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COMFORT AND HEALTH CONSIDERATIONS: AIR MOVEMENT AND HUMIDITY CONSTRAINTS

Final Report - Phase I

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COMFORT AND HEALTH CONSIDERATIONS: AIR MOVEMENT AND HUMIDITY CONSTRAINTS

Final Report - Phase I

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EXECUTIVE SUMMARY

This report describes the results of research completed during Phase I of the project. The report is organized in terms of four separate types of work that have taken place. These are:

1) laboratory studies of air movement and comfort. These are categorized into:
   a) human subject tests
   b) tests on a thermal manikin.
2) development of a computer model of the human body that is sensitive to localized effects of air movement, localized radiant fields, and other environmental influences.
3) review of the influences of humidity on health, particularly as they impact evaporative cooling and naturally cooled architecture.
4) activities related to the revision of ASHRAE Standard 55 'Thermal Environmental Conditions for Human Occupancy' to avoid restrictions on allowable humidity indoors that could be unnecessarily harmful to energy conservation techniques.

1. Laboratory Studies of Air Movement and Comfort (Subtask B.1.a.1)

We have performed a set of laboratory experiments to define the comfort and acceptability effects of naturally turbulent air movement under warm conditions. The experimental design was guided by the issues that have been brought into focus by the recently approved ASHRAE Standard 'Thermal Environmental Conditions for Human Occupancy' (Standard 55-92), and by the deliberations that led to its provisions. Edward Arens, Fred Bauman, and Ph.D. student Marc Fountain have been involved in this discussion throughout the last three years, and are part of the new standing committee to perform an ongoing revision process. The work on the standard has revealed a number of large gaps in our understanding of the role of air movement on cooling and comfort, unknowns that strongly influence the way several alternative cooling strategies are evaluated. The trend in these standards, toward strict limits on maximum allowable air movement, in effect prohibit the natural cooling techniques of wind- and fan-driven ventilation, and impact direct evaporative cooling as well.

To put these issues before the engineering profession, we (Fountain and Arens) prepared an *ASHRAE Journal* paper describing the new Standard 55 and the uncertainties inherent in its air movement provisions. The paper describes the historical reasons for these provisions, including the experimental evidence used in their support. This paper was accepted and published in the August 1993 issue. It is attached in **Appendix A.**

A. Human Subject Tests:

The laboratory experiments focused on developing information that can be used to better represent air-movement cooling in comfort standards. This information is needed to counter what will otherwise become a universal restriction on air movements above 0.2

m/s in occupied spaces. In order to be influential, it is important that the findings are done to the same level of precision as the research that underlies the conventional comfort zone.

Our approach has been 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 produces a naturalistic windspeed turbulence distribution by software control of its variable speed motor. The power spectrum of the fluctuating airstream downstream of this fan is claimed to closely represent that of the natural wind between 10^{-2} and 1 Hz. The fan can also be operated in a constant mode. The fan's mean windspeed is 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 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 'residential' 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: fluctuating and constant.

The subjects were tested at two activity levels (or metabolic rates). The first is directly applicable to the ASHRAE and ISO standards and representative of 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. The procedure for producing the higher metabolism in the laboratory is interesting, and required input from comfort researchers around the country

During the tests, we monitored 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 statistical tests to describe their responses. Their 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 prepared that defines 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 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 they are 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 Appendix 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 will be recommending that the setpoints given by 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 will also be presenting these results to the comfort research community at large, and hope that they will strongly influence the formulation of the future ASHRAE Standard 55 and other such standards.

This study is presented in **Appendix B**. The work is not totally completed at this date, so some additions and changes to the report are expected in the next month.

B. Thermal Manikin Tests in Support of Human Subject Tests

In preparation for the human subject tests, we tested thermal effects of the fan's ventilation on an electrically heated manikin. The manikin, with 16 separate body segments, allows us to be specific about the cooling influences of breezes on the body. The manikin's skin surface temperatures and heat transfers are monitored in conjunction with air movement at various fan settings. Several environmental temperatures and clothing ensembles were tested as well. The manikin was positioned in the same position and environment as the human subjects were subsequently, allowing direct comparison of the two types of measurements. We used one of these fans in conjunction with the thermal manikin to determine the heat loss rates, skin temperatures, and heat transfer coefficients for each of the manikin's 16 body parts. This information is needed to quantify the thermal effects that the subjects are experiencing, and to aid with the development of suitable computer models for ventilation in the future. The results of this work are presented in **Appendix C.**

C. Thermal Manikin Tests in Support of Computer Comfort Modeling.

To link the work to previous air movement studies, we also tested this thermal manikin in the wind tunnel. This 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 comfort modeling in the future.

We also used the manikin to determine the insulation value of padded chairs. This value, determined as 0.15 clo, is significant, and has already allowed researchers to reevaluate the results of field studies where air movement is a significant parameter. This will also be used in computer comfort modeling in the future. The results of the above-described manikin work are presented in **Appendix D.**

2. Computer Comfort Analysis. (Subtask B.1.a.3)

We worked on revising our version of the Stolwyjk multi-node thermal model that we obtained from Shin-ichi Tanabe in order to make it correspond to the data from the segmented manikin. This work will continue in the next year, to prepare for Tanabe's month-long working visit planned for this next fall. A program diskette is available from us, but it is not yet fully functional.

3. Review of Health Effects Related to Humidity in Buildings (Subtask B.1.a.2)

We assembled literature and wrote a report on humidity influences on health, focusing on the humidity impacts found in evaporatively cooled buildings in dry climates such as California's in summertime. The single most salient observation that one can make about this complex subject is that humidity/health effects are inadequately predicted by the humidity as measured in the building's occupied air space. This variable (in the form of relative humidity) is however almost the only one being proposed as the basis for humidity limits in ventilation and indoor air quality standards. There are energy-conservation grounds for making sure that future humidity/health limits be based on humidity variables that are more relevant to the health effects of concern.

Even if relative humidity were the appropriate parameter, there is little to justify the current upper limit of 60% in Standard 62. 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 that is 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.

The report also 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 upcoming standards deliberations. It is attached in **Appendix E.**

As a result of our review of health effects, Arens and Ph.D. student Anne Baughman attended numerous humidity-related committee meetings at the ASHRAE June meeting. 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 beginning its revision cycle, Environmental Health, and the new Task Group on a comprehensive indoor environmental standard chaired by Hal Levin. We also attended TC 5.7, evaporative cooling, and several seminars and fora related to evaporative cooling and the new Std. 62 ventilation requirements. It is pretty clear in all of these meetings that sentiment is building for mandatory humidity limits justified on health grounds. These new limits (currently in the form of non-mandatory 'guidance language' only) could potentially restrict the use of direct evaporative cooling as an alternative cooling strategy. They could also restrict the use of regionally appropriate architecture as ways of saving energy.

We intend to begin to participate in the activities of these indoor air quality and environmental health committees in the coming year. Our objective would be to assure that, as these committees begin to promulgate more binding standards, that the actual physical bases of humidity limits be kept in consideration. If this occurs, and the eventual standards act to control moisture at the locations that the health problems actually originate, energy conserving technologies such as direct evaporative cooling and naturally cooled architecture will be able to remain viable alternatives to compressor-based cooling.

