a study of microbially contaminated buildings, VOC's of the type commonly associated with indoor manmade materials were actually found to be the metabolic by-products of fungi growing in the buildings (Bayer and Crow, 1993). High indoor spore levels of fungi, such as *Cladosporium* and the dry rot fungus *Sepula* have been associated with cases of hypersensitivity pneumonitis. Fungal spores and vegetative mycelium are also known to contain toxic substances (mycotoxins) that can lead to respiratory symptoms unrelated to allergic mechanisms (Flannigan and Miller, unpublished). Flannigan et al. (1991) list a number of toxigenic species isolated from the indoor air of houses.

Most fungi originate outdoors and are saprophytic (i.e. grow on substrates of dead or dying plant and animal matter). Outdoor concentrations vary with the season, the time of day, local weather conditions, and whether the site is rural or urban. For example, phylloplane (leaf-loving) fungi, which include *Cladosporium* and *Alternaria*, are more common in rural areas and show a strong seasonal activity with peak concentrations in the summer. *Penicillium* and *Aspergillus* are the most common soil fungi found in urban environments and airborne spore concentrations of these species remain relatively constant throughout the year (Brundrett, 1990). Fungal spores are typically in the range of 3 to 30 μm in diameter and once they are released into the air, can travel intercontinental distances. Airborne spores enter buildings through ventilation equipment and can set up colonies on surfaces where moisture and nutrient conditions are favorable.

Buildings with no internal sources of fungi have nearly the same proportion of fungal species as outdoor air, with total counts reduced due to settling and filtration within air conditioning equipment. In a study of Canadian office buildings, Miller (1992) found that those buildings not associated with microbial problems had micofloral counts that were qualitatively similar and quantitatively lower than those of outdoor air, while contaminated buildings tended to have a higher proportion of nonphylloplane fungi, particularly *Penicillium and Aspergillus.* In a study of fungal concentrations within day-care centers and dwellings, Hyvarinen, et al. (1993) found that the total concentration of airborne fungal spores were higher in moldy buildings. In addition, the concentrations of *Aspergillus* and *Oidoidendron* in the fall and *Aspergillus* and *Penicillium* in the winter were higher in the mold problem buildings than in reference buildings. The presence of wet-habitat fungi, such as *Phoma, Stachybotrys, Trichoderma* or *Ulocladium* in significant quantities suggests the existence of either rotting vegetation near the air intake or an extremely damp amplification site within the building (Flannigan, 1992). Xerophilic species, including the toxigenic species *Penicillium auranteogriseum* and *Aspergillus versicolor*, can form an appreciable percentage of the population within indoor dust samples. These had not been widely detected until the recent use of new sampling methods designed for detection of xerophilic species (Miller, 1992).

Environmental Requirements

Fungi need water, carbon and nitrogen for growth, as well as minute amounts of other nutrients normally present in natural environments. Typical construction materials containing nutrients used by fungi include wood, cellulose, wallpaper, organic insulation materials, textiles (especially natural fibers) and glues and paints containing carbohydrates or proteins. Although materials such as metal, concrete, plastics, glass fiber, and other synthetic products cannot be used directly by fungi, they can collect organic debris that serve as a nutrient source for fungi. For example, despite air filtration, some dust containing living microorganisms passes through air handling units and settles on porous insulation within ducts. If this insulation material then becomes wet, (e.g. due to condensation) fungi will grow and release spores into the ventilation air (Morey and Williams, 1991; Pasanen et al., 1993).

Fungi acquire most of their nutrients through a solvent process (Griffin, 1981). Thus the moisture on and within a substrate is the important factor determining fungal growth rather than the moisture of the ambient air (Block, 1953). Laboratory studies support this observation. For example, Pasanen et al. (1991), measured colony diameters for both *Penicillium* sp. and *Aspergillus fumigatus* as a function of RH in the range of 11 to 92% and found that fungal colonies grew on wet substrates even at low levels of atmospheric humidity. The authors conclude that growth is dependent on substrate moisture and not directly affected by atmospheric moisture. Systems containing water, such as the water reservoirs of humidifiers, favor growth of bacteria, algae, protozoa and certain types of fungi, especially yeasts. Most fungi, however, prefer surfaces of moist materials to liquid water (Pasanen et al., 1992). Thus since nutrients and airborne fungal spores are abundant within buildings, the availability of moisture on and within surfaces appears to be the limiting factor for growth.

Fungi are able to withstand dry periods to some extent by becoming dormant or by utilizing metabolically-generated water that they add to the substrate. For example, wood will not decay if the moisture content is below 20-25% of its dry weight, except when it has been invaded by a dry rot fungus such as *Merulius lacrymans*, which is able to translocate water (Moore-Landecker, 1982). Soil and wood-inhabiting fungi grow better in moderate rather than high moistures since soil aeration (and therefore oxygen supply) is limited when moisture content is high (Moore-Landecker, 1982).

In general, fungi can grow at temperatures between 0°C and 40°C. Below temperatures of 0°C the fungi may survive but will not continue to grow and above temperatures of 40°C fungi cannot survive for prolonged periods (TenWolde and Rose, 1993). Temperature variations within the range found in most conditioned buildings do not appear to be a limiting factor but may affect growth rates. For example, the study be Pasanen et al. (1992) demonstrated that both *Penicillium* sp. and *Aspergillus fumigatus*, grew at all temperatures from 10 to 30°C, with *Aspergillus* growing fastest at 30°C and *Penicillium* fastest around 20°C.

The potential for fungal growth on a substrate has often been attributed to moisture content (MC), defined as the ratio of "free water" in the material to the material's dry weight after being dried in an oven (free water refers to water held in a porous material by Van der Waals forces [i.e. hydrogen bonding] or capillary attraction, as opposed to water of hydration which is chemically bound to the materials). For wood products percent moisture content is defined as the weight of removed water divided by the weight of oven dried wood. Wood consists of hygroscopic cell walls surrounding cellular spaces filled with water and/or air. Below fiber saturation, the point at which the cell walls are fully hydrated yet with no water contained in the cellular spaces, fungal growth is inhibited since the fungi are not able to readily extract the water held by Van der Waals forces (Wilcox, 1995). The fiber saturation point for wood occurs at a MC's of 25 to 30%.

Although moisture content is commonly referred to, it is not the most appropriate measure of a substrate's potential to support fungus. This is because materials differ in how tightly they hold free water and the measurement of moisture content may vary depending on the procedure used. For example, Block (1953) evaluated fungal growth on a number of different materials, including, leather, wood, cheese, wool and cotton, and found a common mold-growth-threshold value of about MC = 0.1, which has been often quoted in the literature. This is significantly below the fiber saturation point for wood. More recently, Foarde et al. (1993) demonstrated a critical MC of 0.055 to 0.065 for Penicillium growing in porous ceiling tiles.

It has been suggested that for biological purposes the more physically meaningful parameter is water activity, a_w, defined as the ratio of the water vapor pressure at the surface of the moist material to that of a pure liquid water surface at the same temperature and pressure (Ayerst, 1969; Griffin, 1981; Flannigan, 1992). This is also referred to as the 'equivalent relative humidity' (ERH) when written in the form of a percentage (i.e. an a_w.of 0.80 is the same as an ERH of 80%). ERH is equal to RH at the surface of the material only when the system is confined to the extent that the atmosphere above a moist surface is at the same vapor pressure and temperature as that directly at the moist surface. In actual environments however there is usually a gradient of vapor pressure from the surface into the air above or *vice versa*. In this case the relative humidity of the air has only an indirect influence through drying and moistening of the materials it contacts.

In general, favorable conditions for fungal growth depend on the species and the type of substrate on which it is growing. In addition, fungal growth does not occur in isolation but rather within a complex microbiological system that includes yeasts and bacteria as well as molds. The following excerpt from Flannigan (1992) presents his ecological classification of molds in terms of their moisture requirements, and describes the process by which different types of molds take hold and grow:

> "Although all molds growing on surfaces in buildings grow most rapidly in pure culture at a high a_W,. . . individual species can be classified as:
>
> - Primary colonizers, which are able to grow at an a_W of less than 0.80 and also are referred to as xerophilic fungi because they are able to grow at lower a_W than other molds, e.g., species in the *Aspergillus glaucus* group (*A. amstelodami, A. repens*, etc.), *A versicolor*, and *Penicillium brevicompactum.*
>
> - Secondary colonizers, which are able to grow at an a_W of 0.80-0.90, e.g., *Cladosporium cladosporoides* and *C. sphaerospermum.*
>
> - Tertiary colonizers, which are only able to grow at an a_W more than 0.90, e.g., *Alternaria alternata, Phoma herbarum, Ulocladium consortiale,* and *Stachybotrys atra.*
>
> Where there is ingress of water over a restricted area, e.g., as a result of rain water penetrating via a structural fault in a wall, tertiary colonizers may be found at or near the site of ingress and primary colonizers, such as *A. versicolor* and *Penicillium*, at the less wet margins of the affected area (Grant et al., 1989). Pasanen et al. (1992) found that *Aspergilli* and *Penicillia* (primary colonizers) grew under all conditions when samples of timber, plywood, gypsum board, fiberboard, and wallpaper were incubated in atmospheres of 75-76% RH and above, but species of *Cladosporium* (secondary colonizers) and *Stachybotrys* and *Trichoderma* (tertiary colonizers) only developed at the highest RH, where the substrate a_W would be 0.96-0.98. The degree of dampness determines what species are able to grow and sporulate, and therefore strongly influences the composition of the spora in indoor air."

This statement agrees with the findings of Kalliokoski et al. (1993), who carried out a controlled chamber study of fungal growth on a number of moisture-damaged building materials. Based on this study the authors suggest that fungal growth is dependent on temperature, composition and hygroscopicity of materials and fungal species and is likely when ERH exceeds 76-96%. The growth rate of a xerophilic fungi from a number of different ecological sites and contaminated materials was studied in the laboratory by Avari and Allsopp (1983). Optimum ranges for growth were found to be between a_w levels of 0.97 and 0.90. For all of the species studied no growth was observed after one month at a_w levels of approximately 0.80. This study is in agreement with the recommendation by the International Energy Agency Annex that the monthly average water activity of a material surface should not exceed 0.8 (TenWolde and Rose, 1993). This recommendation recognizes the importance of the surface microclimate and was developed in response to the request from building professionals for a simple criterion to judge the likelihood for mold growth.

Field Studies

The most common cause of fungal spore contamination within residences is condensation on surfaces and reoccurring spills or leaks (Seltzer, 1995). Besides superficial condensation, interstitial condensation within porous building materials such as concrete, brick and or plaster, may provide a reservoir for fungal growth. Interior dampness problems are usually related to construction faults, such as inadequate insulation and thermal bridges, in combination with inadequate ventilation and /or the pattern of usage within homes. For example, in a study of 86 newly built energy-efficient residences in the Pacific Northwest, Tsongas (1991) found that one-third had mold growing on indoor wall surfaces and one-third had mold on window frames and/or sills. Although homes were well insulated, condensation still occurred due to internal sources of humidity that were not properly ventilated. Nevalainen et al. (1991) studied residences in Finland, where microbial problems in buildings are relatively uncommon due to the heating and insulation requirements of a cold climate. They found that most of the houses with mold problems had improperly weather-proofed outside walls that allowed rainfall into the insulation material, and/or inadequate drainage that allowed moisture to penetrate in through the floor. Becker (1984) conducted a post occupancy evaluation of 200 homes in a coastal region of Israel, which has mild winters. He concluded that condensation was the main source of fungal growth and that the major factors contributing to mold problems were: location and orientation of the dwelling (affecting wall surface temperatures), occupancy density, cooking habits and the type of paint or wall covering. Abe (1993) developed a biosensor method, using a xerophilic fungus, to study the potential for growth within different microenvironments of a Japanese apartment. A significant variation between and within rooms was evident with lower potentials for growth observed in spaces with walls adjacent to internal spaces and highest potentials observed at cold corners of northern and eastern walls adjacent to the outside.

The most extensive fungal contamination problems occur in hot humid climates and control of indoor humidity in these regions is an important factor. Bayer and Downing (1992) observed fungal contamination in schools in a climate where outdoor humidities ranged from 75% to 90% for most of the year. High indoor humidities resulted in visible mold growth on ceiling tiles, fan coil units, papers and books. In one case, carpeting adhesive was not able to cure in the highly humid conditions and provided a medium for microbial growth. Effective remediation procedures focused on removing/cleaning contaminated materials and controlling indoor humidity levels.

Within commercial buildings, microbiological contamination is frequently a result of inadequacy or absence of preventive maintenance of conditioning systems. Morey (1988) evaluated the occupied space and HVAC systems of 21 commercial buildings for the presence of microbiological reservoirs and amplification sites. Microbiological growth was detected in eighteen of the 21 buildings. In nine of the buildings contamination was found in the porous duct insulation. Other significant sources included stagnant water in drain pans (ten buildings), excessive relative humidity (six buildings), flood damage (six buildings) and the location of outdoor air intakes near external bioaerosol sources (six buildings). Ezeonu et al. (1994) demonstrated that the fiberglass duct liners and boards from eight buildings whose occupants complained of unacceptable or moldy odors were heavily colonized by fungi, particularly by *Aspergillus versicolor*.

Remediation

The most effective remediation procedures depend on the source of the contamination and regional climatic conditions. Control of indoor humidity is an important factor in hot humid climates, however, for other climate types other means of controlling moisture, such as insulation to keep interior surfaces above the dew point, proper placement of vapor barriers to control vapor and air flow between indoors and outdoors, and control of external rain and ground water penetration into the building, may be more critical. Proper maintenance of HVAC equipment is also an important factor, particularly in commercial buildings. This may require design innovations focused at improving accessibility and maintenance procedures. These issues are discussed in further detail in Part II of this paper.

Once a material has become contaminated it is almost impossible to completely eliminate the fungi and removal is often the only option. In a recent study of microbial growth in chipboard, Thogersen et al. (1993) found that water-damage resulted in massive growth and that even after drying, the material still contained spores. Use of biocides is usually discouraged, since most are toxic and continuous use may increase corrosion and encourage the development of resistant strains (Nevalainen, 1993). Bleach treatment has been unsuccessful in cleaning contaminated duct liners (Morey, 1988).

BACTERIA AND VIRUSES

Introduction

Most viral and bacterial respiratory infections are transmitted between human hosts. This may occur by touching an infected person or object they have infected, or by inhaling contaminated airborne droplets expelled from the nose and mouth during sneezing, coughing, and talking. Most of these airborne droplets are large enough to fall to the ground within a meter. Smaller droplets quickly shrink through desiccation to form "droplet nuclei" which are small enough, between 0.5 and 5 µm in diameter, to remain suspended in the air for long periods of time (Laforce, 1986). Droplets within this range are of the greatest important when considering health effects since they are small enough to penetrate deep into the lungs. If these droplets contain viable infectious organisms and are in sufficient numbers they will cause infection in susceptible hosts. Relative humidity can affect the desiccation process of droplets, which in turn affects droplet size and the viability and infectivity of the airborne pathogens (Burge and Feeley, 1991). For more on specific types of infectious disease see Burge (1989 and 1995).

Airborne Viability

Most of the information concerning viability of airborne pathogens has been determined through *in vitro* studies. Evidence from these studies suggests that humidity level has complex effects on the viability and virulence of airborne pathogens that varies from organism to organism, while the effect of temperature is not significant within the range of interest for conditioned environments. In many cases certain bacteria were found to have a window of relative humidity at which they died more quickly (Anderson et al., 1968; Cox, 1966; Brundrett, 1990). For example, Cox (1966) found that *Escherichia coli* strain jepp had minimal viability in the range of 70 to 80% RH and that viability increased at RH values above and below this window. The results of a study by Hambleton et al. (1983) suggest that *Legionella pneumophila* has minimal viability at two humidity levels, between 50 to 60% RH and at 30% RH. Hambleton et al. also demonstrated that at the optimum humidity of 65% RH only about 20% of the cells are viable after one hour. Experiments on the bacterium *Pneumoccus* suggest a sharp decrease in viability in a narrow band at 50% RH (Brundrett, 1990). In a study of the survival of *Streptococcus*, Flynn and Goldberg (1971) found that the change in viable count was insignificant for RH range of 0 to 92%.

In vitro studies of viruses suggest that particular strains including *mengovirus 37A*, *polio virus*, *foot-and-mouth disease virus*, and *encophalomyocarditis virus* are unstable as aerosols in atmospheres below about 70% RH (Cox, 1989). In contrast to these viruses, other strains, including *vesicular stomatitis*, *vaccinia* and *influenza*, are least stable at high RH.. Cox suggests that this difference can be attributed to specific structural differences in the viruses. Mbithi et al. (1991) studied the survival of hepatitis A virus on surfaces at RH levels of 25%, 55%, 80% and 95%. and found that the survival of the virus was inversely proportional to the level of RH and temperature.

Expelled droplets and skin flakes that settle out may survive in dust and transmit disease if re-entrained when surfaces are disturbed. There is evidence that outbreaks of bacterial infections in hospitals have been associated with cleaning processes (Brundrett, 1990). Studies of viability of bacteria in dust suggest that there is a trend of decreasing viability with increasing relative humidity (Brundrett, 1990). In addition, dust is less likely to become airborne at higher humidities.

Field studies of airborne pathogen survival at high humidities are limited. Studies at lower humidities suggest a higher survival rate for airborne viruses at humidities below 30% (Green, 1985). In general, considering the results from *in vitro* studies, there is little evidence to suggest that for humidities in the upper range (> 50% RH) one specific level is better than any other in reducing the viability or number of suspended microorganisms.

Building-Related Sources

A few microbes, pathogenic to humans, are able to flourish in non-human environments. These can be introduced into building systems from outside sources and proliferate if conditions are favorable. The most important example of such a contaminant is *Legionella,* which can lead to fatal pneumonia in susceptible hosts. Aside from Legionnaire's disease, no specific infections have been documented to be of great clinical importance in commercial buildings (Hodgson, 1989).

Hypersensitivity pneumonitis has been directly associated with microorganisms (particularly thermophilic actinomycetes) cultured from poorly maintained humidification and air conditioning systems (Hodges et al., 1974; Fink et al., 1976; Burge et al., 1980). Patients often report a relief of symptoms upon avoidance of the environment containing the offending contaminant (LaForce, 1986). Outbreaks of bacterial infections in hospitals and flare-ups of asthma have also been associated with humidification systems (Covelli et al., 1973; Airoldi and Litsky, 1972; Smith and Massanari, 1977; Solomon, 1974; Bencko et al., 1993) In all these cases the offending humidifiers have been of the spray or mist types that form aerosols in the airstream.

Use of direct evaporative cooling is a potential concern because poor maintenance, which is not uncommon in residential systems, can result in microbial growth within sump water (Macher and Girman, 1990; Stetzenbach 1994). However, it is not apparent that this could lead to an outbreak of disease. One study of direct evaporatively cooled homes in the Los Vegas area traced the presence of gram-negative bacteria to a fouled sump in one of the homes although none of the dwellers were infected (Stetzenbach, 1994). In a laboratory study using tracer organisms, Macher (1994) found "minimal transfer" from the fouled sump into the air under normal operating conditions. Conversely, direct evaporative cooling may help to reduce human-to-human spread of infectious disease because of the relatively high supply rate of outside air required. Increased ventilation has been shown to lead to decreased rates of viral respiratory infections (Burge and Feeley, 1991) and is often a recommended means of reducing indoor air contaminants (ASHRAE Standard 62-1989).

NON-BIOLOGICAL AIR POLLUTANTS

Formaldehyde

Formaldehyde is found in numerous building materials including plywood, particleboard and other pressed wood products, furnishings, carpets and textiles. It is also a major component of urea-formaldehyde foam insulation, which is now banned in the U.S.. Formaldehyde is highly water soluble and causes irritation of the mucous membranes within the eyes and upper respiratory tract at concentrations starting at 0.1 ppm, but is most frequently reported at or above 1 ppm (Berglund, 1992). Formaldehyde is also classified by the EPA as a probable carcinogen. Both ASHRAE and the World Health Organization have set maximum guidelines of 0.1 mg/m^3 to ensure sufficiently low formaldehyde concentrations in indoor air (Puhakka, 1993; Gammage, 1990). The effect of these standards, along with the ban on urea-formaldehyde foam insulation, has been an overall decrease in indoor formaldehyde concentrations within the last decade (Marbury and Krieger, 1991).

The rate of formaldehyde offgassing from pressed wood products decreases exponentially with age and is sensitive to a number of factors, including the initial properties of the material, temperature, and humidity, (Gammage, 1990; Meyer, 1986). Laboratory and field studies agree that temperature is the most significant environmental effect (van Netten et al., 1989, Godish and Rouch, 1986, Arundel et al., 1992). In general, since formaldehyde within binding resins is water soluble, higher humidity levels also tend to increase the offgassing rate. In a controlled environment study within mobile homes, a decrease in humidity from 70 to 30% resulted in an approximate 40% reduction of formaldehyde levels (Godish and Rouch, 1986). In a study of formaldehyde off-gassing from chipboard within a controlled chamber, Anderson et al. (1975) found that the formaldehyde concentration within the air was directly proportional to temperature and air humidity. A change in relative humidity from 30% to 70% doubled the equilibrium formaldehyde concentration, while a 7°C rise in temperature in the range of 14°C to 35°C caused the formaldehyde concentration to double. In a study of twenty homes referred to by Arundel et al. (1992), a significant correlation was found between the indoor relative humidity and the formaldehyde concentration in the air (Arundel et al., 1992).

Seasonal fluctuations have also been observed, with the highest rates of offgassing occurring in summer months when marked increases in temperature, solar gains (which can cause localized increases in wall temperature), and humidity occur (Marbury and Krieger, 1991). Puhakka et al. (1993) studied 46 apartments in Finland and found that the concentration of formaldehyde in the air increased from 0.08 mg/m^3 to 0.20 mg/m^3 when the relative humidity increased from 34% to 70% during a period of 24 hours. In addition, they found that short term increases in relative humidity within a period of 1-5 hours, as occurs when using a sauna or drying clothes, also caused increases in formaldehyde levels. The off-gassing rate of chipboard within a chamber was also examined in this study and it was found that sealing chipboard on all sides with "reactive paint" significantly reduced off-gassing rates.

Ozone

Ozone is well-recognized as a respiratory irritant and a significant problem in urban areas of southern California where the EPA standard for outdoor ozone concentration is often exceeded. Ozone is formed as a result of reactions between photochemically reactive hydrocarbons and oxides of nitrogen under the influence of sunlight. Because of its strongly oxidizing properties and low water solubility, ozone can penetrate deep into the alveoli of the lungs and affect lung function. It is also an irritant to the mucous membranes of the eyes.

The primary source of ozone indoors is infiltration/ventilation of polluted outdoor air. Indoor sources of ozone such as photocopiers and air cleaning equipment exist; however under normal living and working conditions there is no evidence that these would reach high enough levels to be of concern. Once indoors, ozone decomposes through heterogeneous reaction with indoor surfaces. Mueller et al (1973) estimates the half-life of ozone in a typical bedroom to be less than six minutes, while Weschler et al, (1991) suggests a half-life estimate of 11.1 minutes for a typical office environment with a surface to volume ratio of 2.9 m^{-1}. Using this general knowledge, authorities have typically advised the public to remain indoors and reduce infiltration as much as possible during episodes of high outdoor ozone levels. However, this recommendation is not useful for those buildings that depend on natural ventilation or evaporative cooling as a means of cooling. This condition is made more problematic by the fact that ozone episodes often correspond with high outdoor temperatures.

In the study by Weschler et al (1991) ozone concentrations were measured for three office buildings with different ventilation rates. The indoor values closely tracked that of the outdoor values, and, depending on the ventilation rate, were 20 to 80% of those outdoors. Weschler also cites a number of previous studies in which the concentration of ozone in the indoor environments was measured to be 10-80% of outdoor concentrations. Considering the this information along with the fact that people spend greater than 90% of their time indoors, Weschler suggests that exposure (concentration x time) to ozone indoors is a more significant issue than outdoor exposures.

There is little information regarding the effect of humidity on ambient ozone concentrations within indoor environments. One controlled chamber study found that the rate of ozone decay increased as either temperature or humidity were increased (Mueller et al., 1973). However, in the case of direct evaporative cooling, this may not be a significant effect compared to that of the higher ventilation rate. The impact of direct evaporative cooling vs. refrigerated air conditioning was studied by Stock and Venso (1993) in homes in El Paso and Houston. They found that the average indoor/outdoor ratio of ozone concentrations was much higher in homes with evaporative as compared to those with refrigerated air conditioning systems (0.7 vs. 0.1).

The most promising remediation method available is the use of activated carbon filters, which have been shown to be successful in significantly reducing ozone levels (Mueller et al., 1973; Weschler et al, 1991). It may be possible that these could be incorporated into evaporative coolers. However, such factors as the engineering practicality, cost, efficiency and service life would need to be tested under actual usage conditions in order to determine if this option is viable.

Nitrogen and Sulfur oxides

As with ozone, nitrogen and sulfur oxides are produced primarily from outdoor sources. However, nitrogen dioxide, along with nitrous and nitric acids, are also combustion byproducts of gas cooking stoves and heaters and can accumulate indoors as a result of improper ventilation. Nitrogen and sulfur oxides react with water on indoor surfaces to form acid aerosols, which are generally found in higher concentrations indoors (Leaderer et al., 1993). Although nitrogen and sulfur oxides are common pollutants, surprisingly little work has been done thus far in determining the respiratory toxicity of their acid aerosols. Their acidic nature, reactivity and aqueous solubility, however suggest that respiratory damage is possible (Brauer et al., 1993) and increased indoor humidity does seem to increase heterogeneous reaction on surfaces. In one chamber study it was found that at the highest relative humidity tested, 80%, nitrous acid (HONO) concentrations were approximately 8% of the observed NO_2 level, while at 30% and 45% relative humidity resulted in $HONO/NO_2$ ratios of 0.9% and 2.7%, respectively (Brauer et al., 1993). In terms of direct evaporative cooling, again the issue of high ventilation rates may be a significant factor to consider if outdoor air levels of nitrogen and sulfur oxides are high.

DISCUSSION

To the maximum extent possible, building standards should reflect the knowledge available when they are written. The subject of humidity limits is a complex one, and many questions remain at this time. Nonetheless, there is a wide range of research underway through numerous disciplines, much of which can inform the preparation of standards. This paper summarizes this research and suggests a format for putting new information into a building standards context.

A paper by Sterling et al. (1985) also addresses the topic of humidity and health in buildings and is the only cited reference pertinent to humidity in ASHRAE Std. 62-1989. This paper includes a figure that has received wide circulation within the HVAC engineering profession. It graphically depicts humidity impact zones using bars that decrease in width suggesting a decrease in the effect for each of the eight environmental health factors addressed. These bars converge for all of the eight categories into a narrow recommended 'optimum zone' between 40 and 60% RH. Both low and high humidity effects are addressed. There is clearly a need for such a summary, because it has reappeared in numerous journals and conferences (Arundel et al. 1986, 1992). It is also arrestingly drawn and easy to grasp, which adds to its appeal. This figure is the basis of the recommendation in ASHRAE Std. 62-1989 that humidity in the occupied space be between 30 and 60 % RH.

There are issues that may be raised with a figure that attempts to combine the influences of so many factors. One concern is that it does not assign relative weights (severities) for the different health factors. Another is that the practicality of the recommended humidity limits in various climates and building types is not assessed. In practice, these issues need to be addressed. As an example, ASHRAE Std 62-1989 overrides (without explanation) the recommended lower limit of 40%, lowering it to 30% although, based on the figure, the impact of this action is not much different than that of raising the upper limit from 60% to 70%. This may have represented a value judgment by ASHRAE about the relative severity of the different health effects, differences that are not expressed in the figure. Conversely, the change may have been forced by practical reality in conditioning the indoor environments of buildings.

In defense of the figure, it is ultimately necessary for designers to make decisions combining disparate elements even without complete justification. Someone needs to draw a line in the sand. The figure does this for them.

A more severe criticism is based on the factual substantiation of the health impact zones presented. As the figure is drawn and captioned ('decrease in bar width indicates decrease in effect') these zones imply linear relationships between humidity and health effects that are not supported by the literature. In addition, the focus on ambient RH to the exclusion of other environmental conditions is misleading in that it suggests that RH is the controlling environmental factor for all of the pollutants listed without regard to climate and the conditions of the building system.

In addition, the specific points at which these zones begin and end are not consistently supported by the references provided. The recommendations for bacteria (RH below 60%), viruses (RH below 70%), and fungi (RH below 60%) are not supported by the discussion or the references given in the original paper (Sterling et al. (1985) or its more recent versions. The literature cited for the mite recommendation (below 50% RH) is incomplete and the significant impact of seasonal effects and building type are not addressed. Furthermore, the specific categories used in the figure do not clearly follow from the text. for example, it is not clear what the humidity limits for 'allergic rhinitis and asthma' are based on. As the figure is drawn it appears that they are based a combination of the limits for 'mites' and 'fungi', although most of the discussion in the text concerns problems of mist humidifiers and low humidities. The chemical interactions category (RH below 30%) appears to be based on two studies of formaldehyde offgassing rates (the only other chemical interaction mentioned in the text is the conversion of sulfur and nitrogen dioxides to acids, for which no specific limits were cited). In light of the recent reductions in the formaldehyde levels within materials, this limit may be outdated. It is not clear what the category 'ozone production' refers to, although one might infer that it is based on the incorrect assumption that ozone production from office lighting and equipment is a significant pollutant source.

For the purpose of setting upper humidity limits in standards the Sterling paper and figure are clearly inadequate. To promote good building design it is important to identify the specific physical causes of health hazards, and to regulate design practice to solve them.

Table 1. summarizes the results of this review. It addresses the humidity requirements, the actual site of contamination, and means of control for each of the biological pollutants.

Table 1. BIOLOGICAL POLLUTANTS IN INDOOR AIR
Summary of Environmental Requirements and Recommended Remediation Procedures

	health implications	environmental requirements	common sites of contamination	frequently recommended remediation procedures
DUST MITES	**allergic reactions:** asthma, rhinitis, dermatitis **dust mite allergens:** mite body parts and fecal matter are the most common source of allergic reactions within house dust **species most commonly associated with disease:** *Dermatophagoides* *D. pteronyssinus* - more common in humid regions *D. farinae* - more common in relatively dry regions *Euroglyphus* - generally rare, found only in humid regions	**source of nutrients:** shed human and animal skin scales **source of water**: - uptake water vapor directly from air - RH of 70-80% at 25°C is optimal for growth **critical relative humidity:** 55% at 15°C to 75% at 35°C (for more detailed information on the humidity requirements for mites see Arlian, 1992)	- mattresses/bedding - thick carpeting - heavily used upholstered furniture (dust mites are more commonly associated with residences rather than commercial buildings)	- removal of contaminated carpeting, bedding and/or furniture - frequent hot-water cleaning of bedding - encasement of mattresses with semi-permeable vinyl casing - special vacuuming procedures (e.g., HEPA filters, central vacuum system with outside equipment) - surface treatments (e.g., benzyl benzoate) - reduction of ambient humidity or specifically within the microhabitat of mites (e.g., through the use of electric blankets, radiant heating of carpeted floor surfaces, etc.)
FUNGI	**allergic reactions:** asthma, rhinitis, dermatitis *(most common: Alternaria, Aspergillus, Cladosporium, and Penicillium)* **hypersensitivity pneumonitis** (e.g., *Cladosporium, Sepula)* **mycotoxicosis** (e.g., *Aspergillus, Penicillium, Stachybotrys atra, Trichoderma virde)* **infectious disease** (e.g., *Aspergillus fumigatus, A. fumigatus Histoplasma, Cryptococcus)*	**source of nutrients** - organic debris, dirt, organic building materials **source of water:** moisture on and within surfaces - specific water requirement varies from species to species. - growth of xerophilic species is likely to begin at an ERH of 75 to 80%. (for more detailed information on humidity requirements see Flannigan 1992)	- moisture damaged building materials (walls, carpeting, books, etc.) - within fiberglass duct lining in which condensation has occurred - within walls in which condensation has occurred - within poorly maintained conditioning systems containing water (e.g., humidifiers, cooling coil drip pans)	- removal of damaged material where possible (i.e. carpeting, duct liners, wallpaper, etc.) - cleaning of water resistant materials with chlorine bleach - proper maintenance and operation of conditioning systems (e.g., cleaning and disinfecting cooling coils and drain pans, continual operation of forced air systems to avoid condensation) - proper construction techniques to avoid water damage (e.g., proper placement of vapor barriers to avoid condensation within walls, design of drainage systems to avoid flooding and water incursion) - adequate ventilation to reduce internal humidity loads
BACTERIA and VIRUSES	**infectious disease: person-to-person** (e.g. common cold, flu, measles, etc.) **infectious disease: building related** (e.g., *Legionella pneumophila)* **hypersensitivity pneumonitis** (most commonly associated with *thermophilic actinomycetes*)	- virulent bacteria and viruses are transferred to hosts through droplet nuclei expelled when coughing/sneezing or formed within contaminated building systems that form aerosols - bacteria and viruses that grow outside of the human host require liquid water for growth (for detailed information see Cox, 1989)	- infected humans - improperly maintained building systems that have the potential to form aerosols: (e.g., spray-type humidifies, cooling towers etc.)	**person-to-person spread of airborne infection:** - isolation of contaminated persons - increase fresh air exchange rate **growth within building systems:** - remove source of contamination (e.g., replace system, biocide treatment, etc.) - routine cleaning of water systems and/or filters - relocate intake vents (in the case of cooling tower contamination)

CONCLUSIONS

- Most of the identified biological health agents grow on surfaces of the building, its systems, and its furnishings, or in standing water within or outside the building. None of the agents grow in the air of the occupied space or the air within the mechanical system. Their growth is therefore only indirectly related to the atmospheric humidity measured in the occupied space or the ducts of its mechanical system. To control these one needs to assure that the surfaces remain dry. There are a number of ways to achieve this in the design, furnishing, and operation of buildings. It is also necessary to avoid producing aerosols of water from the mechanical system or humidifiers. How this is done is independent of the level of indoor air humidity.

- The single exception to this is dust mite contamination (in particular *D. farinae*), which appears to be directly related to ambient RH. Controlled laboratory studies suggest that optimal conditions for growth are 70-80% RH at 25°C. A number of field studies have found mite contamination in residences with ambient RH's as low as 50%. Rather than ambient RH, however, the more relevant factor may be the RH within the microhabitat of the mite (within a few millimeters of the horizontal surfaces on which they lie). In the laboratory surface and air temperatures can be controlled to provide equilibrium conditions, however, in actual environments equilibrium conditions seldom exist. In one field study, the RH was measured within the carpet of a residence and found to be over 9% higher than the ambient RH. The authors attributed the increased mite contamination found in the carpeting to this localized increase in RH. This difference between surface and ambient RH may possibly explain the discrepancy between the laboratory and field findings. Remedial methods are designed to address contamination at the source. For example, one of the most widely recommended remedial methods is to encase mattresses with a semi permeable polyurethane cover. This discourages moisture from getting into the bedding where the mites live. Researchers have also suggested that electric blankets, which can lower the RH within bedding, are effective in reducing mite levels. In terms of seasonal effects it is not yet known whether use of evaporative cooling a few months out of the year, sometimes only during daytime, leads to increased mites. In general, since mite contamination occurs primarily in residences and affects only a subset of the population, it may be that when necessary they should be controlled by other means such as covering/cleaning bedding, treatment or removal of carpets, and insulation of cooled floor slabs under carpets.

- Fungal contamination occurs primarily as a result of condensation on surfaces and/or water damage. Field and laboratory studies suggest that fungal growth does not become an issue below 70 or even 80% RH unless there are other factors influencing their growth on building surfaces. Studies that reported problems at lower RH values appeared to have problems that could be corrected otherwise. In setting a maximum limit to air humidity in the space, there is little if any evidence from field studies that provides a reason for distinguishing 60% relative humidity from 70%.

- The health impacts of non-biological health agents are hard to assess at this time. Formaldehyde generation is exacerbated in some materials by higher humidity. Because of the greater awareness of the adverse health effects, new building products and furnishings generate far less than before. The effect of this change will need to be evaluated. For a given ventilation rate, indoor ozone concentrations may decrease as humidity increases due to an increased rate of surface reactions. However, at the high ventilation rates associated with direct evaporative cooling, the level of ozone will not be significantly offset by the higher humidity levels. Oxides of nitrogen and sulfur are primarily of outdoor origin, but the severity of their effects on health may increase with higher humidity levels. At this point there is little evidence in the literature to suggest that this is a significant health effect.

- Aside from the environment itself, the other significant source of biological health agents is humans harboring infectious diseases. This source (primarily the respiratory tract, but also the skin) is largely independent of the humidity level in the space. However, the *spread* of infectious disease agents depends somewhat on atmospheric humidity in the space, in that aerosol evaporation rates and deposition rates may affect viability of antigens, bacteria and viruses enclosed in water droplets. Space humidity may also affect the settling rate of dust particles to which bacteria are attached. The viability of these dust-borne organisms also varies with humidity, with viability optima occurring throughout the range of RH. For each of the above considerations, there is little evidence to suggest that any humidity between 50% and 90% is significantly better than any other in reducing the viability or number of suspended infectious disease organisms, as well as the susceptibility of the human receptor.