4. **Review of Humidity Effects on Comfort.** (This work was added to the original Subtask B.1.a.2)

In addition to the work on health, we spent considerable time throughout the year on the issue of humidity effects on comfort, working together with Karl Brown. Brown had noted during the fall that the steady lowering of upper humidity limits in comfort standards in recent decades would have the effect of precluding direct evaporative cooling as a legally defensible engineering design option. This upper limit had reached a new low (lying along the 60% RH line) in the recent revision of Standard 55-92 'Thermal Environmental Conditions for Human Occupancy'. Brown was able to successfully challenge the basis of this limit at the January 1993 meeting. He was then appointed Chairman (and Arens a member) of an ASHRAE subcommittee charged with determining appropriate upper humidity limits to the Standard 55.

We (Brown and Arens) targeted our humidity/comfort effort for the ASHRAE annual meeting in June, when the final amendments to Standard 55-92 were completed. We went through an extensive process of gathering information, corresponding with relevant researchers and committee members, and generating proposals for a new top boundary to the comfort zone. One of these proposals was agreed upon by the humidity subcommittee, and approved by the Standards revision committee at the June meeting. It has now been put out for public review as a proposed addendum by ASHRAE. It is attached as **Appendix F**. Should the comments be resolved this fall the amendment will become part of the Standard in early 1994.

The new top boundary is very substantially different from the earlier one proposed for Standard 55-92, and it is different from that of Standard 55-81 as well. It follows wetbulb contours starting from the 60% RH point on the upper temperature boundary, and passes into higher RH's as the temperature cools. It creates a zone that (conservatively) fits some of the few laboratory results applicable to this problem. In spite of its conservatism, it allows far higher levels of humidity in the space than either earlier version of the standard. It will as a consequence permit direct evaporative cooling in California climates to create indoor environments that meet Standard 55's requirements, whereas before this was almost impossible. This should allow this technology to be part of conventional engineering design practice.

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APPENDIX A

Air Movement and Thermal Comfort

by

Marc Fountain and Edward Arens

Air movement and thermal comfort

The new ASHRAE Standard 55 *provides information on appropriate indoor air velocities for occupant comfort*

By Marc E. Fountain and *Edward A. Arens, Ph.D.*
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Recent HVAC design innovations, energy conservation concerns and new laboratory data on drafts have brought substantial attention to the issue of acceptable levels of air movement in office environments.

Air movement may provide desirable cooling in warm conditions, but it may also increase the risk of unacceptably cool drafts. Detectable air movement may be perceived by the occupants as providing freshness and pleasantness to the breathing air, yet it may also be perceived as annoying.

Clearly, a specific air speed has many possible physiological and subjective consequences. These range from a pleasant sense of coolness to an unpleasant sense of draft, depending on the air temperature, mean radiant temperature, humidity, clothing, metabolic rate and air movement preference of the occupant.

Since the turn of the century, ASHRAE and thermal comfort researchers have worked to define levels of air movement that are acceptable to the widest possible group of individuals within an evolving architectural setting, and to incorporate these results into an indoor environmental standard.

This article outlines the current state of this discussion. Reference is also made to research investigating the effect of air movement on thermal comfort and the development of air velocity limits in the latest ASHRAE thermal comfort standard.

Why is air velocity important?

HVAC engineers design systems to move energy and ventilating air through buildings. Many, if not most, commercial buildings built since the middle of this century use air distribution systems to deliver heated and/or cooled air to occupied spaces.

Accordingly, ASHRAE and other organizations have produced standards and guidelines for distributing this air. Included in these documents are specifics such as: volume of air per unit time, percentage of outdoor air, and type and location of duct outlets.

In general, design recommendations have favored specifying delivered cfm per square foot of occupied space rather than specifying air velocity for achieving thermal comfort. However, the desired end-product of HVAC systems is not cfm per square foot, a cooled building interior or air movement per se; it is the comfort, health and satisfaction of building occupants.

Beyond special cases such as laboratories and clean rooms, efforts in HVAC are primarily directed at producing thermal comfort and air quality that are acceptable for breathing. The focus of this article is the influence of the air movement (created by an HVAC system) on thermal comfort.

Air velocity is one of six main variables affecting human thermal comfort. The other five include three physical variables (air temperature, mean radiant temperature and relative humidity) and two behaviorally regulated variables (metabolic rate and clothing insulation).

In humans, the thermoregulatory system is responsible for maintaining the heat balance of the body using a core setpoint of 98.6°F (37°C) within the constraints of the six variables given above. This system controls the release of metabolic heat by regulating skin temperature, primarily by varying skin blood supply and sweating at the skin surface.

Convective heat transfer at the skin varies with surface temperature and local air motion across the skin surface. Extensive laboratory studies have shown that thermal sensation vote (an important method for measuring thermal comfort) is closely related to skin temperature in cool and comfortable conditions. In warm and warm-humid conditions, moisture on the skin has a strong effect on thermal sensation, particularly after sweating mechanisms have been triggered.

About the authors

Marc E. Fountain is a PhD candidate at the University of California—Berkeley (UCB). He received his BA in physics from UCB. Fountain is a corresponding member of ASHRAE TC 2.1 (Physiology and Human Environment) and has been active in thermal comfort research since 1986 including contributions to ASHRAE Research Projects RP-462 and RP-702.

Edward A. Arens is a professor in the Department of Architecture at the University of California—Berkeley and director of the Center for Environmental Design Research. He received his PhD in architectural science from the University of Edinburgh and his undergraduate and masters degrees from Yale University. Arens is serving on the SPC 55-92R Standards Project Committee, and is a corresponding member of TC 2.1 and a past-chairman of TC 2.5 (Air Flow Around Buildings).

Because heat loss, skin temperature, skin wettedness and thermal sensation are interdependent, local air movement is an important factor in thermal comfort. Accordingly, it has been incorporated in comfort standards from their inception.

Research efforts

With the advent of HVAC systems in the earlier half of this century, the issue of suitable thermal conditions for human occupancy needed attention.

ASHRAE's precursor (ASHVE) began a program of determining suitable indoor thermal environments at its laboratory in Pittsburgh. This effort was spurred by the experience that drafts were the most frequent cause for criticism in the heating systems of that time.

In 1912, Houghten made the first study of air movement and thermal comfort by quantitatively examining the cooling effects of air motion at different temperatures. An initial side-by-side experiment[1] contrasted a condition of air movement up to 500 fpm (2.5 m/s) to a "still-air" condition, both at elevated air temperatures.

A subsequent experiment[2] focused specifically on drafts experienced at the back of the neck and the ankles. Elaborate ductwork was constructed to deliver air directly to the back of the subjects' necks. From this experiment, draft limits were proposed to ensure that 90% of the persons exposed to certain temperature/ velocity combinations on the back of their necks would not feel a draft.

In the late 1950s, ASHVE became ASHRAE and the ASHRAE laboratory equipment was moved to Kansas State University (KSU). At KSU, Rohles[3] exposed subjects to nine experimental combinations of air temperature and air movement within the ranges of 72° to 85.2°F (22.2° to 29.5°C) and 40 to 160 fpm (0.2 to 0.8 m/s).

Rohles found strong relationships between air velocity, air temperature, skin temperature and thermal sensation. Draft discomfort was not observed. Based on this, Rohles recommended an extended summer comfort zone in which air movement up to 157 fpm (0.8 m/s) compensated for elevated temperature. This extended zone was incorporated into *ASHRAE Standard 55-81*.[4]

A later study[5] was motivated by the question of whether the 157 fpm (0.8 m/s) limit was still applicable under the turbulent flow of a ceiling fan. The experimenters found that the subjects considered air movement pleasant at levels beyond what had been previously considered reasonable: up to 196 fpm (1 m/s) at 85°F (29.5°C). The subjects considered the turbulence of the flow a beneficial aspect.