- Direct evaporative cooling through porous media appear to be benign in that field and laboratory studies suggest that biological organisms in the cooling water appear not to be aerosolized or transmitted downstream. The wet pads may have benefits over dry filters in removing incoming pollutants. However, this needs to be experimentally investigated. In addition, the once-through ventilation required by such systems should act to dissipate the concentration of infectious organisms in the air, since such organisms are almost always internally generated. This process also needs to be systematically evaluated.

- Finally, very little of the literature on health effects is expressed in terms of risk to the occupant: first the likelihood of humidity-influenced pollutants occurring in the building, and then the likelihood of the pollutant affecting the occupant.

REFERENCES

Abe, K. 1993. "A method for numerical characterization of indoor climates by a biosensor using xerophilic fungus." *Indoor Air*, Vol. 3, pp. 344-348.

Airoldi, T.; Litsky, W. 1972. "Factors contributing to the microbial contamination of cold-water humidifiers." *American Journal of Medical Technology*, Vol. 38(12), pp. 491-495.

Anderson, I.; Korsgaard, J. 1986. "Asthma and the indoor environment: Assessment of the health implications of high indoor air humidity." *Environment International*, Vol. 12, pp. 121-127.
Anderson, B.; Lundqvist, G.R.; Molhave, L. 1975. "Indoor air pollution due to chipboard used as a construction material." *Atmosphereic Environment*, Vol. 9, pp. 1121-1127.

Anderson, J.D.; Dark, F.A.; Peto, S. 1968. "The effect of aerosolation upon survival and potassium retention by various bacteria." *Journal of General Microbiology*, Vol. 52, pp. 99-105.

Arlian, L.G.; Bernstein, I.L.; Gallagher, J.S. 1982. "The prevalence of house dust mites, dermatophagoids, and associated environmental conditions in homes in Ohio." *Journal of Allergy and Clinical Immunology*, Vol. 69(6), pp. 527-532.

Arlian, L.G. 1992. "Water balance and humidity requirements of house dust mites." *Experimental and Applied Acarology*, Vol. 16, pp. 15-35.

Arlian, L.G.; Bernstein, D.; Bernstein, I.L.; Friedman, S.; Grant, A.; Lieberman, P. et al. 1992. "Prevalence of dust mites in the homes of people with asthma living in eight different geographic areas in the United States." *Journal of Allergy and Clinical Immunology*, Vol. 90(3), pp. 292-300.

Arundel, A.V.; Sterling, E.M.; Biggin, J.H.; Sterling, T.D. 1992. "Indirect health effects of relative humidity in indoor environments." *Desiccant Cooling and Dehumidification*, ASHRAE; pp. 3-12.

Arundel, A.V.; Sterling, E.M.; Biggin, J.H.; Sterling, T.D. 1986. "Indirect health effects of relative humidity in indoor environments." *Environmental Health Perspectives*, Vol. 65, pp. 351-361.

ASHRAE. 1992. *ASHRAE/ANSI Standard 55-1992: Thermal Environmental Conditions for Human Occupancy*, Atlanta: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc..

ASHRAE. 1989. *ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air*, Atlanta: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc..

August, P.J. 1984. "House dust mite causes atopic eczema. A preliminary study." British Journal of Dermatology, Vol. 3(suppl 26), pp. 10-11.

Avari, G.P. and Allsopp, D. 1983. "The combined effect of pH, solutes, and water activity on the growth of some xerophilic *Aspergillus* species." *Biodeterioration 5*, Oxley, T.A. and Barry, S. eds. John Wiley & Sons Ltd. pp. 548-556.

Ayerst, G. 1969. "The effects of moisture and temperature on growth and spore germination in some fungi." *Journal of Stored Produce Research*, Vol. 5, pp.127-141.

Bates, J.M.; Rorek, D.A.; Ballantye, M.H. 1993. "Dust mite counts and mite allergens in family homes before and after dry extraction carpet cleaning." *Indoor Air '93; Proceedings of the 6th International Conference on Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol 2, pp.33-38.

Bayer, C.W.; Downing, C.C. 1992. "Indoor humidity in schools with insufficient humidity control", *Environments for People; Proceeding of IAQ '92,* September 1992, San Francisco, CA, ASHRAE; pp. 197-200.

Bayer, C.W.; Crow, S. 1993. "Detection and characterization of microbially produced volatile organic compounds." *Indoor Air '93; Proceedings of the 6th International Conference on Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol 6, pp.297-302.

Beaumont, F.; Kauffman, H.F.; Sluiter, H.J., and de Vries, K. 1985. "Volumetric aerobiological survey of conidial fungi in the North-East Netherlands. II. Comparison of aerobiological data and skin tests with mould extracts in an asthmatic population." *Allergy*, Vol. 40, pp. 181-186.

Becker, R. 1984. "Condensation and mould growth in dwellings - parametric and field study." Buildings and Environment, Vol. 19, No. 4, pp. 243-250.

Bencko, V.; Melichercik, J.; Melichercikova, V.; Wirth, Z. 1993. "Microbial growth control in spray humidifiers of health factilites." *Indoor Air*, Vol. 3, pp. 20-25.

Berglund, B.; Brunekreep, B.; Knopple, H.; Lindvall, T.; Maroni, L. et al. 1992. "Effects of indoor air pollution on human health." *Indoor Air*, Vol. 2, pp.2-25.

Bjurman, J. 1993. "Thermal insulation materials, microorganisms and the sick building syndrome." *Indoor Air '93; Proceedings of the 6th International Conference on Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol 4, pp.339-344.

Block, S.S. 1953. "Humidity requirements for mold growth." *Applied Microbiology,* Vol. 1, pp. 287-293.

Brauer, M.; Rasmussen, T.R.; Kjaergaard, S.K. 1993. "Indoor nitrous acid, formation and human exposure effects." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 3, pp. 141-146.

Brundrett, G.W. 1990. *Criteria for Moisture Control.* London/Boston/Singapore, Butterworth & Co.; ISBN, 0-408-02374-0.

Burge, H.A.; Solomon, W.R.; Boise, J.R. 1980. "Microbial prevalence in domestic humidifiers." *Applied and Environmental Microbiology,* Vol. 39(4), pp. 840-844.

Burge, H.A. 1988. "Environmental allergy, definition, causes, control." *Proceedings of IAQ '88*, ASHRAE.

Burge, H. A. 1989. "Indoor air and infectious disease." *Occupational Medicine: State of the Art Reviews*, Vol. 4(4), pp. 713-721.

Burge H.A.; Feeley, J.C. et al. 1991. "Indoor air pollution and infectious diseases." *Indoor Air Pollution.* Samet, J.M. and Spengler, J.D. ed. Johns Hopkins University Press, pp. 273-284.

Burge, H.A. 1995. "Aerobiology of the indoor envieonment." *Occupational Medicine: State of the Art Reviews*, Vol. 10(1), pp. 27-40.

Cabrera, P; Julia-Serda, G.; Rodriguez, de Castro, F.; Camminero, J.Barber, D.; and Carrillo, T. 1995. "Reduction of house dust mite allergens after dehumidifier use." *Journal of Allergy and Clinical Immunology*, Vol. 95(2), pp. 635-6.

Center Labortories, 1994. Personal communication.

Colloff, M.J. 1992. "Exposure to house dust mites in homes of poeple with atopic dermatitis." *British Journal of Dermatology*, Vol. 127(4), pp. 322-7.

Covelli, H.D.; Kleeman, J.; Martin, J.E.; Landau, W.L.; Hughs, R.L. 1973. "Bacterial emission from both vapor and aerosol humidifiers." *American Review of Respiratory Disease,* Vol. 108, pp. 698-701.

Cox, C. S. 1966. "The survival of Escherichia coli sprayed into air and into nitrogen from distilled water and from solutions of protecting agents, as a function of relative humidity." *Journal of General Microbiology,* Vol. 43, pp. 383-399.

Cox, C.S. 1989. "Airborne bacteria and viruses." *Science Progress*, Vol. 73, pp. 469-500.

deBoer, R. and van der Geest, L.P. 1990. "House dust mite (Progylphidae) populations in matresses, and their control by electric blankets." *Experimental and Applied Acarology*, Vol. 9(1-2), pp. 113-22.

Ezeonu, I.M.; Noble, J.A.; Simmons, R.B.; Price, D.L.; Crow, S.A.; Ahern, D.G. 1994. "Effect of relative humidity on fungal colonization of fiberglass insulation." *Applied and Environmental Microbiology*, Vol. 60(6), pp. 2149-2151.

Fink, J.N.; Hensley, G.T. Schlueter, D.P.; Unger, G.F. 1976. "Interstitial lung disease due to contamination of forced air systems." *Annals of Internal Medicine,* Vol. 84, pp. 406-413.

Fernandez-Caldas, E.; Trudeau, W.L.; Ledford, D.K. 1994. "Environmental control of indoor biologic agents." *Journal of Allergy and Clinical Immunology*, Vol. 94(2), pp.404-412.

Flannigan, B.; McCabe, E.M.; McGarry, F. 1991. "Allergenic and toxigenic micro-organisms in houses." *Journal of Applied Bacteriology* Symposium Supplement; Vol. 70, pp. 61S-73S.

Flannigan, B. 1992. "Approaches to assessment of the microbial flora of buildings." *Environments for People; Proceeding of IAQ '92,* September 1992, San Francisco, CA, ASHRAE; pp. 139-145.

Flannigan B.; Miller, D. unpublished. "Health implications of fungi in indoor environments - an overview".

Flynn, D.D.; Goldberg, L.J. 1971. "Effect of relative humidity on aerosol persistence of Streptococcus salivarius." *Archives of Environmental Health,* Vol. 23, pp. 40-42.

Foarde, K; Dulaney, P.; Cole, E.; VanOsdell, D.; Ensor, D.; Chang, J. 1993. "Assessment of fungal growth on ceiling tiles under environmentally characterized conditions." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 357-362.

Friedman, F.M.; Friedman, H.M.; O'Connor, G.T. 1992. "Prevalence of dust mite allergens in homes and workplaces of the Upper Connecticut River Valley of New England." *Allergy Proceedings*, Vol. 13(5), pp. 259-62.

Gammage, R.B. 1990. "Exposure to formaldehyde in indoor air." *Risk Analysis*, Vol. 10, No. 1, pp. 77-83.

Godish, T. and Rouch, J. 1986. "Mitigation of residential formaldedyde contamination by indoor climate control." *American Industrial Hygiene Association Journal*; Vol. 47, pp. 792-797.

Grant, C.; Hunter, C.A.; Flannigan, B.; Bravery, A.F. 1989. *International Biodeteriation*, Vol. 25, pp. 259-284.

Gravesen, S. 1979. "Fungi as a cause of allergic disease." *Allergy,* Vol. 34, pp. 135-154.

Green, G.H. 1985. "Indoor relative humidities in winter and the related absenteeism." *ASHRAE Transactions,* Vol. 91 Part 1.

Griffin, D.H. 1981. *Fungal Physiology*, Wiley and Sons.

Hambleton, P.; Broster, M.G.; Dennis, P.J.; Henstridge, R.F.; Conlan, J.W. et al. 1983. "Survival of virulent Legionella pneumophila in aerosols." *J. Hyg. Camb.* Vol. 90, pp. 451-460.

Hart, B.J.; Whitehead, L. 1990. "Ecology of house dust mites in Oxfordshire." *Clinical and Experimental Allergy,* Vol. 20, pp. 203-209.

Harving, H.; Korsgaard, J.; and Dahl, R. 1994. "House-dust mite exposure reduction in specially designed, mechanically ventilated "healthy" homes." *Allergy*, Vol 49(9), pp. 713-8.

Harving, H.; Korsgaard, J.; Dahl, R.; Beck, H.I.; Bjerring, P. 1990. "House dust mites and atopic dermatitis. A case-control study on the significance of house dust mites as etiolofic allergens in atopic dermatitis." *Annals of Allergy,* Vol. 65, pp. 25-31.

Hens, H.; Senave, E. 1990. "Condensation and energy, Zolder case study." *Ventilation System Performance,* 11th AIVC Conference; September 18-21, 1990; Belgirate, Italy, pp. 81-99.

Hodges, G.R.; Fink, J.N.; Schlueter, D.P. 1974. "Hypersensitivity pneumonitis caused by a contaminated cool-mist vaporizer." *Annals of Internal Medicine,* Vol. 80, pp. 501-504.

Hodgson, M.J. 1989. "Clinical diagnosis and management of building-related illness and the sick building syndrome." *Occupational Medicine: State of the Art Reviews,* Vol. 4(4), pp. 593-606.

Htut, T. 1994. "Airborne house dust mite allergen: are short-duration avoidance measures helpful?" *Indoor Environment,* Vol. 3, pp. 48-53.

Hung, L. L.; Yang, C. S.; Dougherty, F. J.; Lewis, F. A.; Zampiello, F. A.; Magniaracina, L. 1992. "Dust mite and cat dander allergens in office buildings in the Mid-Atlantic Region." *Environments for People; Proceedings of IAQ '92,* October 18-21, 1992, San Francisco, CA, ASHRAE; pp. 87-93.

Hyvarinen, A.; Reponen, T.; Husman, T.; Ruuskanen, J. and Nevalainen, A. "Characterizing mold problem buildings - Concentrations and flora of viable fungi." *Indoor Air,* Vol. 3, pp. 337-343.

Kalliokoski, P.; Juutinen, T.; Pasanen, P., Pasanen, A. 1993. "Fungal growth and activity on moist building materials." *Indoor Air '93; Proceedings of the 6th International Conference on Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol 4, pp.299-303.

Kalra, S.; Owen, S.J.; Hepworth, J.; Woodcock, A. 1990. "Airborne house dust mite antigen after vavuum cleaning." Lancet, Vol. 336, p. 449.

Korsgaard, J. 1983. "Mite asthma and residency, A case-control study on the impact of exposure to house-dust mites in dwellings." *American Review of Respiratory Disease,* Vol. 128, pp. 231-235.

Korsgaard, J. 1983. "House-dust mites and absolute indoor humidity." *Allergy,* Vol. 38(2), pp. 85-92.

LaForce, F.M. 1986. "Airborne infections and modern building technology." *Environment International,* Vol. 12, pp. 137-146.

Lang, J.D.; Mulla, M.S. 1977. "Distribution and abundance of house dust mites, Dermataphagoides in different climatic zones of southern California." *Environmental Entomology,* Vol. 6(2), pp.213-216.

Lang, J.D.; Mulla, M.S. 1978. "Seasonal dynamics of house dust mites, Dermatophagoides, in homes in southern California." *Environmental Entomology,* Vol. 7(2), pp. 281-6.

Leaderer, B.P.; Sullivan, J.; Koutrakis, P.; Wolfson, J.M. 1993. "A passive monitor for the measurement of nitrous acid and sulfur dioxide." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 2, pp. 233-238.

Lintner, T.J.; Brame, K.A. 1993. "The effects of season, climate, and air-conditioning on the prevalence of Dermatophagoides mite allergens in household dust." *Journal of Allergy and Clinical Immunology,* Vol. 91(4), pp. 862-867.

Macher, J.M. 1994. Personal communication.

Macher, J.M.; Girman, J.R. 1990. "Multiplication of microorganisms in an evaporative cooler and possible indoor air contamination." *Environment International,* Vol. 16, pp. 203-211.

Marbury, M.C.; Krieger, R.A. 1991. "Formaldehyde." *Indoor Air Pollution: A Health Perspective*. Samet, J.M. and Spengler, J.D. ed., Johns Hopkins University Press. pp. 223-251.

Mbithi, J.N.; Springthorpe, V.S.; Sattar, S.A. 1991. "The effect of relative humidity and air temperature on survival of Hepatitis A virus on environmental surfaces." Applied and environmental Microbiology, Vol. 57(5), pp. 1394-1399.

McDonald, L.G.; Tovey, E. 1992. "The role of water temperature and laundry procedures in reducing house dust mite populations and allergen content of bedding." *Journal of Allergy and Clinical Immunology*, Vol. 90(4 pt 1), pp. 599-608.

Menzies, R.; Tamblyn, R.; Comtois, P. 1992. "Case-control study of microenvironmental exposures to aero-allergens as a cause of respiratory symptoms - Part of the sick building syndrome (SBS) symptom complex." *Environments for People; Proceedings of IAQ '92,* October 1992, San Francisco, CA, ASHRAE.

Meyer, B. 1986. "Formaldehyde exposure from building products." *Environment International*; Vol12, pp. 283-288.

Miller, J.D. 1992. "Fungi and the building engineer." *Environments for People; Proceedings of IAQ '92,* October 1992, San Francisco, CA, ASHRAE; pp. 147-159.

Moore-Landecker, E. 1982. *Fundamentals of the Fungi*, Second Edition. New Jersey, Prentice-Hall Inc.

Morey, P.R. 1988. "Microorganisms in buildings and HVAC systems, a summary of 21 environmental studies." *Proceedings of IAQ '88*, ASHRAE; pp. 10-24.

Morey, P.R.; Williams, C.M. et al. 1991. "In porous insulation inside an HVAC system compatible with a healthy building?" *Healthy Buildings; Proceeding of IAQ '91*; Sept. 1991; Washington, DC, ASHRAE.

Mueller, F.X.; Loeb, L.; Mapes, W.H. 1973. "Decomposition rates of ozone in living areas." *Environmental Science and Technology,* Vol. 7(4), pp. 342-346.

Murray, A.B.; Zuk, P. 1979. "The seasonal variation in a population of house dust mites in a North American City." *Journal of Allergy and Clinical Immunology,* Vol. 64(4), pp. 266-269.

Murray, A.B.; Ferguson, A.C.; Morrison, B.J. 1985. "Sensitization to house dust mites in different climatic areas." *Journal of Allergy and Clinical Immunology,* Vol. 76(1), pp. 108-112.

Nevalainen, A.; Pasanen, A.L.; Nininen, M.; Reponen, T.; Kalliokoski, P.; Jantunen, M.J. 1991. "The indoor air quality in Finnish homes with mold problems." *Environment International,* Vol. 17, pp. 299-302.

Nevalainen, A. 1993 "Microbial contamination of buildings." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 3-12.

O'Rourke, M.K.; Fiorentino, L.; Clark, D.; Ladd, M.; Rogan, S. et al. 1993. "Building characteristics and importance of house dust mite exposures in the Sonoran desert, USA." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 155-160.

Pasanen, A.L.; Kallioloski, P.; Pasanen, P.; Jantunen, M.J.; Nevalainen, A. 1991. "Laboratory studies on the relationship between fungal growth and atmospheric temperature and humidity." *Environment International,* Vol. 17, pp. 225-228.

Pasanen, A.L.; Heinonen-Tanski, H.; Kalliokoski, P.; Jantunen, M.J. 1992. "Fungal microcolonies on indoor surfaces - An explanation for the base-level fungal spore counts in indoor air." *Atmospheric Environment,* Vol. 26B, pp. 117-120.

Pasanen, P.; Pasanen, A.; Jantunen, M. 1993. "Water condensation promotes fungal growth in ventilation ducts." *Indoor Air*, Vol. 3, pp. 106-112.

Platts-Mills, T.A.E.; Hayden, M.L.; Chapman, M.D.; Wilkins, S.R. 1987. "Seasonal variation in dust mites and grass-pollen allergens in dust from the houses of patients with asthma." *Journal of Allergy and Clinical Immunology,* Vol. 79(5), pp. 781-791.

Platts-Mills, T.A.E.; Chapman, M.D. 1987. "Dust mites, immunology, allergic disease, and environmental control." *Journal of Allergy and Clinical Immunology,* Vol. 80(6), pp. 755-775.

Platts-Mills, T.A.E.; de Weck, A.L. 1989. "Dust mite allergens and asthma - A worldwide problem." *Journal of Allergy and Clinical Immunology,* Vol. 83,1-3, pp. 416-427.

Puhakka, E.; Karkkainen, J. 1993. "Formaldehyde concentrations in indoor air in new buildings; factors that affect the prevalence of formaldehyde." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8; Helsinki, Finland; Vol. 2, pp. 147-152.

Reed, C.E.; Swanson, M.C. 1986. "Indoor allergens, identification and quantification." *Environment International,* Vol. 12, pp. 115-120.

Reiser, J. Ingram, D. Mitchell, E.B. Warner, J.O. 1990. "House dust mite allergen levels and an anti-mite mattress spray (natamycin) in the treatment of childhood asthma." *Clinical and Experimental Allergy*, Vol. 20(5), pp. 561-7.

Seltzer, J.M. 1995. "Biologic contaminants." *Occupational Medicine:State of the Art Reviews*, Vol. 10(1), pp. 1-25.

Smith, P.W.; Massanari, R.M. 1977. "Room humidifiers as the source of Actinetobacter infections." *JAMA*; Vol. 237(8), pp. 795-797.

Smith, T.F.; Kelly, L.B.; Heymann, P.W.; Wilkins, S.R.; Platts-Millls, T.A.E. 1985. "Natural exposure and serum antibodies to house dust mite-allergic children with asthma in Atlanta." *Journal of Allergy and Clinical Immunology,* Vol. 76(6), pp. 782-8.

Solomon, W.R. "Fungus aerosols arising from cold-mist vaporizers." *Journal of Allergy and Clinical Immunology,* 1974; 54(4), pp. 222-228.

Sorenson, W.G. 1989. "Health impact of mycotoxins in the home and workplace: an overview." *Biodeterioration Research 2:* O'Rear, C.E and Llewellyn, G.C. eds. Plenum Press. pp. 201-215.

Sterling, E. M.; Arundel, A.; Sterling, T. D. 1985. "Criteria for human exposure to humidity in occupied buildings." *ASHRAE Transactions,* Vol. 91 Part 1.

Stetzenbach, L.D.; Buttner, M.P.; Meldrum, J.R.; Hern, S.C. 1990. "Characterization of airborne microorganisms in homes serviced by evaporative cooling systems." *Indoor Air '90; Proceedings of the 5th International Conference on Indoor Air and Climate*, July 29-Aug.3, 1990; Toronto, Canada; Vol. 2, pp. 67-72.

Stock, T.H.; Venso, E.A. 1993. "The impact of residential evaporative air cooling on indoor exposure to ozone." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 251-256.

TenWolde, A and Rose, W.B. 1993. "Criteria for humidity in the building and the building envelope." *Bugs, Mold and Rot II: Proceedings of Workshop on Control of Humidity for Health, Artifacts and Buildings*; Nov 16-17, 1993, Oak Ridge, TN; pp. 63-65.

Thogersen, K; Gunnarsen, L.; Nielsen, P.A. 1993. "The effects on indoor air quality by water-damaged chipboards." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 2, pp. 537-542.

Tsongas, G. 1991. "A field study of indoor moisture problems and damage in new Pacific Northwest homes." *Healthy Buildings; Proceeding of IAQ '91*; Sept. 1991; Washington, DC, ASHRAE, pp. 202-209.

van Netten, C.; Shirtleffe, C.; Svec, J. 1989. "Temperature and humidity dependence of formaldehyde relaese from selected building materials." *Bulletin of Environmental Contamination and Toxicology*, Vol. 42, pp. 558-565.

Verhoeff, A.P.; van Strien, R.T.; van Wijnen, J.H. and Brunekreef, B. 1995. "Damp housing and childhood respiratory symptoms: the role of sensitization to dust mites and molds." *American Journal of Epidemiology*, Vol 141(2), pp. 103-10.

Voorhorst, R.; Spieksma-Boezeman, M.I.A.; Spieksma, F.TH.M. 1964. "Is a mite (Dermatophagoides) the producer of the house-dust allergen?" *Allergy und Asthma Band*; Heft 6, pp. 329-334.

Weschler, C.J.; Datta, V.N. and Shields, H.C. 1991. "Indoor ozone exposures from the infiltration of outdoor ozone." *Indoor Air Pollution: Radon, Bioaerosols and VOC's*. Kay, J.G.; Keller, G.E.; and MillerJ.F. ed. pp. 83-99.

Wickman, M.; Nordvall, S.L. Pershagen, G.; Korsggard, J.; Johansen, N.; Sundell, J. 1994a. "Mite allergens during 18 months of intervention." *Allergy*, Vol. 49(2), pp. 114-9.

Wickman, M. Emenius, G., Egmar, A.C. Axelsson, G.; Pershahen, G. 1994b. "Reduced mite allergen levels in dwellings with mechanical exhaust and supply ventilation." *Clinical and Experimental Allergy*, Vol. 24(2), pp. 109-14.

Wickman, M.; Nordvall, S.L.; Pershagen, G.; Sundell, J.; Schwartz, B. 1991. "House dust mites sensitization in cihildren and residential characteristics in a temperate region.", *Journal of Allergy and Clinical Immunology*, Vol 88(1), pp. 89-95.

Wilcox, W, Forest Products Labortory, U.C. Berkeley. 1995. Personal Communication.

ACKNOWLEDGMENTS

The authors would like to thank Alison Kwok, Ph.D. candidate at U.C. Berkeley, for help with the literature search. We also wish to thank William Fisk, Indoor Environment Program, Lawrence Berkeley Laboratory, and Professor Wayne Wilcox, University of California Forest Products Laboratory, for their detailed reviews of the manuscript. The research reported here was funded by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor.

INDOOR HUMIDITY AND HUMAN HEALTH

PART II

BUILDINGS AND THEIR SYSTEMS

Edward Arens, ASHRAE Member
Anne Baughman, ASHRAE Student Member
Center for Environmental Design Research
University of California, Berkeley

ABSTRACT

This paper continues a review of the humidity effects on health as addressed in indoor ventilation and environmental standards. Part I identifies a number of health-related agents that are affected by indoor humidity, common sites of contamination within buildings, and common remediation measures. Part II discusses the physical causes of moisture related health problems in buildings, subdividing them by climate and mechanical system type. It examines studies done on moisture problems in these differing environments, showing that in most if not all cases the causes of the problem are only indirectly related to indoor humidity in the space. To do a better job of controlling such problems, the building- and system-specific causes of the problems should be studied. A number of specific research needs are identified.

INTRODUCTION

Health-related agents that are affected by indoor humidity include dust mites, fungi, bacteria and viruses, and non-biological pollutants. All of these affect human health primarily through their inhalation from the air, although some of them have lesser effects through the skin. The primary biological health problems related to higher levels of humidity are associated with growth on surfaces, or with contaminated aerosols produced by spray humidification systems. The interpersonal transfer of biotic agents through the occupied airspace is not as extensively determined by ambient humidity. Airborne levels of non-biological pollutants may be affected by humidity through influences on offgassing and surface reaction rates.

Humidity in buildings is usually measured in the airspace of the occupied interior. Not all of these listed humidity/health effects are directly affected by the humidity of the air. For example, fungi depend on the moisture of the surface on which they are growing. The moisture content of this substrate may be a function of the humidity of the surrounding air, or may come from totally unrelated sources. For example, field studies have shown that mildew can form as low as 10% RH in some cases whereas in others RH values as high as 95% have not produced biological activity (Pasanen, et al. 1991a,b). Clearly there are other factors at work producing these observations. Even if the surface moisture is caused by air humidity alone, the relationship between these two may be a complex function of surface materials, textures, and exposure to air movement. In addition, the surface may be in a part of the building or its mechanical system where temperatures differ from those in the main airspace, resulting in different rates of condensation/evaporation from the moldy surface. Intermittent operation of the mechanical system may increase this effect.

Biological agents require appropriate conditions in the building for their germination, growth, release to the air, and transport to the human host. To understand humidity/health effects one must ideally consider the organisms and their life cycles in the context of the building, its surface materials, its mechanical system, its operation schedule, and its surrounding climate (e.g. the entire ecosystem of the organism). This is rarely done in the literature. Laboratory studies have characterized some of these pieces of the puzzle in considerable detail, but the applicability of such studies to buildings is often difficult to determine. At the other side of the experimental spectrum, field studies have often identified health-affecting agents in buildings but not discovered or reported either the specific location of their origin, or the mechanisms by which humidity influences their growth and release into the human-occupied zone. Correlations between health effects and indoor air humidity are therefore often building-specific, and are risky to generalize.

In writing indoor environmental standards that use generalized criteria, there is a tendency to set very restrictive limits in order to include all classes of problem cases. Restrictive limits can have undesirable effects such as increased energy required for conditioning spaces and reduced options in modes of space conditioning. For example, in arid climates such limits affect the use evaporative cooling that can offset energy intensive compressor cooling. They also directly affect a substantial fraction of the cooling load in hot humid climates. In order to develop more precise standards, it is useful to examine the types of processes that lead to health problems, and to categorize types of buildings/climates/etc. by how many of these processes they contain. It appears likely that the biotic/health problems at any given level of interior air humidity are different for buildings in different types of climates and for different types of environmental control systems.

In this paper we have categorized the different climate types as:

- hot-dry climates (thermal flows through the building envelope are inward and water vapor flows outward)
- hot-humid climates with interior cooling and/or dehumidification (both thermal and vapor flows through the envelope are inward)
- hot-humid climates without cooling or dehumidification (thermal flows to and from the building's thermal mass)
- cold climates (both thermal and vapor flows through the envelope are outward)

In addition, the following building/system-related categories are useful in examining potential humidity/health effects:

- surface properties in rooms and in HVAC ducts, including temperature, hygroscopicity, air movement
- water in cooling and humidification systems
- intermittency of operation in cooling systems
- moisture sources *not* resulting from the humidity in the interior air, including rain penetration into the building's structure, rising damp through foundations, and plumbing leaks

Each of these categories represents a set of different opportunities for humidity/health effects. The various health agents will be discussed in this context. Given the complexity of the biotic/health problem in buildings and their mechanical systems, the links of humidity to biotic/health factors should be determined as explicitly as possible.

EFFECTS OF MICROENVIRONMENTS ON BIOTIC GROWTH

The surfaces that suffer biotic growth differ among building types. West and Hansen (1989) suggest that in commercial buildings, moisture-associated air quality problems commonly stem from the proliferation of microbes on moist hygroscopic surfaces within the HVAC system. In residences, mold contamination is usually found on room surfaces (Aberg, 1989) and dust mites on carpeting and furnishings within the occupied space (Arlian et al., 1982). Which particular surfaces are affected depends on specific characteristics of the building's construction and operation, the climatic characteristics of the region, the type of HVAC system used, and the maintenance of the building, its system, and its furnishings.

For molds, the key issue for growth occurring on surfaces is the equivalent relative humidity (ERH) or water activity. This parameter is influenced by the following processes:

- surface temperatures and the adjacent air humidity
- hygroscopic properties of the materials
- air movement at surfaces

Although dust mites are not directly dependent on the equivalent relative humidity (ERH) of the substrate, the fungi that some mites require for digesting skin scales are (Flannigan, 1992; Hart and Whitehead, 1990). The mites themselves live within textiles of furnishings and carpets in microenvironments buffered from and quite different from the space environment. It is the relative humidity within these microenvironments that is most important, since mites extract water vapor directly from the surrounding air. O'Rourke in her studies of houses in Tucson observed mites most commonly in ground floor carpets on cold slab floors. This is probably explained by the increased local relative humidity within the cooled carpet pile. If the floor is cool enough or the space environment moist enough, dewpoint will be reached and condensation will occur. Even if this occurs only occasionally, the condensed water will be retained in the carpet and its backing for an extended period, providing a higher local vapor pressure and higher relative humidities in the carpet.

EQUIVALENT RELATIVE HUMIDITIES RELATED TO SURFACE TEMPERATURES AND THE HUMIDITY OF ADJACENT AIR

Thermal gradients and vapor pressure gradients

Vapor pressure is proportional to temperature. If a surface becomes cold relative to the adjacent air, its relatively depressed vapor pressure can allow water to condense onto the surface from the air. For a given type of material, the amount of water eventually condensed (and its ERH) are functions of both the surface temperature and the vapor pressure of the surrounding air. Different types of surface materials will reach different ERH values; this is described in the section on moisture absorption below.

For a given temperature difference across a material, the temperature gradient is proportional to its thermal resistance and its thickness. Resistances are summed for multiple layers as found in building wall and roof assemblies. The layers include the air films (boundary layers) at the surfaces, whose resistance (for a given air speed) is largely fixed. Thus, if a wall's solid materials have low thermal resistance, the resistance of the interior boundary layer (under still air) will be relatively high, and a substantial temperature drop may develop across this film when the wall is exposed to an overall temperature difference. The wall's surface temperature may be higher or lower than the interior air; when it is lower, condensation may occur on the surface as described above. This may be the situation in cold climates where the thermal gradient across a wall is outward. It could also occur during transient conditions, such as when mechanical systems are shut down or switched to economizer mode. In these cases hot-humid air may come into contact with a cooled interior surface, resulting in surface condensation.

There is also a water vapor gradient across walls separating different vapor pressures. For this gradient, the resistance is the permeance of the building materials. The vapor gradient describes the vapor pressure available at various depths within the wall assembly. The thermal gradient occurring at the same time determines the saturation vapor pressure at each depth in the wall. Where vapor pressures exceed the saturation vapor pressure at a given depth, condensation will occur within the wall assembly. This is the general case of the surface condensation example given above.

Condensation occurs in building assemblies when thermal and vapor pressure gradients are both outward, and when thermal and vapor pressure gradients are both inward. The former occurs under heating conditions in cold climates, the latter in hot-humid climates when the interior is mechanically cooled and dehumidified. Condensation does not occur when the thermal and vapor gradients are opposite, as is the case in direct-evaporatively cooled buildings in hot-arid climates.

Cold climates: outward thermal and vapor gradient

The majority of field studies of 'sick buildings' have been performed in cold climates, and results linking (in particular) mold growth to space humidity are often inapplicable to building environments in hot climates. The mold found by Pasanen (1991) during extremely dry (10% RH) heating conditions was due to leaks and condensation on cold surfaces. Many European studies have been done in older, poorly insulated, housing where cold surfaces are common. Interior mold growth in cold climates is nearly always a wintertime effect. Becker (1984), studying mildew in masonry buildings in Israel, found no difference between rooms having high and low internal moisture generation: all the mildew problems occurred on thermal breaks in outside walls. The lowered interior surface temperatures (in winter) dominated the surface condensation process. Similarly, part of the mold effects discovered by Aberg (1989) in Angola were due to ceiling surfaces cooled by nighttime radiation to the sky. Cold-climate effects are thus possible even in the tropics when nocturnal radiative cooling is high.

Humidity problems are exacerbated when low ventilation rates are used for energy conservation, and when there is inadequate exhaust of internal humidity sources. In the Pacific Northwest, Tsongas (1991), found substantial numbers of houses experiencing humidity problems. Condensation problems occurred primarily on the inner surfaces of outside walls. Few of these buildings had functioning moisture exhausts, and the spot check RH measurements (which found average values from 47 to 56% during the winter) may have missed cooking periods when condensation was produced. Ten Wolde (1984), recommended that "few moisture problems will occur when a home's RH is below 40%". The discussion in the paper covered mildew in wall corners and (exterior wall) closets, condensation on windows, decay in walls or on the underside of roof sheathing. These are all effects due to thermal transmission outward through walls, and would not be applicable, for example, in summertime cooling situations.

Hot-humid climate with mechanical cooling: inward thermal and vapor gradient

Gatley (1992), Shakum (1992), and Banks (1992) discussed mold problems in buildings (primarily hotels) in hot-humid climates close to the Gulf of Mexico. They all gave interior RH recommendations although most of the effects cited were related to inward penetration, by diffusion and infiltration, of warm humid outdoor air into mechanically cooled rooms. A major problem is that the most impermeable layer in the wall construction is a commonly-used vinyl wallpaper that acts as a vapor barrier at the wrong side of the wall. Much mold growth takes place behind such coverings. The other primary problem had to do with operating the corridors at negative pressures relative to ambient, so that humid air tended to migrate inward through the envelope or through-wall air conditioners. A recent study (Spaul 1993) found that indoor spore counts in buildings with improper vapor barrier placement could be controlled by pressurizing the building.

Chilled mass encountering warm moist air may cause surface condensation. In humid climates, this effect can occur when mechanically-cooled space is opened to natural ventilation or economizer cycle operation. It also can occur when cold air duct systems are turned off at night and on weekends, and warm moist air can migrate in and condense on the chilled surfaces. Substantial fungal growth can occur in the ducts, particularly to unfaced fiberglass insulation inner linings. (This was described at the ASHRAE forum on humidity, Chicago, Jan. 1993).

Bayer (1992) describes humidity/health problems in Southeastern schools where RH levels were reported above 75% for the majority of the year, evidently reaching saturation on occasion. It appears as if the problems are primarily due to intermittent operation of the HVAC system, resulting in large inflows into the cool interior of air that had not been dehumidified. The problems were alleviated by providing a continuous system and controlling interior humidity levels below 70%.

Kohloss (1987) reviews air-conditioning practice in the hot-humid tropics, and suggests that the ASHRAE humidity limits of that time were too low for tropical use. He states that mold and mildew are "usually well under control as long as RH is below 70%", and recommends raising the humidity limits in Standard 55 so that it is 65% at the warmer boundary of the summer comfort zone, rising to 69% at the cooler boundary.

Much of the literature understandably focuses on problem buildings. On the other side, it might be instructive to observe existing practice in acceptable spaces. A recent informal sampling of many air conditioned spaces in Singapore found not one RH value below 65%, with many above 80%. The spaces were well maintained, showed no superficial evidence of biological contamination, and were considered acceptable by their occupants (Arens, 1994).