A further fan study[6] compared fixed fans to oscillating fans. It was found that, for the same mean velocity, oscillating fans were preferred.

In another fan study,[7] subjects more active than the sedentary levels of the other studies (standing and moving about at a moderate pace) found that air velocities up to 235 fpm (1.2 m/s) improved comfort.

Yet another fan study[8] concluded that fan cooling with velocities up to 196 fpm (1.0 m/s) at temperatures up to 88°F (31°C) produced comfortable conditions. Similar results have been found in naturally ventilated buildings in the field.[9]

Two important studies were done in the late 1970s by McIntyre in the United Kingdom. The first study examined the subjects' sense of acceptability resulting from higher air velocities at higher temperatures.[10] McIntyre found that the subjects chose fans speeds lower than what was required to maintain their bodies' thermal neutrality, but that air movement could compensate for air temperature up to 82.5°F (28°C).

The second study looked at drafts directed at the face.[11] The conclusions were that people who felt cool found the air movement unpleasant, while people who felt warm found the air movement pleasant. Also, initial cool sensations from drafts lessened over time.

During the last decade in Japan, several experiments have looked specifically at the ability of air motion to compensate for higher summer temperatures. Tanabe and Kimura[12] found subjects regularly preferred air movement of 196 fpm (1 m/s) at an air temperature of 82°F (28°C) and very few regarded the air movement unpleasant under the conditions studied.

Another study by Tanabe and Kimura[13] found that sinusoidally fluctuating air movement resulted in a greater perceived cooling effect than random, constant or pulsed air movement. It also had a greater effect on mean skin temperature.

Meanwhile, in Denmark, a large program in thermal comfort research has been ongoing since the late 1960s. Included are several very extensive studies of the effects of air movement.

In one study, Fanger[14] found that a thermally comfortable subject has a skin temperature that is independent of air velocity. This suggests that any combination of temperature and velocity yielding that skin temperature will produce comfort.

In another study, Fanger and Pedersen[15] exposed subjects to well-defined turbulent air flow directed at the back of the neck and the ankles. They determined that turbulent flow is less comfortable than uniform flow with the same mean velocity, and that certain frequencies of turbulence are more uncomfortable than other frequencies.

Fanger and Christensen[16] measured the sensitivity of the back of the neck with a horizontal diffuser on the ceiling directed slightly downward. This study produced a draft chart predicting the percentage of people feeling a draft at a given air velocity and air temperature.

Table 1. Evolving Air Velocity Limits in Thermal Comfort Standards

Year	Issuer	Mid-Zone Air Temp. °F	(°C)	Maximum Air Velocity, fpm	(m/s)	Comments
1896	ASHVE	N/A		30 cfm, no air velocity recommended		ASHVE committee reviews European ventilation standards
1915	ASHVE	66°	(19°)	30 cfm, no air velocity recommended		Code of Minimum Requirements for Ventilation
1920	ASHVE	66°	(19°)	160	(0.81)	Synthetic Air Chart
1932	ASHVE	70°	(21°)	50	(0.25)	ASHVE Ventilation Standard
1938	ASHVE	70°	(21°)	50	(0.25)	Code of Minimum Requirements for Comfort
1966	ASHRAE	74.8°	(24°)	45	(0.23)	First Standard 55
1974	ASHRAE	74.8°	(24°)	(70)	(0.36)	Comfort velocity = 30 fpm (0.15 m/s)
1981	ASHRAE	74.8°	(24°)	50	(0.25)	Extended summer zone to 155 fpm (0.79 m/s)
1984	ISO	71.5°	(22°)	30	(0.15)	Extended summer zone to 50 fpm (0.25 m/s)
1993	ASHRAE	74.8°	(24°)	30	(0.15)	Tu=40% at 74.8°F (24°C)

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A subsequent study[17] focused on turbulence intensity as a controlled variable. In this study, the researchers found increased discomfort with increased turbulence. They also present a modified draft risk chart for inclusion in future thermal comfort standards. The results from this study are incorporated into *ASHRAE Standard 55-92.*[18]

Of necessity, each experiment can only examine a subset of the variables influencing thermal comfort. The method each researcher uses to bound the experiment and present the subjects with the experimental conditions can have a significant effect on the results.

Fountain[19] raised numerous issues concerning the above laboratory experiments in this regard. One important conclusion was that existing laboratory studies do not present a clear picture concerning the levels of air velocity that produce comfort.

Variations in methods between experimenters can produce widely differing recommendations. The next section of this article discusses how the results of these experiments have been used to develop *ASHRAE Standard 55.*

Air velocity and ASHRAE standards

Limits in ASHVE and ASHRAE standards for indoor air temperature have steadily risen while air velocities have steadily dropped since the turn of the century (see *Table 1*).

More recently, the ASHRAE standards[4,18] have followed the DIN and ISO standards[20, 21] in terms of more stringent air movement restrictions. The current *ASHRAE Standard 55-92* contains two figures for air velocity and comfort that are complementary but may be difficult to apply in engineering practice.

Figure 3 in this standard (reproduced here as *Figure 1*) allows higher air velocities under occupant control to offset the effect of higher operative temperatures. (Operative temperatures are approximately equal to air temperature plus mean radiant temperature divided by two.)

It is applied in practice by selecting the operative temperature rise of the environment and then choosing the air velocity needed for comfort along the appropriate temperature difference curve.

Figure 4 in the *Standard 55-92* (reproduced here as *Figure 2*) has the objective of eliminating drafts, defining the effects of different levels of air velocity and turbulence intensity on comfort. Turbulence intensity is defined as the standard deviation of fluctuating velocities divided by their mean for the measuring period.

Together, the figures are designed to be applied within the combined temperature range of 68° to 84°F (20° to 29°C). The curves represent percent discomfort curves, with 15% discomfort being used for the draft figure and 20% for the increased air movement figure.

The curves in *Figure 1* are computed values representing constant heat loss at the skin surface under various combinations of thermal conditions. Constant heat loss approximates equal comfort, and the predictions of these curves are consistent with the results of several laboratory studies.[5,6,7,8,10,12,13]

As incorporated in *ASHRAE Standard 55-92*, this figure can only be used if the local air movement is under the control of the occupant, with *Figure 2* covering all other situations.

The draft risk curves in *Figure 2* are solidly based on laboratory data at the lower end of their temperature range.[17] However, in the higher temperature range above 73.5°F (23°C), the draft curves are extrapolations to conditions where data were not collected and where other research is in disagreement.[3,8,22]

If this part of the curve is too restrictive, several possibly effective environmental conditioning strategies involving air movement may be excluded by the standard.

Figure 3 shows air velocity requirements suggested by the standard, and by various studies discussed in this article. The range of supposedly acceptable conditions is considerable.

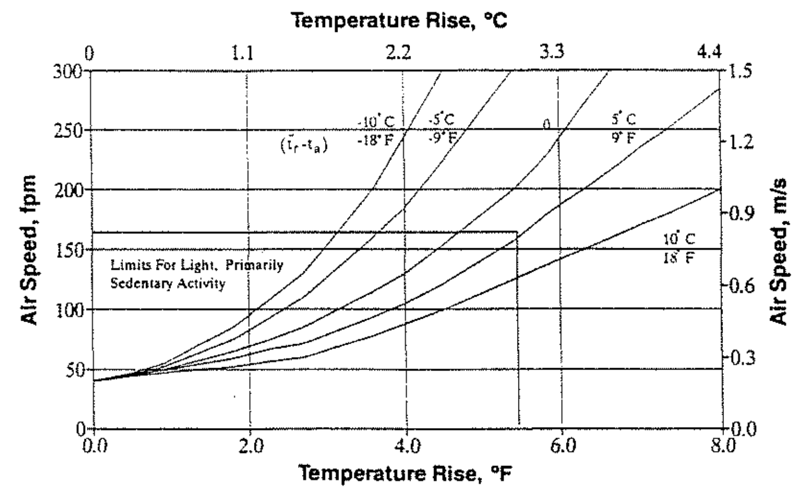

Figure 1. Air speed required to offset increased temperature.

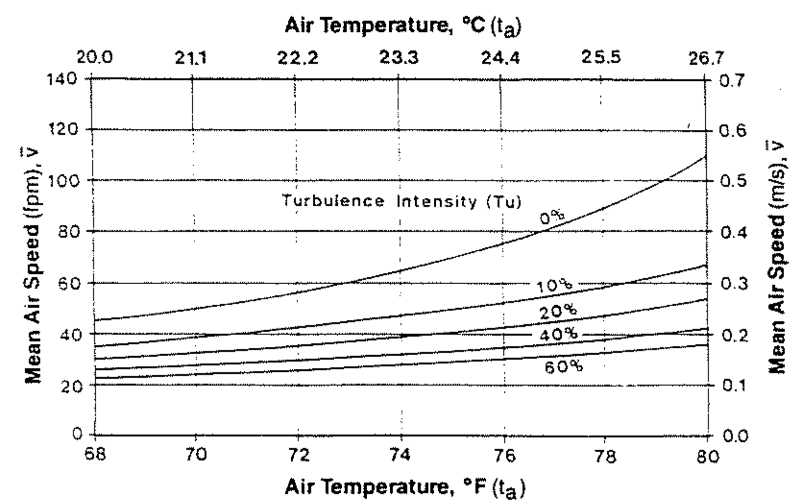

Figure 2. Allowable mean air speed as a function of air temperature and turbulence intensity.

Draft risk data for a turbulence intensity of 40% (typical of indoor office environments) are applied in the standard between 68° to 78.8°F (20° to 26°C). Using this draft risk curve, air movement is restricted to 24 fpm (0.12 m/s) at 68°F (20°C) and 40 fpm (0.2 m/s) at 78.8°F (26°C).

On the other hand, the (Ta=Tr) curve from *Figure 1* starts at the point 40 fpm, 78.8°F (0.2 m/s, 26°C) and extends to 160 fpm, 84.2°F (0.8 m/s, 29°C). Although the curves in *Figure 1* were developed for 78.8°F (26°C) and above, they can be shown to apply as well in the range of 73.5° to 78.8°F (23° to 26°C). Thus, they can be used to produce the zone of occupant-controlled comfortable conditions shown in *Figure 3*.

This figure also presents data from three experiments,[5,8,12] the Fanger draft risk zone and *ASHRAE Standard 55-81* air velocity limits. They are in broad agreement about the ability of the occupant-controlled air movement zone to provide comfort.

On the other hand, the new draft risk limit represents a significant air movement restriction over the previous *Standard 55* zone. The difference in the ranges of the acceptable conditions in *Figure 1* and *Figure 2* is obvious and should be investigated in the future.

Conclusion

It is not clear today what air velocity levels are appropriate for the range of temperatures found indoors. Two important aspects of moving air—draft risk and desirable occupant cooling—are addressed as separate issues in the new *ASHRAE Standard 55-92* because a single recommendation cannot be produced from the existing research.

The velocity limits prescribed in the standard clearly have an impact on the various ventilative cooling strategies that are possible in buildings. These strategies include fan ventilation, direct evaporative cooling, operable windows and task conditioning systems using locally controlled air outlets.

It is important that HVAC standards such as *Standard 55-92* encourage and not restrict the potential for new designs to improve comfort and conserve energy. ASHRAE research could usefully undertake a comprehensive examination of the influence of air movement on human thermal comfort aimed specifically at providing recommendations for the next standard revision.

Acknowledgments

The ideas presented in this article would not have reached fruition without the spirited involvement of Fred Bauman, Byron Jones and Bjarne Olesen, all of whom made significant contributions to the air velocity portion of the new *ASHRAE Standard 55-92*. Richard de Dear and Shin-ichi Tanabe also provided assistance in refining the concepts. ■

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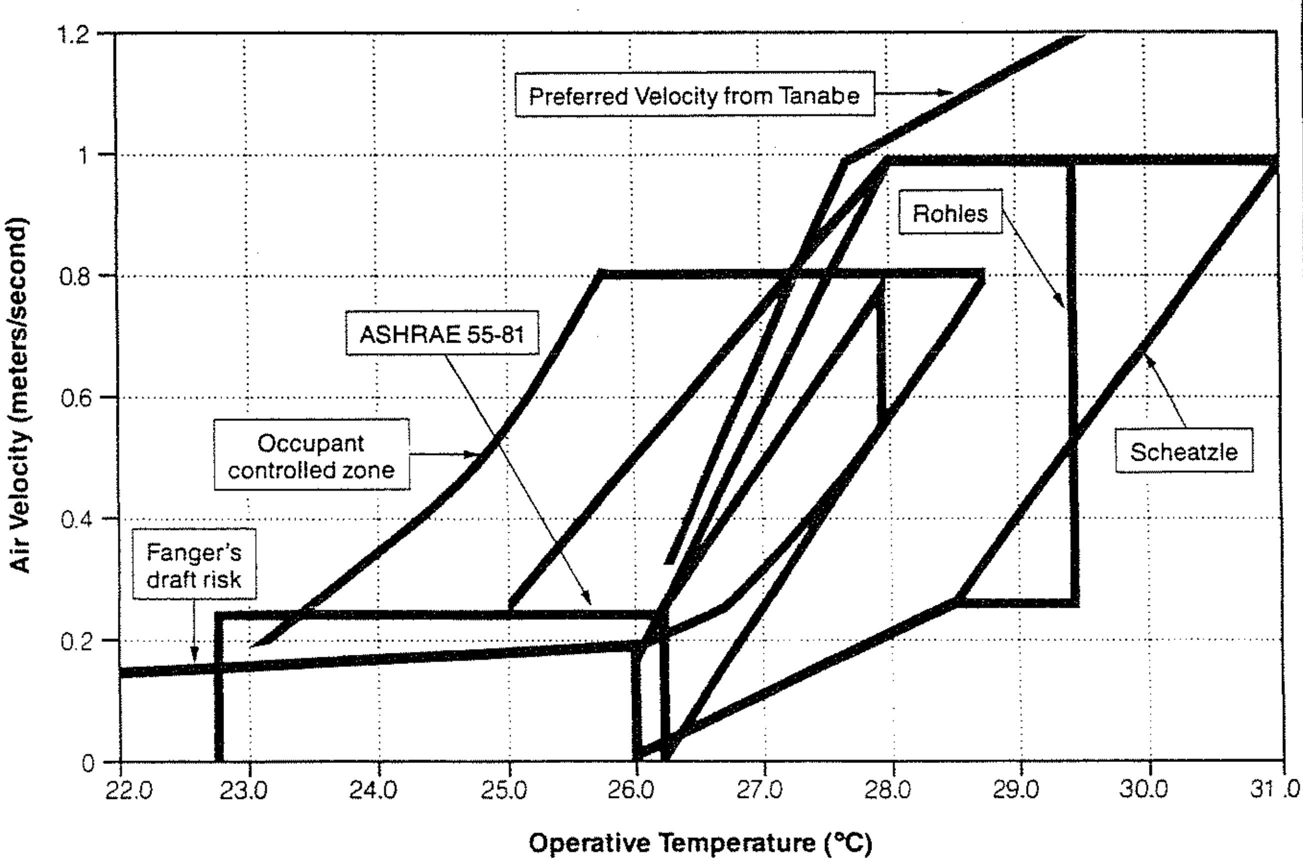

Figure 3. Range of velocity requirements.