Hot-humid climate without mechanical cooling or dehumidification: temperature gradients to thermal mass

Surface condensation can occur in passively or naturally ventilated buildings when moist air encounters a thermally massive building element cooled by previous climatic conditions. It can also occur (rarely) during thunderstorm passage in cool weather. Because neither daily air temperature or mass temperatures fluctuate significantly in humid climates, naturally-occurring condensation due to thermal capacitance is not large. In dry climates, mass may be cooled substantially below daytime temperatures by nocturnal ventilation, but this mode of cooling is unlikely to reduce the mass temperature below the subsequent day's dewpoint temperature unless a humid airmass moves in outside or much moisture is generated indoors. In a lightly insulated structure, radiant cooling to the night sky can cause interior surfaces to drop below the dew point and condense water (Aberg, 1989, as discussed above).

EQUIVALENT RELATIVE HUMIDITIES RELATED TO SORPTION ONTO SURFACES

Moisture sorption processes

The amount of moisture adsorbed to or absorbed into (the nonspecific term is 'sorbed') a material depends on physical and chemical characteristics of the material. In general, water can be held to surfaces by chemical or physical bonds, or by mechanical attachment. Water that is *chemically* bonded to the surface (usually by covalent bonds, water of hydration) is too strongly attached to the surface to be useful to biological growth. Water held by *physical* (van der Waals) bonds coats smooth surfaces in single or multiple molecular layers. These bonds are roughly a tenth the strength of chemical bonds and some layers may be available for biological growth. *Mechanically attached* water has no bonding, but is attracted by surface tension effects in pores and capillaries. Most of this is available to biological organisms.

Wong (1990) categorized building materials that physically bind water into three types of media: non-porous, hygroscopic porous, and capillary-porous.

- In non-porous media, condensation of liquid water can only occur at the surface. Examples given by Wong are (clean) smooth plastics, glass, glazed surfaces, and sheet metal.

- Hygroscopic porous media have very small pores (microcapillaries). These pores are capable of exerting a powerful mechanical attraction on atmospheric moisture because once the small diameter pores begin to fill, their liquid surface area is a strongly concave meniscus. This has the effect of depressing the vapor pressure at the surface of the water, allowing the liquid pockets to remain in equilibrium at lower ambient vapor pressures than could a plane surface of water. Hygroscopic porous media tend to swell and shrink as water is gained or lost. Examples given are wood, natural textile fibers, clay.
- In capillary-porous media, pores are visible and the amount of physically bound water negligible. These do not have lower surface vapor pressures to attract moisture, and do not shrink or swell. Examples are: bricks, concrete, gypsum board, and packings of sand.

In principle, hygroscopic porous media might appear to permit fungal hyphae access to condensed water at lower ambient RH values than would be possible on plane surfaces. However, the reverse seems to be true at least for dry wood, where water condensing in pores is adsorbed by cellulose molecules in the cell walls and becomes unavailable for fungal use (Wilcox, 1994). Because of this, the hygroscopic nature of dry wood actually reduces the availability to molds of water that would normally form on surfaces when the ambient RH is 100%. This is a temporary effect, in that permanent exposure to 100% RH would eventually bring the wood to its fiber saturation point, where it loses hygroscopicity. However, wood paneling has been found to adsorb/desorb large amounts of humidity on a diurnal cycle without surface condensation occurring (Kubler, 1982, Okano, 1977). Ikeda et al. (1993) found that the addition of 24 mm of hygroscopic material to a wall exposed daily to several hours of 100% RH reduced the room RH by 4 to 10% and prevented surface condensation for periods as long as 60 days.

In general, the effects of hygroscopicity on mold growth is not well described in the literature. Data on ERH requirements of biological organisms are being developed as discussed in Part I of this paper. Wilcox (1994), on the other hand, maintains that liquid water on the surface, at least intermittently, is a requirement for mold growth on that surface. There does not appear to be much information on the relationship between surface condensate, ERH, and the RH of the adjacent air for common building materials. In particular, it would be useful to have the characteristics of various types of paints, since they cover such a large fraction of building interior surfaces. It has also been noted that older indoor surfaces may be covered with deposited aerosols, affecting their moisture absorption characteristics (Fisk, 1994).

Moisture sorption on walls and duct surfaces

A study of mold growth on surfaces of bakeries done by Coppock and Cookson (1951) found that non-porous brick had more surface condensation than porous brick, with mold growth beginning at 80% RH, whereas no mold was found on natural brick until 88%. However, porous materials might accumulate more nutrients over time from atmospheric dust. Whitewash over natural brick caused mold growth above 80% RH perhaps because of nutrients in this paint. A glossy painted wood grew nothing at all in the range 70-95% RH. Coppock and Cookson recommended that for mold control on all types of surfaces RH should be kept below 70%.

Other researchers have noticed differences in the mold susceptibility of latex as opposed to other paints. For example, Becker (1984) found less mold growth on inorganic paints (whitewash) than on latex emulsions. Hens (1985-as cited by Aberg) exposed painted plasterboard panels with latex and oil paints to 75 and 95% RH at 20°C for 50 days. No growth was detected on either type of paint at 75% RH. At 95% RH the latex showed mold while the oil paints did not. It may be unwise to generalize from these studies in that many paints contain fungicide additives that could be determining the results more than the paint's intrinsic characteristics.

Foarde et al. (1992) inoculated acoustical ceiling tiles with *Penicillium aragonense* and exposed them to RH levels from 33 to 97% for a two week period. As long as the moisture content of the tiles remained below 3% the inoculated colonies did not grow. This occurred for all humidities including 85% RH. At 97% RH the colonies grew. They also did a variant of the experiment in which they soaked the blocks initially (as with a roof leak) and then exposed them to the same humidities with and without fan-supplied air movement to dry the blocks. They found that if the moisture content could be restored to below 3% within three days, microbial growth was contained. This drying rate was achieved with the fan for all but 85% and 97% RH levels. Without the fan, none of the humidities dried the sample adequately.

The fibers and/or binder in unfaced fiberglass duct insulation is *per se* hydrophobic, and does not adsorb or absorb atmospheric moisture. However, once dirt has accumulated or mold has become established (as after a single flooding), then it becomes hygroscopic. Quoting Burge (1987): "Fiberglass-lined ductwork cannot be effectively cleaned if mold growth on the fiberglass itself has occurred (as opposed to dust and spore accumulation). Microbiologically, fiberglass exposed to humid air in the supply airstream is not a good idea. Fiberglass lining should not be used in areas of high humidity or where water air washers are part of the system." Morey (1991) and West and Hansen (1989) also comment on the hygroscopicity of organic dirt on fiberglass.

Surface treatments

Nikulin et al. (1993) found that the boron fire retardant added to cellulose insulation prevented fungal growth (*S. atra*) at very high humidities (100%) where cellulose would normally have been a natural substrate at humidities above 84% RH. The preventative mechanism was not discussed, but boron is known to be an exellent fungicide and insecticide. A number of surface treatments are available for dust mites as discussed in Part I of this paper.

AIR MOVEMENT IN SPACE; VELOCITIES AT SURFACES

Air movement near the surface increases the mass transfer of moisture to and from the surface. It appears that mold growth is suppressed in many typical building situations by the architectural provision of air movement over surfaces. For example, it is common practice in naturally-ventilated buildings in Hawaii and elsewhere to use louvered closet doors to eliminate mildew on the clothes inside. If this is not done, mildew is known to occur. The occupied spaces in Hawaiian buildings tend to be open and mildew is uncommon. There is not much specific information available on this subject in the literature. It is possible that air movement has its primary effect by periodically desiccating organisms on the surface and thereby disrupting their growth.

The *smoothness of surfaces* affects the air movement within the boundary layer of the surface. This may be a factor in the fine texture of paints and other surfaces, but is particularly important at the larger scale offered by carpets, furniture, bedding, and the unfaced fibrous insulation mentioned above. The protection offered by the roughness or the fibers buffers the surface microclimate and substantially reduces the transfer of both moisture and heat to and from the surface. The resulting stability is an advantage to biological organisms such as mites, which tend to be most populous in carpets and carpet backings. This may also be true for molds but evidence was not found in the literature. Another effect of roughness is the increased trapping of particulate air pollutants. As with the topic of air movement within buildings, there is not much empirical literature on the microenvironments at and within building surfaces, and on the ways in which microclimatic fluctuations influence the growth and spread of biological pollutants.

The dynamic behavior of air humidity in rooms, walls, and wall cavities can be modeled numerically. El Diasty et al. (1992) demonstrate a simulation of indoor humidity levels, moisture transport, moisture absorption/desorption, and surface condensation/evaporation for different wall types. They also provide references to other such work. Such models could be used to predict the moisture conditions available for microorganisms over typical daily and seasonal cycles of indoor temperature and humidity. They could in the future form a basis for designing and evaluating biological tests, and also for developing more sophisticated criteria and standards for indoor humidity.

WATER IN ENVIRONMENTAL CONDITIONING SYSTEMS

Humidifiers: steam vs. spray

Aerosol-generating ultrasonic and spray-based humidifiers have been implicated in spreading diseases such as humidifier fever (caused by allergens from humidifier water protozoans and bacteria). British studies have also linked them to increased sick building syndrome symptoms (Fisk, 1994). Aerosol-generating humidifiers are generally discouraged in the literature and steam humidifiers are recommended instead because they do not form aerosols.

Evaporative coolers: solid medium versus spray

There are few studies on the air quality effects of direct evaporative coolers. Since most systems use a recirculating water reservoir there is a potential for biological growth within the reservoir and on the evaporative pads. However, since the systems are designed to have relatively low air velocity across the pads, the water evaporates into the air without creating an aerosol and biological contaminants should, in theory, not become airborne. This seems to be supported by field observations (O'Rourke, 1993; Macher, 1990) as discussed in Part I of this report.

Industry guidelines for evaporative coolers using the new synthetic solid media suggest a bleed rate from the reservoir equal to 30% of the recirculation rate, regardless of the loss to evaporation (ASHRAE forum on evaporative cooling, Denver, June 1993). Although the bleed is primarily to prevent salt buildup, making its rate constant presumably also acts to control the amount of growth within the reservoir. A similar industry suggestion is that evaporative cooling systems should completely drain their sumps daily, which would also act to control growth.

It is possible to evaporatively cool incoming supply air with aerosol-generating sprays. We have heard of examples of this in commercial buildings but have no experience with any of them, either directly or in the literature. Such systems could presumably present the same health hazards as spray humidifiers, and appear to be discouraged in the industry. (This sentiment appeared to be the consensus at the June 1993 ASHRAE forum on evaporative cooling).

Cooling coils in air conditioning systems

Under dehumidification the cooling coil becomes coated with a film of condensate from the incoming air stream. This condensate is led to the drain via the drip pan. The drip pan can be a major source of health problems when improperly drained. The standing water is often contaminated with bacteria and protozoa, and since its liquid surface is in direct contact with the supply airstream, it has the potential to contaminate the building. The literature cites this as a cause of a number of observed cases of sick building syndrome. The exact mechanism by which the pollutants are injected into the airstream does not appear to have been described.

Aerosols containing pollutants can enter buildings through outside-air inlets positioned near aerosol-forming cooling towers. Since cooling towers contain warm water, *Legionella* is often present. Cooling tower mist was the cause of the large original outbreak in Philadelphia, and appears to have been the cause of other outbreaks as well.

HUMIDITY/HEALTH IMPLICATIONS FOR EVAPORATIVE COOLING OF BUILDINGS IN A HOT-ARID CLIMATE.

Direct evaporative coolers operate with high rates of outside air supply, at least three times that of a typical air conditioned building. In general, high rates of outside air ventilation should reduce the buildup of indoor-generated pollutants. Various studies of office buildings have shown less complaints when they are naturally ventilated (Mendel, 1993). However, if outdoor air pollution is worse than inside, once-through ventilation would increase the pollutant levels indoors. This was the case for ozone in the comparison of El Paso evaporatively cooled houses to Houston air-conditioned houses (Stock and Venso 1993).

Direct evaporative coolers operate with the thermal gradient inward while the humidity gradient is outward. Only one paper was found addressing the problems of biotic factors in such buildings. This paper, a field study of mites in a 190 houses in Tucson, Arizona, 96% of which were evaporatively cooled, showed populations of *Dermatophagoides farinae* varying with season, but present in over half the houses (O'Rourke, 1993). Molds were not discussed but personal communication with the author added that, when present, mold appeared to be primarily a result of ubiquitous leaks coming from the roof-mounted evaporative cooling units.

O'Rourke also said that the great majority of the Tucson houses were cooled by old direct-evaporative 'swamp coolers', even during the high humidity 'Monsoon' (July through September) where evaporative cooling is pushed to its capacity.

Evaporative cooling produces maximum indoor RH's of around 80% during operation. Wu (1990) measured (by weighing) substantial adsorption/desorption in the furnishings and structure of the space during the cyclical operation typical of summer cooling. The adsorption/desorption did not result in major changes in the space temperature under the ventilation rates used. The moisture gained during the cooling period was evaporated during off-cycle periods. Kubler (1982) calculated over 20 gallons of daily adsorption/desorption for a wood house whose interior cycles between 60 and 80 % RH. This could represent a quarter to a third of the total daily moisture added to the supply air by an evaporative cooler. The higher adsorptivities by hygroscopic materials provide a substantial effect in preventing intermittent surface condensation (Ikeda et al., 1993).

DISCUSSION: HUMIDITY/HEALTH IN STANDARDS AND DESIGN PRACTICE

Comfort Standards (ASHRAE Standard 55, ISO 7730, DIN 1946) are based on measurements of temperature and humidity in the occupied space only. The humidities specified at the warm side of the comfort zone range between 60 and 70% RH. The difference between 60 and 70% RH at this temperature is very important in cooling system design, and affects the viability of direct evaporative cooling.

The current ventilation standard (ASHRAE Standard 62) is based on air change rates, with guidance language concerning humidity limits in the occupied space (60% RH) and in ducts (70% RH). (At time of writing, it has been proposed that the 70% requirement be removed in the Standard 62 revision for being impractically restrictive .)

To directly address biological *health* influences, an air quality standard should be expressed in terms of surface temperatures and humidities throughout the building and its mechanical system (i.e. walls, ducts, and drip pans), as well as the air temperatures and humidities in the occupied space. In this way the ERH can be determined for surface materials where biological growth is a possibility. For this type of specification, procedures will be needed to assess surface moisture properties by measurement and/or calculation.

Ten Wolde and Rose (1994) recommended a set of interim performance criteria for humidity inside the building as well as within the building envelope. Among them is the requirement that the monthly mean ERH at all interior building surfaces, including building envelope cavities, be less than 80% (for concurrent surface temperatures between 0° to 40° C.) Washable non-porous surfaces such as glass and tiles might have the looser criterion of stating that prolonged surface condensation should be avoided, and special provisions might be instituted for dust mite control. These recommendations are not contradicted by evidence reviewed in this paper.

CONCLUSIONS

General Observations

- To date, the influence of high humidity on health has not been addressed in a way that considers all the relevant characteristics of building environments. None of the several types of buildings and environmental control systems has been comprehensively assessed, least of all the subset of evaporative cooled buildings. Where health effects are noted, the specific causes are usually not determined. This situation impacts our ability to set rational standards and building specifications pertaining to high levels of humidity.

- Most of the identified biological health agents grow on or within surfaces of the building, its systems, and its furnishings, or in standing water within or outside the building. None of the agents grow in the air of the occupied space or the mechanical system. Their growth is therefore only indirectly related to the atmospheric humidity measured in the occupied space or the ducts of its mechanical system. To control these one needs to assure that the surfaces remain dry. There are a number of ways to achieve this in the design, furnishing, and operation of buildings. It is also necessary to avoid producing aerosols of water from the mechanical system or humidifiers. How this is done is independent of the level of indoor air humidity.

- In general, molds do not become an issue below 70 or even 80% RH unless there are other factors influencing their growth on building surfaces. In setting a maximum limit to air humidity in the space, there is little if any evidence from field studies that provides a reason for distinguishing 60% relative humidity from 70%. Reported problems at lower RH values appeared to be due to causes other than space RH, such as rain penetration or thermal bridges in the envelope. The results tend to support Ten Wolde and Rose's recommended humidity criteria, which extend to 80% in winter and 70% in summer, with possible special provision for dust mite control.

- In general, the principles and practices of moisture control in buildings are known and available in the professional literature (Lstiburek and Carmody 1993 is a good example). This knowledge has often been neglected in practice, and the results are well documented in both the health and biodeterioration literatures. Water deposited within buildings by leaks and inadequate vapor control will result in mold problems almost completely independent of the level of indoor air humidity.

- Evaporative cooling in hot-arid climates is biologically relatively benign, since building surfaces are warmer and drier than conditioned air. Exceptions may be: 1) lightweight furnishings that are permeated by the temperature and relative humidity of the interior air, providing a habitat for mites, and 2) floor slabs that are cooler than the interior because of direct coupling to cooler earth temperatures. This latter effect has been suggested for both mites and molds but as yet has not been experimentally proved.

- Direct evaporative cooling through porous media also appears to be benign in that biological organisms in the cooling water do not seem to be aerosolized or transmitted downstream in significant concentrations. The wet pads may have benefits over dry filters in removing incoming pollutants. However this needs to be experimentally investigated. In addition, the higher outside ventilation rate of required by such systems should act to dilute the concentration of indoor-generated pollutants, including airborne infectious organisms.

- For evaporatively-cooled building designs, smooth floors should be substituted for wall-to-wall carpets in the homes of mite-susceptible individuals. These floors are easier to clean. In addition, for cool floor slabs, the smooth surface 1) reduces the temperature difference between the room temperature and the surface, and 2) reduces the ERH at the surface due to increased convective evaporation.

- Carpet treatment with biocides appears to be well-established in Europe, although the long-term health effects of such treatment is unknown. One treatment, based on the acaricide benzyl benzoate, is now approved for 49 U.S. states.

- Fiberglass-lined ducts lose their hygrophobic properties after a single immersion, and are thereafter hygrophyllic. The accumulation of organic dust adds to this undesirable effect. The widely cited opinion of building health professionals is that these should be avoided in the future, or sealed in some manner from the air stream.

Specific Needs Identified:

- ERH (or water activity a_W) needs to be determined in typical building situations, and its relationship to atmospheric humidity tabulated for a range of temperatures. Field studies should attempt to locate the specific sources of biological agents and quantify the characteristics (temperature, ERH, material properties) of the surfaces on which they are growing.

- Information on the local RH within the carpet boundary layer is needed for studying mites. Such measurements would be analogous to ERH for molds, but at a larger physical scale.

- In the literature, intermittent moisture exposure is almost never addressed, yet is probably the most common condition in building systems. Effects of periodic moistening and drying out on organisms (mites and molds) influences their growth and survival. Information is needed on the effect of daily and longer-term moisture cycles on surface moisture, ERH, and on the organisms themselves. Information is also needed on how such cycles are affected by the operation of the building and its mechanical system. Dynamic moisture models might be used in conjunction with experimentation to provide such information.