Air movement

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APPENDIX B

Laboratory Studies of Air Movement and Comfort: Human Subject Tests

APPENDIX B

Methods, results, and analysis of the human subjects' tests

This appendix presents methods, results, and analysis from the climate chamber experiments on human subjects. The methods section describes the physical conditions to which the subjects were exposed, subjective survey forms, and how measurements of the environment were made. The results section presents the specific physical environments that the subjects created and how they responded on the comfort surveys. The analysis section compares the results to existing comfort standards and also to predictions from the most widely used computer models of thermal comfort. A 'zone of likely use' is presented that incorporates the physical and subjective results to define a range of physical environmental conditions within which alternatives to compressor cooling (such as increased air movement) might be pursued in California. It is expected that environmental conditions outside the zone of likely use will rarely be experienced in a residential setting and therefore lie beyond the scope of interest for CIEE.

1. METHODS

1.1 Overview

The human subject tests followed the general procedure of a 'preferred condition' test. That is, the subjects were requested to adjust one variable of their thermal environment, the air velocity, continuously as they pleased to make themselves comfortable. At the end of the exposure period, the subject was asked to move aside for five minutes, and detailed physical measurements of the environment they produced were made. The experimenters controlled all other variables that affect thermal comfort including air temperature, mean radiant temperature, relative humidity, clothing and metabolic rate. Two specific modes of operation of a floor-standing fan were tested. The first was a 'constant fan speed' mode where the subject had a choice of five fan speeds ('off' and four non-zero speeds) that produced a specific constant air velocity until the fan speed setting was altered. The second mode also utilized a choice of five fan speed settings but within each of the non-zero settings, the fan motor produced air velocities that fluctuated around the mean value with a specific sequence of frequencies being produced in repetition. This mode is called the '1/f' mode of operation, and is intended to produce a variable air flow environment similar to that created by wind-driven ventilation through an open window.

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 (1988) and will not be discussed here. A mobile measurement cart similar to the cart presented in Benton et al. (1991) collected the measurements of the physical environment and is presented in section 1.3 below. The subjects recorded their thermal sensation, thermal preference, air movement preference, and whether they were 'bothered by the air movement' every 15 minutes during the experiment. In addition, the subjects completed a background survey asking for general demographic information and their preferences for certain home environment characteristics. The surveys are presented in section 1.4 below.

1.2 Controlled environment chamber

The Controlled Environment Chamber (CEC) used for both the manikin and human subjects tests is located in the Building Science Laboratory of the Center for Environmental Design Research at the University of California, Berkeley.

Measuring 18 feet by 18 feet by 8 feet, 4 inches, the CEC is configured to appear as a realistic open-plan office with partitions, floor coverings, windows, lighting, and furniture exactly as one would expect to find in any modern office building. It has a raised access floor and a suspended ceiling enabling researchers to supply and return air from above, below, both above and below, and also through a dedicated 'spot-cooling' line. The windows, on the west and south walls, are triple-paned with a double-paned outer skin and then a wider air gap between the skin and the inner pane. In this air gap (the annular space) conditioned air is circulated to allow adjustment of the interior pane window temperatures. Lighting is provided by four 2-bulb fluorescent fixtures located randomly in the drop ceiling.

The climate in the CEC is controlled by a dedicated HVAC system with the detail and complexity of some whole-building systems. Three independent air supply systems can be operated simultaneously through separate air-handling-units: main supply, annular space supply, and spot-cooling supply. A 7.5-ton chiller and a 60-gallon hot water heater provide cold and hot water to coils situated in the air ducts. Return air is either exhausted or recirculated according to the position of damper 1. Supply air temperature is controlled by the positions of mixing valves feeding the hot and cold water coils. A steam humidifier adds additional moisture to the supply air if required. Electronic sensors in the ducts, water system, and the space monitor temperatures as well as valve and damper positions for controlling the system. A digital computer with commercially-available software for building HVAC control is used to automatically configure the system to produce an environment desired by the experimenter. The CEC has a high thermal mass compared to other climate chambers worldwide and has a correspondingly slower response to step-changes. However, the CEC provides a sense of realism seldom achieved in the laboratory, unconfounding (at least partially) the psychological experience of being a human subject in a laboratory experiment. The realism extends beyond the psychological as the CEC's thermal mass maintains very stable physical conditions (once equilibrium is reached) with very little interference from the mechanical system and very low background air velocities.

For the purposes of this experiment, solar gain was deemed more undesirable physiologically than the psychological effects of not having a view so the interior surface of the windows were covered with a layer of aluminum foil and then a layer of brown paper to eliminate solar gain. The annular space was conditioned to set the temperature of the brown paper equal to the ambient room temperature. A single partition divided the room in half with one subject occupying the south half and another subjects occupying the north half of the chamber. The chamber was furnished with outdoor patio furniture, flowers, book and magazines to create a home-like, rather than office-like atmosphere.

For all experiments a ceiling supply and ceiling return configuration was chosen for similarity to HVAC installations in the field. A floor-standing fan was placed to the side of each subject, approximately 2 meters away. Control of the fan was exercised by the subject via a remote infrared switching device. The possible setting of the fan ranged from '0' to '4'.

The chamber was turned on and brought to the required temperature 2 to 3 hours prior to the initiation of an experiment. Enough time was allowed for the CEC's thermal mass (walls, floor, and ceiling) to reach equilibrium with the air. The annular space setpoint temperature generally needed to be adjusted one degree upward (depending on the weather) relative to the ambient air temperature setpoint to counteract losses to the outside. Space temperature for control purposes was measured with a thermistor hung from the ceiling at the east end of the central partition at a height of 1.7 meters.

1.3 Mobile measurement cart

As part of the on-going research program in thermal comfort at the Building Science Laboratory, a mobile measurement cart for collecting physical environmental data has been designed and built for use on a variety of thermal comfort research projects. Although developed primarily for field work, the cart incorporates laboratory grade instrumentation and consequently found ready application during this series of experiments.

The cart design meets the following specifications:

The system is capable of collecting concurrent physical data (air temperature, dew-point temperature, globe temperature, radiant asymmetry, air velocity, and illuminance) from an array of transducers placed to represent the immediate environment of seated subjects.

The physical measurement transducers and their interrogation meet the ASHRAE 55-81 (1981) and ISO 7730 (1984) standards for accuracy and response time.

Physical measurements can be made as close as possible to the exact physical position of the subject completing a subjective questionnaire.

The physical measurements are completed in five minutes per workstation.

All physical data are collected in machine-readable form. Compiling data in digital files during the collection process eliminates keypunch errors and expedites daily summary sheets for error checking.

The instrumentation package is mobile and portable, its battery power capable of a full day's operation without recharge.

The data acquisition system provides a real-time display of measured values for error-checking purposes. These values are hidden from the sight of test subjects to avoid bias in their answers to subjective questions.

The field equipment is fully automated, requiring only the flip of a switch to initiate the data collection sequence

1.3.1 Transducers

To meet these specifications requires an array of transducers, an integrated signal processing and data acquisition system, and a laptop computer for data reduction and display in real-time. All equipment is mounted on a two-wheeled chassis of 3 inch by 1 inch aluminum tubing with a wooden 'chair' attached to the front (see Figure B1). In addition to battery storage, the 'seat' of the chair shields the sensors in way similar to the way the occupant's chair shields the occupant. Several signal processing devices were custom-built to our specifications for this application and they are mounted under the seat and in the seat back. Behind the seat back is the laptop computer that provides the cart operator with a real-time view of the transducer values and presents a stripchart-format time history of the previous ten minute's data.

1.3.1.1 Temperature

The cart's transducers were chosen to meet the response time and accuracy requirements of ASHRAE Standard 55-81 and ISO Standard 7730 for thermal assessment. In general, the temperature sensors are accurate to within 0.2 degrees Celsius and have a time-constant of several seconds. The sensors used have a vinyl-coated tip on a flexible signal wire. Where globe temperature was measured, a table tennis ball was mounted on the cart with one of the temperature sensors in the center of the 'globe'. The globe is painted grey for the proper emissivity and responds to the balance between radiation and convection in the physical environment. The globe should reach equilibrium well within the 5 minute measurement period. A short discussion of globe temperature and its measurement is provided in Benton, Bauman and Fountain (1990).

1.3.1.2 Air Velocity

Air velocity is measured at three heights by omni-directional temperature-compensated anemometers with a time constant of 0.1 seconds. A fast response time is essential for accurate estimation of turbulence intensity in the airflow. Each sensor has two nickel-plated quartz spheres supplied with a small electrical current. The current heats the spheres which in turn are cooled by passing airflow. Velocity is measured by regulating the electrical current needed to maintain the spheres at a constant temperature.

1.3.1.3 Dewpoint temperature

Dewpoint temperature is measured by a chilled-mirror dewpoint transducer. In this transducer, a heated chimney draws a small sample of room air into a measuring chamber where a small mirror is continuously cooled. A nearby LED shines a beam of light at the mirror where it is reflected to a photosensor. When the mirror reaches the dewpoint temperature of the air sample, water condenses on the mirror scattering the light beam so the signal to the photosensor is interrupted. Then the temperature of the mirror is measured and sent to the central datalogger.

1.3.1.4 Plane radiant asymmetry

Radiant asymmetry is measured by a commercially available plane radiant asymmetry sensor. Plane radiant temperature is defined as the uniform surface temperature of a hemisphere that produces the same incident radiation on a black surface as the actual environment. Radiant asymmetry is the difference between the plane radiant temperatures of small planes facing opposite directions. The radiant asymmetry probe consists of two pairs of gold-plated and black-painted elements connected to thermopiles. Each side of the probe has a gold and a black element. The measurement is based on the fact that the gold element exchanges heat primarily by convection while the black element exchanges heat by both convection and radiation. Thus any voltage generated across the thermopiles results from heat transfer by radiation between the black element and the environment. Illuminance is an ancillary parameter that may be useful in later analysis. A cosine-corrected silicon photometer measures illuminance in the horizontal plane.

1.3.2 Data acquisition

The cart's data acquisition system consists of several signal processors feeding a central datalogger programmed to poll the sensors and relay the data to a laptop computer for display and storage. Since both the air velocity and air temperature sensors are inherently non-linear transducers, signal processing is required to convert these measurements to engineering units. In the case of the temperature sensors, a linearization bridge on the signal side is required, while more extensive circuitry is necessary for controlling the current supplied to the anemometers and providing temperature compensation. The signals from all transducers and signal conditioning are sent continuously to the heart of the system, a microdatalogger. The datalogger measures the sensor signals and converts each to engineering units using polynomial curve fits or linear conversions as appropriate. The microdatalogger is connected to a lightweight laptop computer that serves as data display, operator interface, and data storage device.

1.3.3 Measurement timing and protocol

The microdatalogger also controls the timing and sequence of measurements. A data collection sequence is initiated by the operator flipping a switch mounted on the top of the cart. This instructs the datalogger to begin storing data from the sensors and is indicated by an LED glowing solid green near the cart switch. The laptop computer continuously displays data in a stripchart fashion with an indicator showing whether the data is being stored or not. For the first minute, the system monitors the transducers as they move toward equilibrium with the physical environment at the workstation. After the first minute, the datalogger shifts into 'burst' mode. Burst mode is the only state in which the datalogger can sample the anemometers quickly enough to measure turbulence intensity. During the next three minutes, the datalogger is occupied with the air velocity measurement, collecting 60 data points per second while the LED blinks green. When the burst measurement is complete, the air temperature, globe temperature, and humidity sensors can be assumed to be in equilibrium and the 21x collects data from these sensors at the rate of one sample per second for the remaining one minute. During the last minute of data collection, the LED glows solid red and turns off when the measurement sequence is complete and the cart can be safely moved. The total number of air velocity readings taken during the three minute measurement burst is 7,200, too much data to process in real-time. So, as the cart is being moved to the next workstation, a post-measurement processing sequence reduces the 7,200 readings to engineering units, calculates turbulence intensity, and stores the final values on the hard disk with data from the other transducers.

MOBILE MEASUREMENT CART MARK II

transducers at 1.1 meters (air temp., globe temp., air velocity, radiant asymmetry, & illuminance)

Campbell 21-X data acquisition system

laptop computer for operator interface

transducers at 0.6 meters (air temp., globe temp., air velocity, & dew point)

pseudo seat provides shielding for sensors while containing batteries and storage for subjective survey laptop computer

transducers at 0.1 meters (air temp., globe temp., & air velocity)