- Data are needed on the hygroscopic properties of indoor paints. The studies showing latex emulsions being relatively prone to mold growth were done some years ago, probably before the development of latex acrylics and other current paints. The recent replacement of oil-based paints and even varnishes with water-based versions suggests that typical indoor finishes are very different than in the past. The effects of fungicidal additives should also be determined.

REFERENCES

Aberg, O. 1989. "Moisture and mold in dwellings in a tropical coastal climate." Lund University, Center for Habitat Studies. *Building Issues*, Vol. 1(1).

Arens, 1994. Personal trip log.

Arlian, L.G.; Bernstein, I.L.; Gallagher, J.S. 1982. "The prevalence of house dust mites, dermatophagoids, and associated environmental conditions in homes in Ohio." *Journal of Allergy and Clinical Immunology,* Vol. 69(6), pp. 527-532.

ASHRAE. 1992. *ASHRAE/ANSI Standard 55-1992: Thermal Environmental Conditions for Human Occupancy,* Atlanta: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc..

ASHRAE. 1989. *ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air,* Atlanta: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc..

Banks, N.J. 1992. "Field test of a desiccant-based HVAC system for hotels." *ASHRAE Technical Data Bulletin, Control of Humidity in Buildings,* Vol. 8(3), pp. 39-46.

Bayer, C. W.; Downing, C. C. 1992. "Indoor conditions in schools with insufficient humidity control." *Environments for People; Proceedings of IAQ '92,* October 1992, San Francisco, CA, ASHRAE, pp. 115-128.

Becker, R. 1984. "Condensation and mould growth in dwellings - Parametric field study." *Building and Environment,* Vol. 19(4), pp. 243-250.

Burge, H.A. 1987. "Approaches to the control of indoor microbial contamination." *Proceedings of IAQ '87,* ASHRAE; pp. 33-37.

Coppock, J.B.M.; Cookson, E.D. 1951. "The effect of humidity on mould growth on constructional materials." *Journal of the Science of Food and Agriculture,* Vol. 2, pp. 534-537.

DIN 1946 (Gesundheitstechnische Anforderungen). Ventilation and Air Conditioning; Technical Health Requirements (VDI ventilation rules). Raumluftechnik; 1963. (in German).

El Diasty, R., Fazio, P., and I Budaiwi. 1992. "Modelling of indoor air humidity: the dynamic behaviour within an enclosure." *Energy and Buildings*, Vol. 19, pp. 61-73.

Fisk, W. 1994. Personal communication, June, Lawrence Berkeley Laboratory.

Flannigan, B. 1992. "Approaches to assessment of the microbial flora of buildings." *Environments for People; Proceeding of IAQ '92,* September 1992, San Francisco, CA, ASHRAE; pp. 139-145.

Foarde, K.; Cole, E.; VanOsdell, D. et al. 1992. "Characterization of environmental chambers for evaluating microbial growth on building materials." *Environments for People; Proceedings of IAQ '92,* October 1992, San Francisco, CA, ASHRAE.

Gately, D.P. 1992. "Designing for comfortable cooling season humidity in hotels." *ASHRAE Technical Data Bulletin, Control of Humidity in Buildings,* Vol. 8(3), pp. 29-38.

Hart, B.J.; Whitehead, L. 1990. "Ecology of house dust mites in Oxfordshire." *Clinical and Experimental Allergy,* Vol. 20, pp. 203-209.

Ikeda, T., Kobayashi, Y., Dobashi, Y., and M. Imanaka. 1993. "Properties of temperature and humidity of each room and prevention of vapor condensation and vapor condensation damage in dwellings." *Indoor Air '93, Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 6, pp. 189-194.

Kohloss, F.H. 1987. "Economical comfort cooling in the humid tropics." *Proceedings of the First ASHRAE Far East Conference on Air Conditioning in Hot Climates,* Singapore, pp. 186-193.

Kubler, H. 1982. "Effect of wood on humidity in homes." *Forest Products Journal,* Vol. 32, No. 6, pp. 47-50.

Lstiburek, J., and J. Carmody. 1993. *Moisture Control Handbook, Principles and Practices for Residential and Small Commercial Buildings.* Van Nostrand, NY, 214 pp.

Macher, J.M.; Girman, J.R. 1990. "Multiplication of microorganisms in an evaporative cooler and possible indoor air contamination." *Environment International,* Vol. 16, pp. 203-211.

Mendel, M.J. 1993. "Non-specific symptoms in office workers: a review and summary of the epidemiologic literature." *Indoor Air,* 3, pp. 227-236.

Morey, P.R.; Williams, C.M. et al. 1991. "Is porous insulation inside an HVAC system compatible with a healthy building?" *Healthy Buildings; Proceeding of IAQ '91*; Sept. 1991; Washington, DC, ASHRAE.

Nikulin, M.; Berg, S.; Hintikka, E.L.; Pasanen, A.L. 1993. "Production of stachybotryotoxins on some building materials at different relative humidities and temperatures." *Indoor Air '93, Proceedings of the 6th International Conference on Indoor Air Quality and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 397-400.

Okano, T. 1977. "Investigation of a test house in Hachioji." *Wood Industry* Vol. 33 No. 10, pp. 418-423.

O'Rourke, M.K.; Fiorentino, L.; Clark, D.; Ladd, M.; et al. 1993. "Building characteristics and importance of house dust mite exposures in the Sonoran desert, USA." *Indoor Air '93; Proceedings of the*

6th International Conference on Indoor Air Quality and Climate, July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 155-160.

Pasanan, A.L.; Pasanen, P.; Jantunen, M.J.; Kalliokoski, P. et al. 1991a. "Significance of air humidity and air velocity for fungal spore release into the air." *Atmospheric Environment,* Vol. 25A(2), pp. 459-462.

Pasanen, A.L.; Kallioloski, P.; Pasanen, Jantunen, M.J.; Nevalainen, A. 1991b. "Laboratory studies on the relationship between fungal growth and atmospheric temperature and humidity." *Environment International,* Vol. 17, pp. 225-228.

Shakun, W. 1992. "The causes and control of mold and mildew in hot and humid climates." *ASHRAE Technical Data Bulletin, Control of Humidity in Buildings,* Vol. 8(3), pp. 18-28.

Spaul, W.A. 1993. "Building pressurization as an effective control for bioamplification as a result of moisture infiltration in a hot humid climate." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 2, 5 pp..

Stock, T.H.; Venso, E.A. 1993. "The impact of residential evaporative air cooling on indoor exposure to ozone." *Indoor Air '93; Proceedings of the 6th International Conference on Indoor Air and Climate,* July 4-8, 1993; Helsinki, Finland; Vol. 4, pp. 251-256.

TenWolde, A., and W.B. Rose. 1994. "Criterial for humidity in the building and the building envelope." *Bugs, Mold, and Rot II, Proceedings of Workshop on Control of Humidity for Health, Artifacts, and Buildings*: 1993 November 16-17. NIBS, Washington DC, pp. 63-65.

TenWolde, A.; Suleski, J.C. 1984. "Controlling moisture in houses." *Solar Age*, Vol. 1, pp. 34-37.

Tsongas, G. 1991. "A field study of indoor moisture problems and damage in new Pacific Northwest homes." *Healthy Buildings; Proceeding of IAQ '91*; Sept. 1991; Washington, DC, ASHRAE, pp. 202-209.

West, M.K.; Hansen, E.C. 1989. "Determination of material hygroscopic properties that affect indoor air quality." *Proceedings of IAQ '89*, ASHRAE; pp. 56-59.

West, M.K.; Hansen, E.C. 1989. "Effect of hygroscopic materials on indoor relative humidity and air quality." *Proceedings of IAQ '89*, ASHRAE; pp. 56-59.

Wilcox, W., Forest Products Laboratory, U.C. Berkeley. 1994. Personal communication.

Wong, S.P.W.; Wang, S.K. 1990. "Fundamentals of simultaneous heat and moisture transfer between the building envelope and the conditioned space air." *ASHRAE Transactions,* Vol. 96(2), pp. 73-83.

Wu, H. 1990. "Moisture up-take and energy efficiencies associated with the use of evaporative coolers." Environmental Testing Laboratory, Arizona State University, Report CAED90-HW003, 43 pp.

ACKNOWLEDGMENTS

The authors would like to thank Alison Kwok, Ph.D. candidate at U.C. Berkeley, for help with the literature search. We also wish to thank William Fisk, Indoor Environment Program, Lawrence Berkeley Laboratory, and Professor Wayne Wilcox, University of California Forest Products Laboratory, for their detailed reviews of the manuscript. The research reported here was funded by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor.

APPENDIX C

Design Criteria and Guidelines for Air Movement and Humidity

Comfort and Health

Design Criteria and Guidelines for Air Movement and Humidity in Ventilated and Evaporatively Cooled Houses.

Edward Arens
Zhang Hui

U.C. Berkeley, January 25, 1995

This booklet provides information on two of the alternatives to compressor-based cooling: ventilative and evaporative cooling. For ventilative cooling, we will look first at the basic criteria for comfort, and then at principles for designing buildings that provide comfort with ventilation. For evaporative cooling, we will discuss the design criteria related to comfort and health, and show data assessing the effectiveness of this technology in California. We will not address how to design such systems here.

I. VENTILATIVE COOLING:

Air movement is one of the six physical variables determining human thermal comfort: air temperature, air movement, relative humidity, mean radiation temperature, metabolic rate, and clothing insulation. Air movement in buildings is either produced by fans or by 'natural ventilation' from outdoor wind or indoor stack effect. There are two basic processes by which air movement provides cooling in the summertime: (1) it can remove the undesirable internal heat gains of the building, thereby cooling the building interior and (2) it can cool the occupants themselves, since increased air movement increases the rate at which the human body's metabolic heat production is removed from the skin surface.

In the first process, removing internal gains, the air movement must involve exchange of air between the indoors and outdoors, since the mass of air exchanged determines how much heat can be carried out of the building. This mass (or volume) transfer is often what is specifically referred to as 'ventilation' by engineers. By removing heat from the interior, air movement can reduce or eliminate the need for mechanical cooling.

For the second process, cooling the occupants themselves, the air movement can either originate outdoors (as through an open window) or be recirculated interior air (as from a ceiling fan). The effect of the air movement here is increased convection from the occupant's skin, allowing the body to dissipate its metabolic production at a higher ambient air temperature than would be possible if the air was still. This is also referred to as 'ventilative cooling' in the comfort literature. It might be better for clarity to use the terms 'convective cooling' or 'air movement cooling' for this second process, but at present the terminology is the same for both. When cooling the occupants, air movement reduces the need for compressor-based cooling by allowing a higher interior air temperature to be comfortable to them.

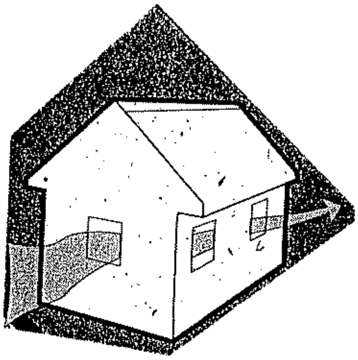
Air movement may provide desirable cooling in warm conditions, but it may also increase the risk of unacceptably cool draft. Draft is the unwanted local cooling of the body caused by air movement. In cool environments, the velocity limits for draft are quite low, around 0.2 meters/second. However, quite high velocities can be acceptable to humans when conditions are warm, with upper limits ranging from 0.8 to 1.5 m/s. The upper limit is often more dictated by inconvenience (paper blowing about) than by personal comfort effects. It is desirable in air movement cooling for the occupants to have personal control over the air movement: one would expect this to be the in residences. Figure 1 shows comfort zones for air movement cooling found by various researchers. There is general agreement in these and other studies that this large size comfort zone is realistic, and is produced by various types of fans. Figure 2 presents the DOE-2 simulation results for the Title-24 construction house in 44 locations in California for 2% design weather conditions. It shows that 98% of the overheated hours in hot summer days could fall in the comfort zone providing there is sufficient air movement.

Figures 3 and 4 show simulated room air temperatures during two typical summer days and two typical peak days, respectively, in Santa Rosa, using a prototypical two-story building modeled on DOE-2. The figures demonstrate that in typical summer days, all the room temperatures outside of the ASHRAE standard would be comfortable if sufficient air movement could be provided. For example, the maximum room temperature in the typical summer days is 85 °F, which could be still comfortable with velocities ranging between 0.35-1.0 m/s as shown in the "Zone of Likely Use". There will still be few hours for the peak summer days which can not be compensated by air movement.

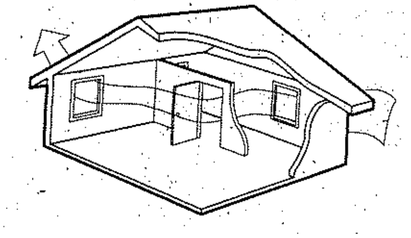
In general, air movement in residences may be produced by natural ventilation, fans, or direct evaporative coolers that operate with a high air flow rate. These are summarized in the Design Principles section below.

DESIGN PRINCIPLES

1.) Ventilative Cooling of the Building Interior



Ventilation cools building interiors when the heat content of the air outdoors is lower than that of indoors.. The cooling effectiveness is greatest when the temperature difference is greatest. As a result, the most useful ventilation hours often occur at night, although there are many daytime hours throughout the year when ventilation can be used. Since ventilation is often provided through open windows, privacy (both visual and acoustical) and security are important issues that need to be considered along with the aerodynamic arrangement of the windows. If a fan is used to promote ventilation, the noise and appearance of the fan need to be considered as well. The fan should not be too perceptible in the bedrooms, which are often the closest rooms.



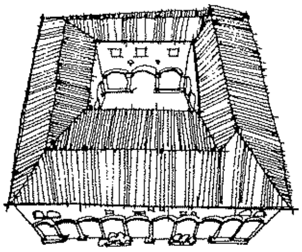
A. Open Windows

PRINCIPLES: Natural ventilation in buildings is produced by pressure differences between the inside and the outside of the buildings. When windows are opened, the pressure differences will push the air in and out through the openings. The magnitude of the pressure difference and the resistance to flow across the openings in the buildings will determine the rate of air flow through the openings. The two main forces producing pressure differences are the wind force and the thermal buoyancy force or 'stack effect'. The wind pressures result from the momentum of the moving outdoor air. The stack forces result from the differences in weight between a warm column of indoor air and the same column outdoors. The greater the distance between the inlet windows (at the bottom of the column) and the outlet (at the top), the greater the stack effect. In most houses the height differences are sufficiently modest that the wind-driven ventilation overwhelms stack effect as soon as the wind becomes appreciable, say over 4 mph. The stack effect may help or hinder the wind ventilation, depending on the directions of the two forces.

DESIGN GUIDELINES: Small rooms with large window openings can have high rates of wind-driven air exchange and interior air movement even if the windows are only on one wall (known as 'single-sided ventilation'). In such cases, it helps to have the window sash protrude outward from the facade to help capture airflows running along the facade (casement windows are best for this). It is good to have windows that open high and low (such as in casement windows and in double-hung windows) to allow stack effect to function. In general though, it is preferable to have 'cross ventilation', especially in larger or deeper rooms, or where the window open area is small relative to the room.

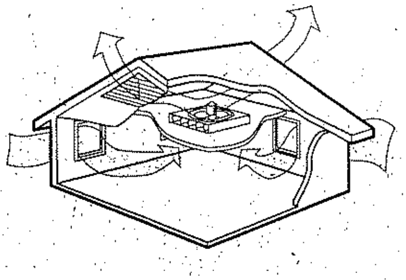
If a climate has a prevailing wind direction in the hot summer, the inlet air windows should face the breeze. Windows on the *windward* and *leeward* facades generally provide the strongest interior air movement. If the windows are directly opposite each other in relatively shallow rooms, it is possible that the center of the room will have strong velocities while the sides will get poor circulation (called 'short-circuiting'). When windows are on windward and *side* facades, they may provide good ventilation over a larger interior area than when directly opposite each other. In general, if one can fit windows on two walls of a room or of linked group of rooms, cross ventilation will occur. It will be least successful when the openings are all on side and leeward walls, both of which are experiencing suction. But even in this least desirable situation, there is usually sufficient turbulence in built-up surroundings to provide an oscillating pressure field that will cause the cross ventilation to flow back and forth.

To encourage stack effect, the windows for outgoing air can be located in higher positions. This allows ventilation to be driven by temperature differences even in the absence of outdoor wind.



To the extent possible, one should try to locate the open windows away from streets to improve the privacy, security, and to avoid street noise. If possible, the windows would open to a garden or trees, letting the occupants feel closer to the outdoors, and with the incoming air somewhat cooler than that from the streets. In suburban and urban settings, the most effective location for windows to be used for natural ventilation would be facing controlled spaces, such as courtyards and enclosed yards. These have the potential to assure privacy, increased security, and reduced street noise. They also have the potential for very effective shading of windows and facades, and for local cooling of the air being drawn into the building.

B. Whole House Fan



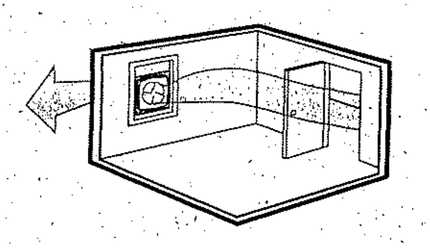
PRINCIPLE: In much of the U.S. South, summer winds are low, reducing the effectiveness of the natural ventilation design approaches described above. Whole house fans are widely used in these situations in order to assure ventilation. They are usually installed in the ceiling, and blow exhaust air into the attic, from whence it escapes via attic vents. Whole house fans create a negative air pressure inside the residence. When windows are opened, the outside air enters to relieve the negative pressure. This causes outside air ventilation to cool the house, and also produces an artificial breeze (especially near the open windows) that can cool the occupants.. The exhaust flow through the attic helps reduce the heat built up from solar gain through the roof. The fan is usually turned on only when the air outside is cooler than the air inside, such as in the late afternoon or early evening. In the morning, the fan should be turned off and the windows closed before the outdoor temperatures begin to rise above the interior temperature.

In an insulated house, the indoor air temperatures can be kept cooler than the outside air throughout the day by closing windows and reducing solar gains to a minimum by pulling the drapes. It of course helps to have either the architecture or the landscaping provide exterior shading on windows, walls and roof, and to use light colors on roof and walls. As the outside air temperature decreases in the early evening, the windows may be opened to bring in cooler outdoor air. The indoor temperature will not decrease as quickly as the outside air since the heat stored in the building's thermal mass needs to be released. Even with numerous windows open, the thermal mass of the house will cause it to cool about half as fast as the outside air. Cooking dinner may add heat to slow this rate futher. The rapid air changes induced by a fan (ranging up to 40 house volumes per hour for typical fan sizes, though in the Deep South they range to 60 per hour) makes the house interior closely follow the natural fall of the outside air temperature. In the climates where the outside temperature range is large (typical for inland California), whole house fans ventilating at night are very effective for precooling the building's structure in preparation for the next day. During night ventilation, indoor temperatures may be cool, but occupants are not affected by this when in bed.