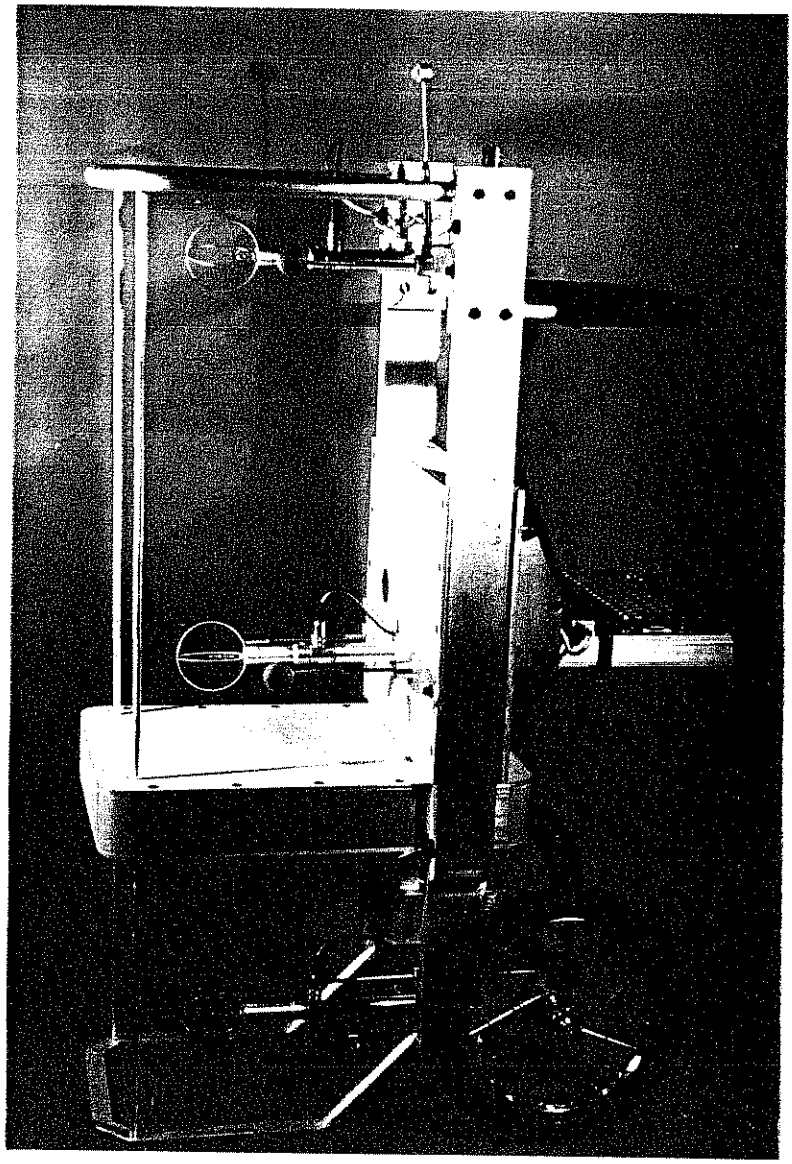

Figure B1

1.4. Survey Instruments

Two survey instruments were used during the human subject's tests. The first was a one-time background survey asking demographic and 'preferred environment' questions. The second survey was a repeated 'comfort' survey asking for thermal sensation, thermal preference and other votes at four designated times during the 2 1/2 hour experiment..

1.4.1 Background survey

The first section of the background survey asks basic demographic questions indicating the age, sex, ethnicity, and education level of the subject. The next section presents a variety of characteristics of home environments, for example: 1) types and level of sounds, 2) lighting, 3) air quality etc., and the subject is requested to indicate the importance of each item by circling a number on a scale that reflects how they feel. The scale has four levels: "not at all important," "slightly important," "moderately important," and "very important." The background survey questions and format draw upon existing survey instruments in use at the Building Science Lab, see Schiller et. al. 1988 for a description of the survey development. Figure B2 presents the Background survey.

1.4.2 Comfort survey

At four designated times during the test, the subjects were requested to fill out a 'comfort survey' asking for: 1) a thermal preference vote, 2) an air movement preference vote, 3) an overall thermal sensation vote, 4) a comfort vote for each of five parts of the body, and 5) an air movement acceptability vote. Thermal sensation in the repeated survey is asked along a seven-point scale and thermal preference along a three-point scale. Since warmth and comfort are confounded variables, the warmth and comfort questions are posed separately. In most previous work where sensations are asked for different body parts, the subjects could not separate sensations from their whole-body sensation for more than four regions. We added the head area to the four major quadrants of the body since we expected this unclothed area to be significantly affected by air movement. An air movement preference vote on a three point scale, similar to the thermal preference vote, is asked, and an air movement acceptability vote as well. The air movement acceptability question asks, "Are you bothered by the air movement?" Figure B3 presents the comfort survey

1.5 Experimental protocol

Human subjects were recruited to participate in this experiment. Human subject tests provide the ultimate link to field environments. Although the variance is always high when realistic environments are tested, human subjects provide real-world results incorporating factors beyond heat-balance. The heat balance data are more readily obtained from a thermal manikin.

The sample size was limited by the project budget and competition for climate chamber time with other projects. The goal was to achieve a sample size of over fifty subjects in the constant velocity fan experiments and over fifty in the fluctuating fan experiments. The sample was drawn from the local campus community with many being students in the College of Environmental Design or others who are taking classes in the department. Students, faculty, and employees were invited through flyers posted in campus building and announcements in classes. An advertisement was placed in a local newspaper requesting volunteers from the general public. Those responding to the recruitment announcement or the advertisement were given a brief description of the experiment, a consent form (Figure B4) and then were scheduled into a time slot for the experiment. Participation in the experiment was not made part of the academic work of any student, and confidentiality was ensured by assigning students a numerical code for all of the analysis.

The subjects were instructed to arrive at the climate chamber wearing shoes, socks, underwear, jeans, and a T-shirt or other light short-sleeved shirt. This clothing ensemble (0.5-0.6 clo) was chosen to approximate typical clothing levels found in residential settings. A standard uniform, frequently used in previous laboratory comfort studies was not used for the following reasons: 1) a uniform detracts from the realism of the experiment, 2) standard uniforms do not ensure uniform clothing insulation as this depends on how the clothing is worn, and 3) "Experiments in which standard clothing is used tend to find an increased, not a decreased, inter-individual difference in thermal preference." (Wyon and Sandberg, 1990).

The protocol for both constant velocity and 1/f experiments was as follows. Upon arrival at the laboratory, the subject's oral temperature was taken to confirm that he or she is not suffering from any disease that might bias thermal sensation. Oral temperature and other pertinent information is recorded on the experimental record (Figure B5). The subject is then randomly assigned to one of the two test configurations in the chamber and given the background survey. Since the laboratory chamber has been pre-heated to the test temperature, the subject is asked from the beginning to adjust the source of air movement to continually maintain comfort while reading or doing paperwork. The subject is in the chamber for approximately 1 hour adjusting the air movement source for comfort before the first set of physical measurements are made. Every 10 minutes the subject performs an activity. The activity, walking up and down a step 10 times, raises their metabolic rate to 1.2

met (or 70 W/m^2), a level typical of residential environments. Periodically, they are also asked to fill out the comfort survey (described in section 1.4). After the first 80 minutes, they are asked to move away from the desk for physical measurements. The mobile cart (described in section 1.3) is placed exactly where the subject was sitting and collects data for five minutes. When these measurements are complete, the subject returns to the desk for an exact repeat of the first 80 minutes, but without the added activity of walking up and down the step. This second period is characterized by a sedentary metabolic rate of 1.0 met (or 58.2 W/m^2)

Table 1 shows a matrix of the experimental conditions tested.

Table 1
Human subjects tests
(each cell indicates the number of cases tested)

Ta room	Constant	1/f
24 deg C	NA	6
25 deg C	NA	8
26 deg C	NA	9
27 deg C	8	11
28 deg C	12	13
29 deg C	11	16
30 deg C	10	9
31 deg C	3	4

1.6 Design of the exercise routine

The 'high activity'part of the tests was designed to equal the metabolic rate of Standard 55 comfort standard, 1.2 Met. This represents a typical metabolic level found in office work, and probably represents housework 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 subjects' exercise protocol involved getting up from his/her seat once every ten minutes, moving to a nearby eight-inch step, and stepping up and stepping 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 activity in between. The metabolic activity generated by this exercise was estimated as follows.

(In inch-pound units),

150 lb person x 2/3 foot/step x 12 steps = 1200 ft·lb.

Assuming a muscular efficiency of 15%,

1200 ft·lb ÷ (η = 15%) = 8000 ft·lb.

The thermal equivalent of this is:

8000 ft·lb ÷ 785 Btu/ft·lb ≈ 10 Btu/(12 step exercise).