DESIGN GUIDELINES: To be effective, windows must be open when the whole house fan is operated. It is not necessary to open windows all the way to ventilate with a whole house fan. They can be opened 4-6 inches (100-150 mm) and fixed in a secure position by stops or window locks. The total open window area should be at least two times the open area of the fan wheel. The total open window area should be three times the whole house fan open area if there is insect screening at the windows.

The attic vents need to be larger than normal for effective whole house fan ventilation. The free exhaust area should be approximately twice that of the area of the fan itself, and three times the area if screening is used. Openings should be distributed throughout the attic or placed to the lee side of the building for adequate ventilation.

Think carefully about where to put the whole house fan in order to get better cooling effect and produce less disturbance to the occupants. In a large house, a central location allows the fan to draw air from all parts of the house with less blockage. Since it is usually good running at night to increase the night ventilation, it is desirable to keep it away from bedrooms..



C. Window Fan
PRINCIPLE: Window fans are usually exhaust fans placed in window openings to produce interior air flow. The fan is turned on only when the air outdoors is cooler than the air indoors.

DESIGN GUIDELINES: Place the fan in high windows so that it will exhaust warmer air. Open the incoming air windows at the occupied level, drawing to the extent possible from cool air sources (such as from north side of the house or from where there are big shading trees). Be careful to avoid blockage between the fan and the open windows.

D. Direct Evaporative Cooler with High Air Flow Rate
PRINCIPLES: Evaporative coolers are explained in Section II below. For direct evaporative coolers, the supply air cannot be recirculated, and it is usually exhausted through opened windows. Some air movement cooling may occur in rooms as a result of the airflow from the evaporative cooler.

DESIGN GUIDELINES: The system must be operated with sufficient exhausts (windows) to assure flow of cooled air throughout the interior space.

2) *Cooling the Occupant by Air Circulation*

Air circulation fans such as ceiling fans and room fans increase the heat loss from the human body without changing the room air temperature. Such fans can provide inexpensive cooling when wind driven ventilation is inadequate, and since they are readily controlled by the occupants, can be used to spot cool areas where specific thermal loads or activities require additional cooling.

A. Ceiling Fan
PRINCIPLE: Ceiling fans are mounted near the ceiling and create air movement in the range of 100 to 150 feet per minute. They do not affect outside air circulation through the house, but increase the rate of the air movement within individual rooms. They are often reversable to allow them to recirculate warm upper air downward in the wintertime.

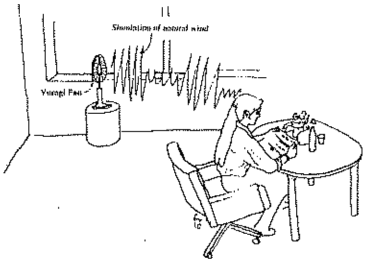
GUIDELINES: For naturally ventilated buildings in which high air movement is required for comfort, ceiling fans are required for each primary occupied space. Fans should be selected to provide air movement not great enough to disturb loose papers but great enough to enable human comfort (this is usually figured to be in the range of 0.8 to 1.5 m/s (1.8 to 3.3 mph). Figure 5 shows the typical distribution of air velocity under a ceiling fan. Control over speed variability, minimum and maximum speeds, noise level, power requirements and minimum floor to ceiling heights must be considered when choosing ceiling fans. Occupancy sensors can be used to assure that the fan operates only when a person is in the room.

B. Wall-Mounted Fan

PRINCIPLES: Fans can produce horizontal plumes that travel greater distances than are possible from ceiling fans. When a fan is mounted to blow air along one wall down the long axis of a room, a circulation will be created in which air returns on the other side of the room. If this is mounted above head height, it will be less perceptible to the occupants but still produce air movement in the occupied zone.

GUIDELINES: Figures 6a and 6b show an example of a wall-mounted fan in a ventilated house/office in Houston. There are such wall-mounted fans in each room. The fans are mounted in the corners just above head height so that the velocity plume will not disturb either the occupants or the hot air near the ceilings. The fans are said to be very effective, and so quiet and well-balanced that they have operated without people's attention for over 10 years.

B. Standing Fan



PRINCIPLES: Standing fans are usually used to cool occupants directly, although in small rooms they may work for the whole room. Since they are easy to move around, they can be arranged to meet personal requirements. By making air movement personally controllable, people's thermal satisfaction with the environment is usually increased. On the downside, they tend to be noisier than other fans, and their velocity plume within the occupied zone may become excessively noticeable.

GUIDELINES:.

Figure 7 is a distribution of velocity from a stand fan. The air flow velocity is intentionally fluctuated in this particular fan in order to simulate the natural wind pattern. It was suggested by the manufacturer that this provides a more pleasant sensation than a more constant air stream. We were unable to confirm this in comfort tests that we did, but it is possible that the effect is true at low velocity levels.

II. EVAPORATIVE COOLING:

1.) Principles and Effectiveness: In hot and dry summer climates such as inland California's, evaporative cooling is very effective. Evaporative cooling devices can be classified as *direct, indirect,* and *indirect/direct (two-stage)* evaporative coolers

Direct evaporative coolers pass hot dry outdoor air through a water-soaked pad on the way to the building interior. The evaporated water will both cool the air and increase the its humidity. The occupant will perceive the drop in air temperature far more than the increase in humidity. The indoor humidified air cannot be recirculated through the cooler, and must be exhausted from the house. This evaporation is very efficient. An indirect evaporative cooler cools the incoming air by passing it through a heat exchanger, on the other side of which evaporation is taking place. The cooling efficiency is less than for direct evaporative coolers, but no humidity is added to the room air. The two-stage evaporative cooler combines direct and indirect evaporative cooling for the greatest efficiency. It will precool the incoming air by passing it through the indirect evaporative cooler heat exchanger. Then the cool but dry air is further cooled by direct evaporative cooling.

A direct evaporative cooler uses around 15% of the electricity used by an air-conditioner, together with 5-15 gallons of water per day (cited by the Los Angeles Department of Water and Power). This is a small amount of water compared to an individual's daily domestic use (50 to 100 gallons per day). A two-stage cooler monitored in Phoenix used 30% of the energy of a heat pump, and 86 gallons per day.

From DOE-2 simulation results carried out at LBL, a two-stage evaporative cooler can keep indoor temperatures of a typical house below 78 °F for the whole summer in climates like Santa Rosa, Pasadena, Riverside, and Sacramento (this could not be accomplished by either direct or indirect coolers alone). In Santa Rosa, the annual energy use was 37% of the energy used by a conventional air-conditioner.

2.) Effects on Health: Since direct evaporative coolers increase indoor air humidity, there are concerns about their impact on human health. The indoor relative humidity is commonly between 60 and 70% during evaporative cooler operation, and apparently will reach up to 80% at times (we ourselves have seen no hard data on this). Since past ASHRAE standards have suggested, variously, 60, 65, 70 and 80% RH as upper humidity limits (the trend seems to be downward), it appeared to be useful to investigate the literature for evidence of health effects caused by humidity. It turned out no one had done this before from the perspective of designing buildings for evaporative cooling. The following is a summary of the results of this review.

Most of the health effects of humidity are caused by biological agents such as molds and dust mites. These grow on or very near the surfaces of the building, and their growth is only indirectly related to the humidity in the indoor air. To control these one needs to assure that the surfaces remain dry. It is also necessary to avoid producing aerosols of water from the mechanical system or humidifiers, since biological organisms from sumps or water supplies can be transmitted in such aerosols.

Evaporative cooling in hot-dry climates (such as California's inland in summer) appears to be relatively benign biologically, since building surfaces are usually considerably warmer and drier than the conditioned air emerging from the cooler. The surface moisture level needed to produce molds is unlikely to occur from the indoor air humidity produced by an evaporative cooler. (It can occur if the cooler leaks water, a common problem with the old-style roof-mounted swamp coolers).

It is unknown at this time whether dust mites are encouraged by the intermittent humidity produced by seasonal evaporative cooling (often intermittent on a daily cycle as well). However the humidity level that is often cited as conducive for mites (a relative humidity around 60 or 70%) is close to what an evaporative cooler produces in the occupied space when it is running. It is probably important that the relative humidity in the environments where mites live (furnishings and carpets) not be allowed to rise above this. Elevated relative humidities may occur very close to floor slabs that are cooler than the interior air, due to coupling to earth temperatures below, or by being part of a hydronic or air-based cooling system. For one floor slab cited in the literature, cooled temperatures within the carpet pile increased the humidity within the pile of a carpet 9% over that in the airspace above. It may be desirable avoid designing *carpeted* floor slabs that are cooled by an active system, or by excessive earth contact, when there is direct evaporative cooling in the space above. Dust mites should not be a problem on uncarpeted floors, even if cooled.

Direct evaporative cooling through porous media (all residential systems seem to be of this type) also appears to be benign in that biological organisms in the cooling water do not seem to be aerosolized or transmitted downstream in significant concentrations. The wet pads may in fact act as filters to outdoor pollutants, and the higher ventilation rates required by evaporative coolers should act to dilute the concentration of indoor-generated pollutants, including airborne infectious organisms generated by the occupants.

Because the pollutant ozone is generated outdoors, evaporatively cooled houses with their once-through ventilation may experience higher levels of indoor ozone than air conditioned spaces where the indoor air is largely recirculated. Conversely, the increased indoor humidity from direct evaporatively cooled surfaces may increase the outgassing of formaldehyde from some building materials. With the high ventilation rates, this may not be a problem. At this time one would have to say that these are only potential problems, and there is very little information available on either of them.

Figure 8 is a representation of the current Standard 55-92, as recently amended. The upper humidity limits enclose a zone that is known to be thermally comfortable. From our review of the health data, we believe that these boundaries are also acceptable from a health perspective, especially when applied in the evaporative cooling context. The extension of this comfort zone due to air movement is shown in Figure 1.

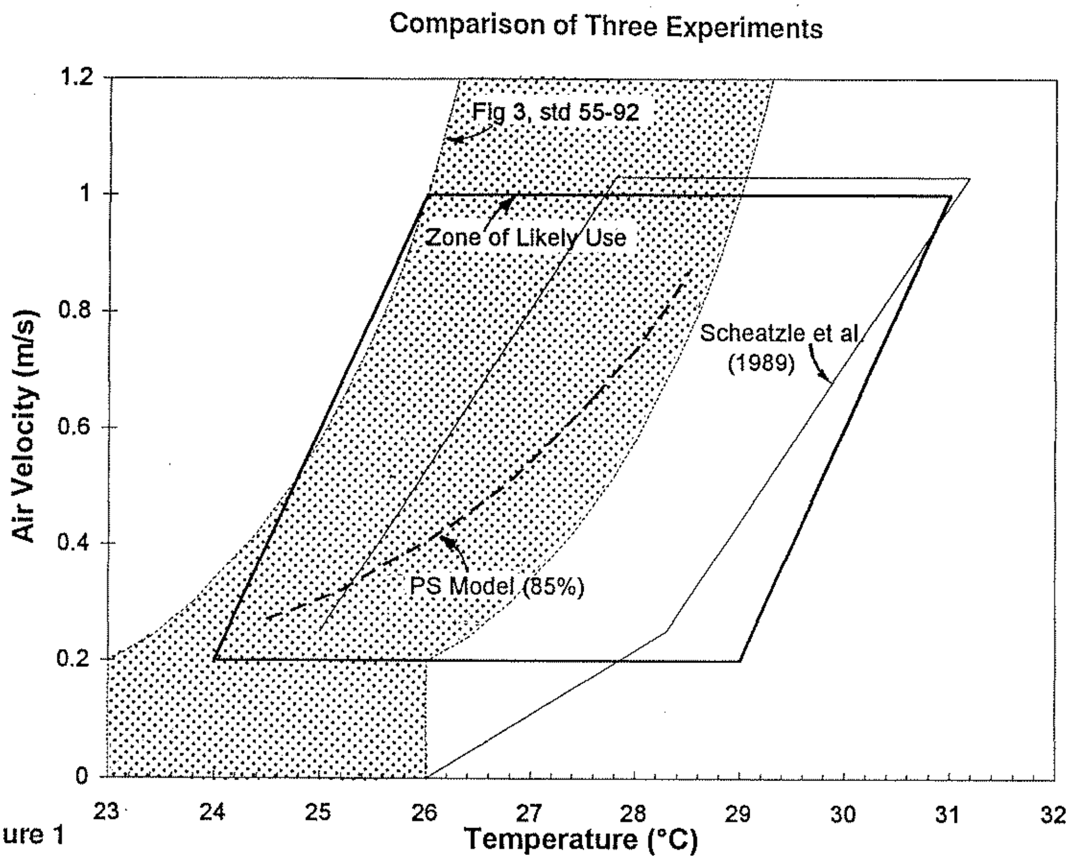


Figure 1

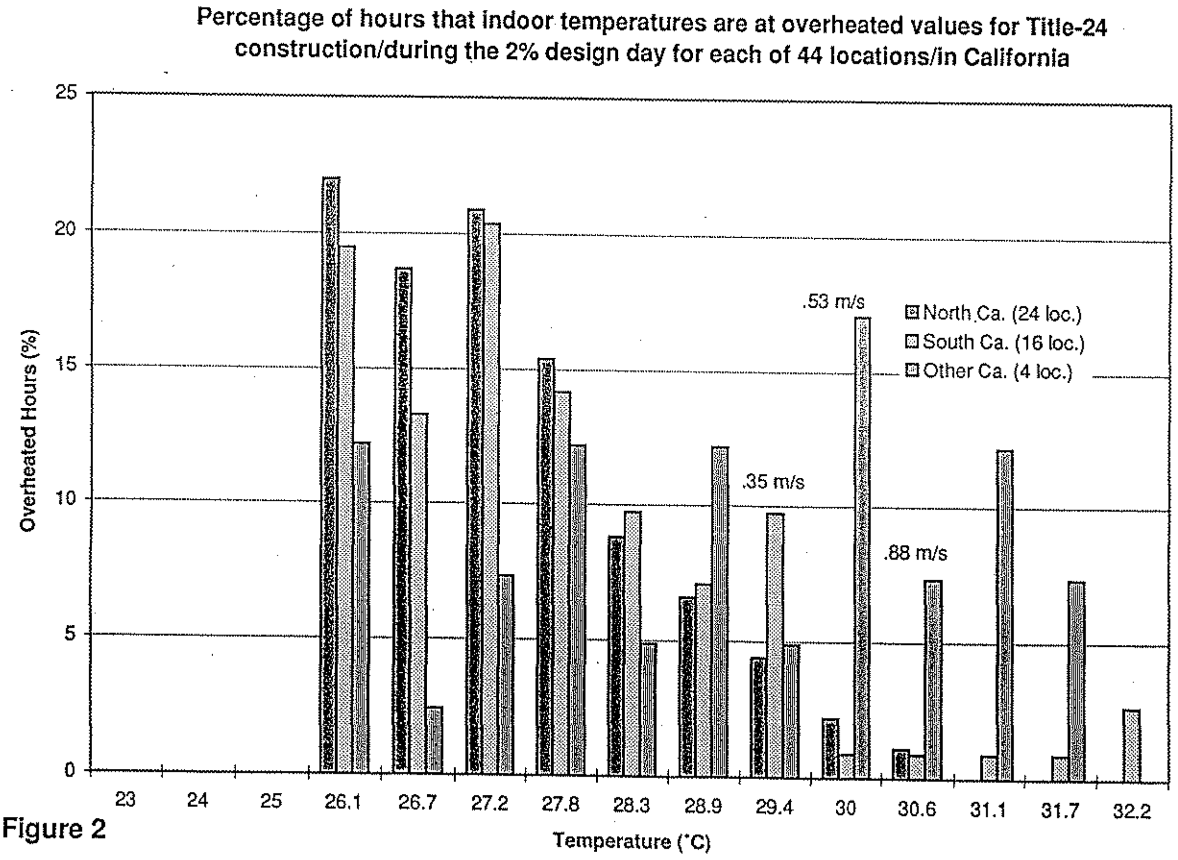
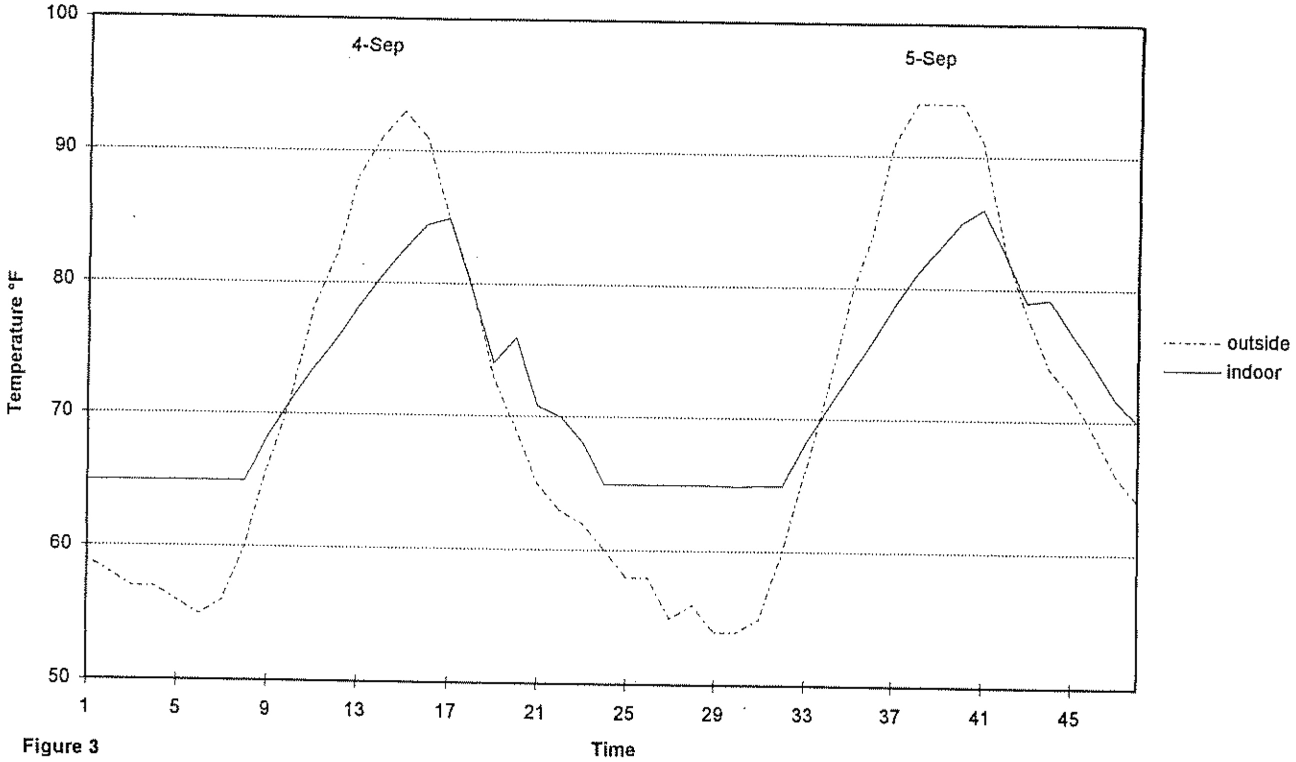
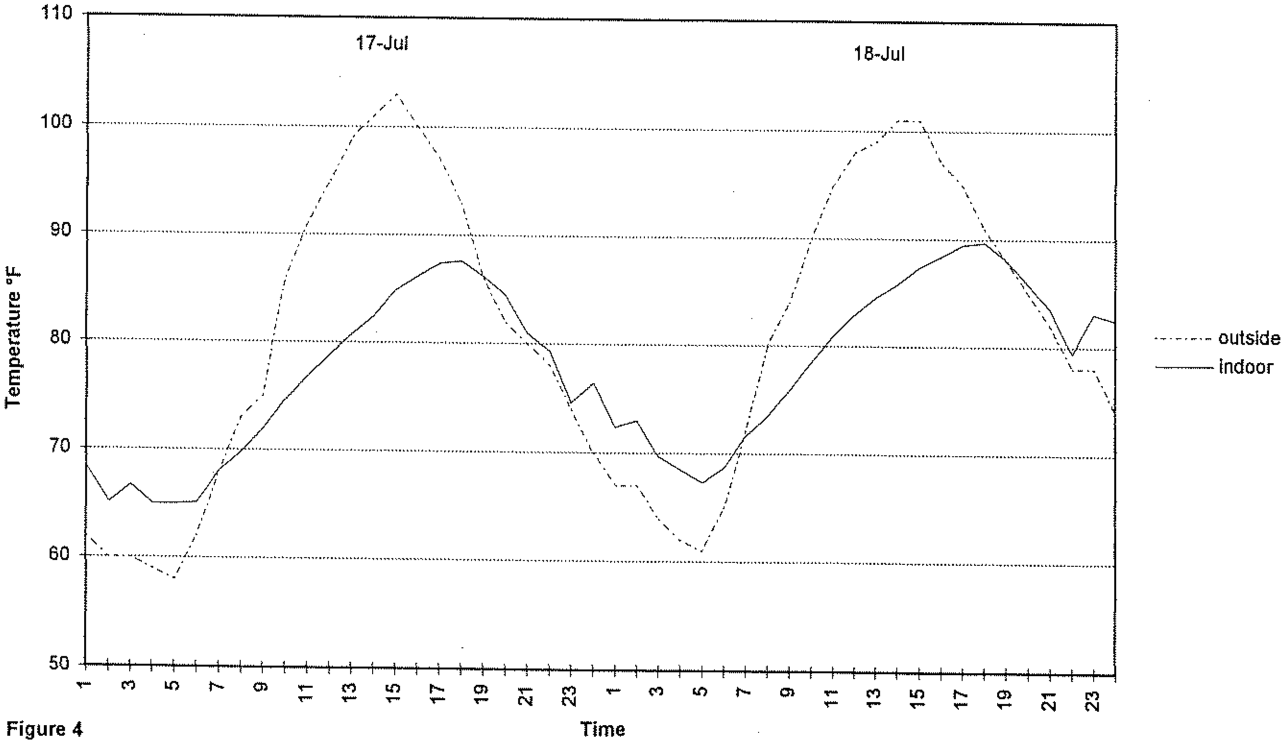


Figure 2



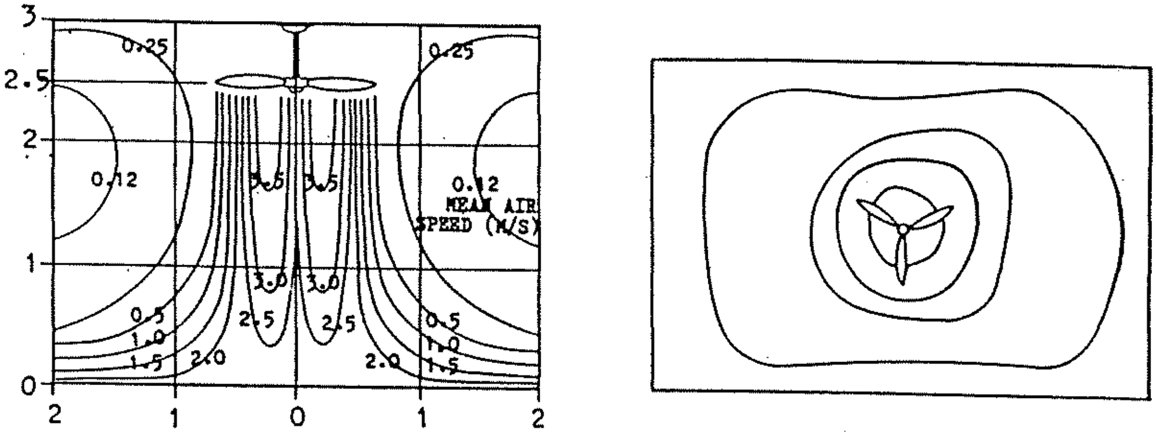
Typical two-story residential building with Title-24 construction/window venting/on two typical summer days/in Santa Rosa

Figure 3



Typical two-story residential building with Title-24 construction/window venting/on two peak summer days/in Santa Rosa

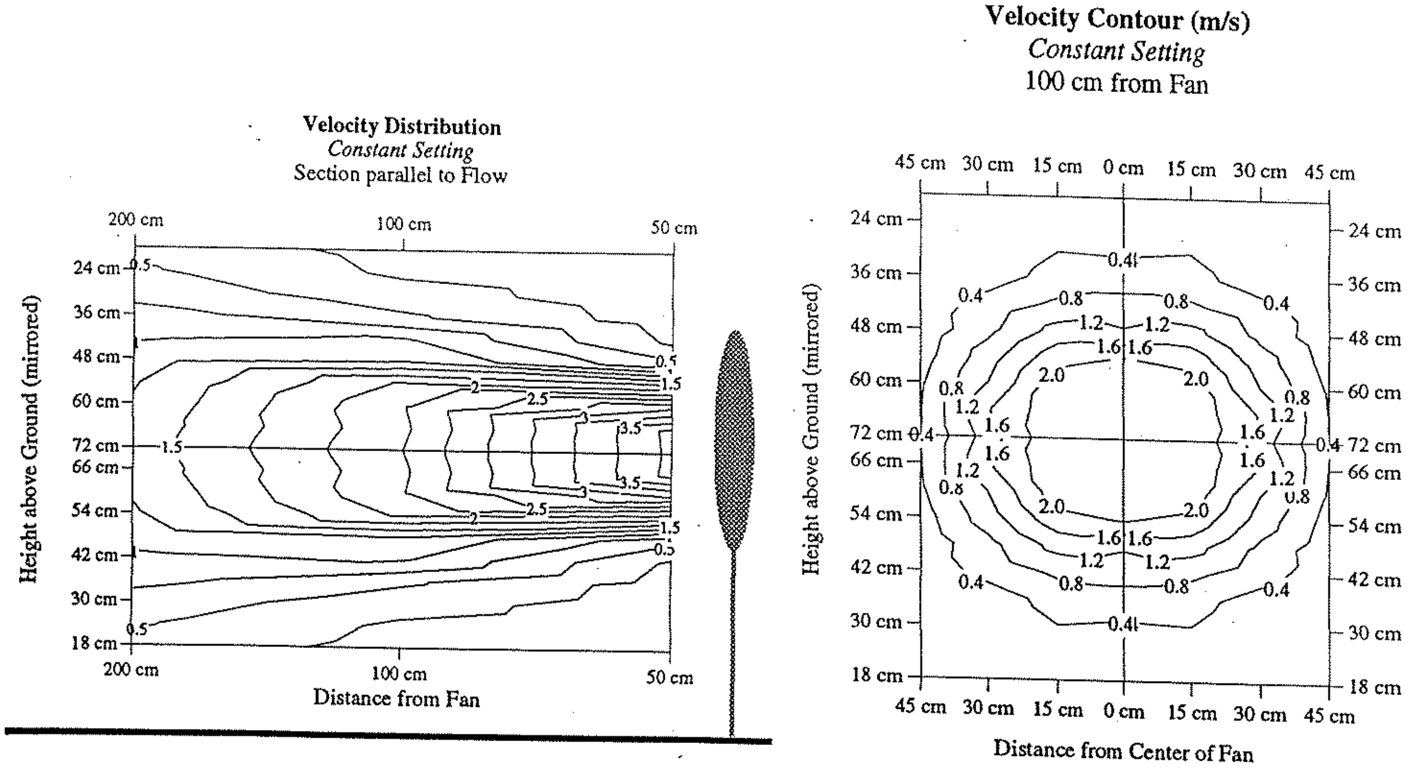
Figure 4



SECTION

PLAN

FIGURE 5


Velocity Distribution
Constant Setting
Section parallel to Flow

Velocity Contour (m/s)
Constant Setting
100 cm from Fan

FIGURE 7

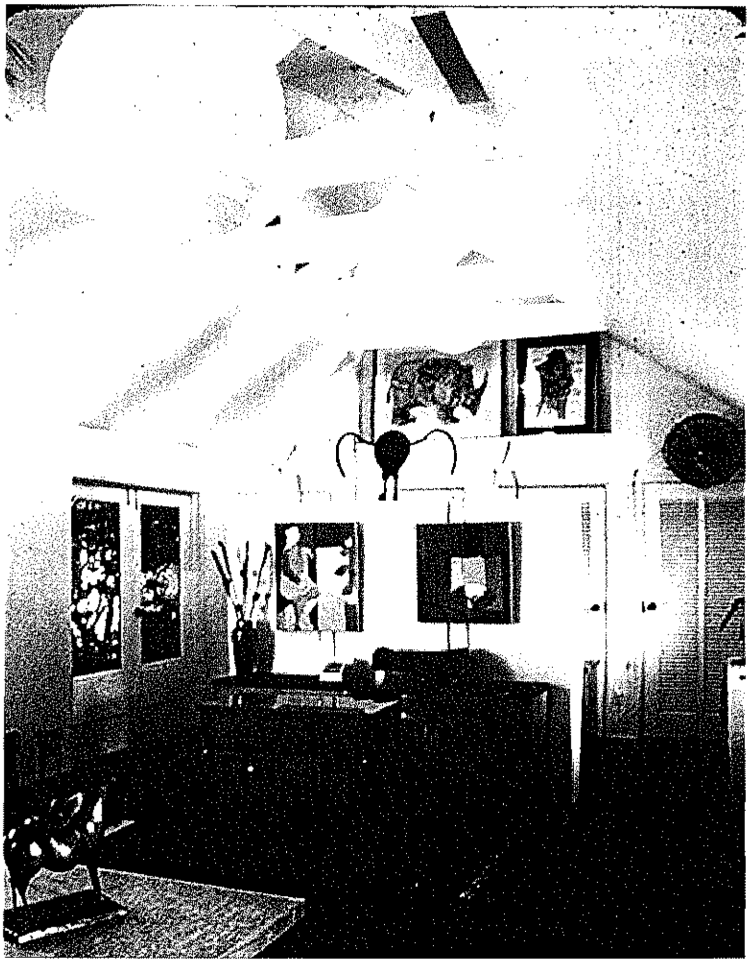
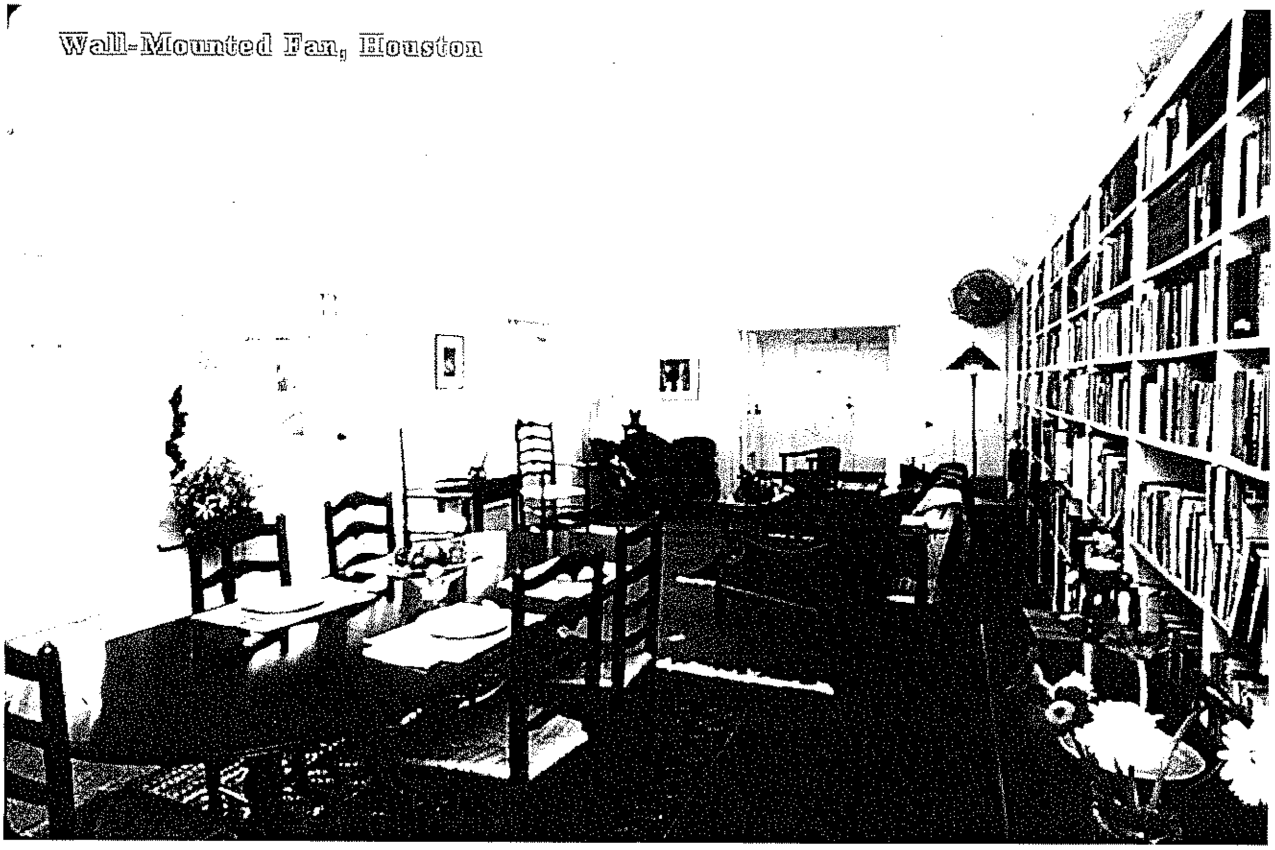
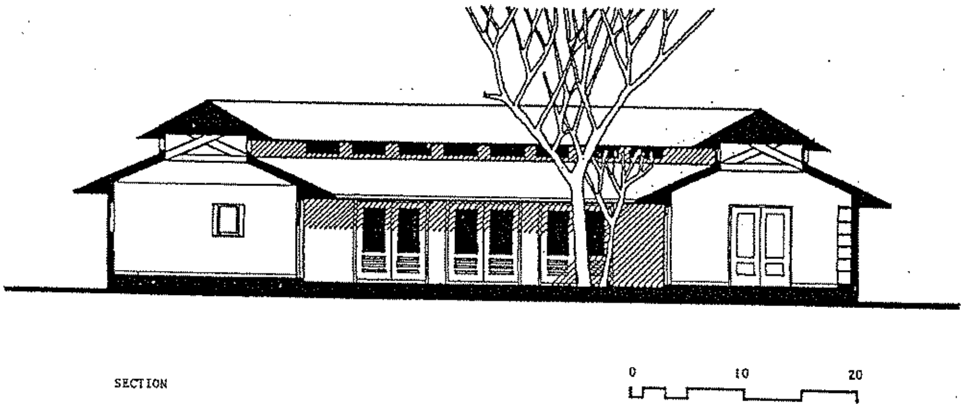


FIGURE 6A

Wall-Mounted Fan, Houston




SECTION
0
10
20

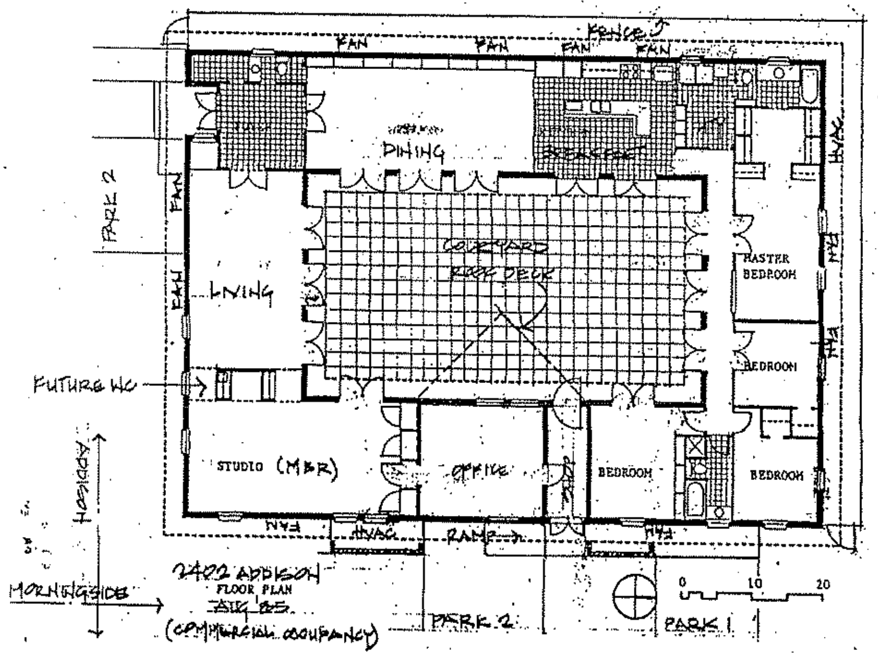

FENCE
FAN
FAN
FAN
FAN
DINING
BREAKFAST
HVAC
PARK 2
FAN
FAN
LIVING
COURTYARD
ROOF DECK
MASTER BEDROOM
HVAC
BEDROOM
HVAC
FUTURE WC
STUDIO (MBR)
OFFICE
BEDROOM
BEDROOM
ADDISON
FAN
HVAC
RAMP
HVAC
2402 ADDISON
FLOOR PLAN
AUG '85
(COMMERCIAL OCCUPANCY)
MORNINGSIDE
PARK 2
PARK 1
0
10
20

Figure 6B

FIGURE 8 **ASHRAE Summer Comfort Zones**