At 6 exercises/hour, 6 x 10 = 60 Btu/hr (= 'Btuh').

(Converting to SI),

60 Btuh ÷ 3.413 Btuh/W ≈ 18 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) / 104 = 1.17 Met ≈ 1.2 Met

Two additional assumptions were made. First, the ASHRAE Handbook (ASHRAE 1993) 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 deal with down-steps. 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.

2.0 RESULTS

2.1 Characteristics of the fan

2.1.1 Fan velocity profile

Figure B6 shows the air velocity profile across the face of the fan for several different configurations of the fan. Three of the four profiles are for fan-speed-setting number four, the highest speed. Velocity profiles for fan-speed-setting number four are shown for three distinct distances from the fan, 2 meters, 2.5 meters, and 3 meters. In general, the subjects were within this range of distance from the fan. The fourth profile is for fan-speed-level number one at a distance of 2 meters. This setting represents approximately the minimum air velocity that the subjects feels when the fan is in operation. The horizontal axis of Figure B6 shows the height above the floor while the vertical axis indicates the air velocity at that height. One of the most distinct features of this fan is the relatively uniform distribution of velocity with height. Within a range of 30 cm (knee height) and 80 cm (neck height for a seated person) the air velocity distribution is considerably more uniform than that produced by an ordinary desk fan. A subject exposed to this type of air velocity distribution will more closely experience 'whole-body-cooling' than if they were using an ordinary desk fan or other localized air movement source.

2.1.2 Fan power consumption over time

Figures B7 and B8 show the current draw (in amps) of the two fans being used concurrently. Figure B7 presents current draw for a 'constant fan speed' experiment. Note that one subject chooses an acceptable air velocity at the beginning of the experiment and requires no further adjustment of the environment. The other subject ramps the air velocity up at the beginning and makes several adjustments during the experiment. Figure B8 shows a similar situation for a '1/f' experiment. Here note that the current draw is never constant as in the previous example. The figure clearly shows the fluctuating nature of the fan motor's operation, a pattern that is closely correlated to the air flow on the subject. At fan-speed-level number four, the fan draws approximately 0.3 amps or 36 watts.

2.2 Physical environment

Table 2 presents a summary of the physical environmental variables that were measured by the mobile measurement cart. Each value represents an average over all subjects.

Table 2

Physical Environment Summary

Statistics	Air Temperature 1.1 meters deg. C	Air Temperature 0.6 meters deg. C	Air Temperature 0.1 meters deg. C	Globe Temperature 1.1 meters deg. C	Globe Temperature 0.6 meters deg. C	Globe Temperature 0.1 meters deg. C
Average	28.0	28.0	27.9	28.1	28.1	28.0
Maximum	32.0	31.8	31.1	32.0	31.9	31.1
Minimum	23.6	23.7	23.7	23.7	23.8	23.8
Std Dev.	1.8	1.8	1.7	1.8	1.7	1.7

Statistics	Dewpoint Temperature 0.6 meters deg. C	Plane Radiant Asymmetry deg. C	Illumination lux	Air Velocity 1.1 meters* m/s	Air Velocity 0.6 meters* m/s	Air Velocity 0.1 meters* m/s
Average	25.5	0.0	62.5	0.9	0.64	0.21
Maximum	NA	0.7	1079.0	1.9	1.41	0.49
Minimum	NA	-0.8	NA	0.0	0.04	0.02
Std Dev.	1.7	0.3	149.0	0.5	0.32	0.08

Some additional calculated values:

Statistics	Relative Humidity 0.6 meters percent	Average Air Temperature deg. C	Average Globe Temperature deg. C	Average Operative Temperature deg. C	Average Air Velocity m/s	Average Turbulence Intensity percent
Average	47.8	28.0	28.1	28.1	0.8	44
Maximum	54.7	31.6	31.7	31.6	1.6	100
Minimum	37.3	23.7	23.8	23.8	0.1	7
Std Dev.	2.5	1.8	1.7	1.8	0.4	24

*

There was a programming error in the mobile cart that caused it to disregard a large amount of the burst mode air velocity data. Therefore, the mean air velocities presented are averages from the final one minute of the five minute measuring period. The one minute sample is an average of 60 readings taken once per second in largely constant airflow produced by these air movement sources.

The maximum air velocity is nearly 2 m/s at the sitting head level while the average of all cases is nearly 1 m/s. Globe temperatures were slightly higher than air temperatures overall. Load variations in the climate chamber are more easily smoothed if the required response is heating, not cooling, a situation which results in this slight systematic bias. Furthermore, this climate chamber has a high-thermal-mass as a result of using real-world furnishings. The trade-off for having a realistic environment is some sacrifice in climate control since surface temperatures are relatively slow to change. Relative humidity was well controlled at just below 50%. Turbulence intensities are typical for office environments with most ranging between 30% and 60% around an average near 45%.

2.2 Subjective responses

This section presents an overview of the subjective response to the environment by the subjects.

2.2.1 Thermal sensation

Figure B9 presents the percentage of subjects voting in each thermal sensation category as a function of space temperature in the 'constant fan speed' experiment. Up to 29 deg. C, less than 20% of the subjects found the environment warmer than 'neutral', i.e. they voted within the range of 'neutral' to 'slightly warm' on the thermal sensation scale. At 30 deg C., however, over 30% percent found the environment more than 'slightly warm' although they could cool themselves by adjusting the fan. Figure B10 presents the same results for the '1/f' experiment. Below 27 deg C., some subjects register votes below neutral, even though the fans were either off or on the lowest fan speed setting. Within the range of 27 deg C. to 29 deg C, most subject can adjust the fan to their liking; both the range of fan speed choices and the preponderance of neutral votes reflect this. Above 29 deg. C, the ability of the fan to cool the subjects is significantly reduced.

2.2.2 Effect of activity on thermal sensation

Figures B11 and B12 present the mean thermal sensation of the group of subjects exposed to the same space temperature and choosing the same fan speed. Figure B11 (low activity) shows that mean thermal sensations were generally below zero (but still above -1) for subjects exposed to temperatures below 27 deg. C. This is due to the fan having a minimum speed well exceeding the air speed suggested in the comfort standards. As the temperature increases, higher fan speeds are chosen and higher thermal sensations are registered as well. The psychophysical explanation for this is captured in the phrase "Of course I'm hot, that's why I have the fan on!" Figure B12 shows the effect of subjects experiencing the same conditions as those represented in Figure B11 but also performing the additional metabolic activity. Note the dramatic increase in thermal sensation at higher temperatures and the fact that most of the subjects chose fan speed settings 3 or 4 above 27 deg. C. Recall that a fan speed setting of 4 produces an air velocity profile that is above 1.0 m/s over most of the body.

2.2.3 Sensations on different body areas.

The subjects considered their head area the coolest overall. This is expected since the head is unclothed and experiences the greatest heat loss. However, in most cases, the head was not "cooler than comfortable" as would be predicted by most comfort models given the amount of air movement experienced. No right left asymmetry was experienced over the sample as a whole since the fans were evenly distributed as to which side of the body they were directed upon. The most noticeable difference is between the lower body and upper body with the lower body being perceived as the warmest. This result is consistent with the velocity profile presented in Figure B6. Since a preference for thermal environments that produce a cool head and warm feet is frequently expressed and usually difficult to obtain with a conventional ceiling-supply-based HVAC system, this must be considered a fortuitous result.

2.2.4 Direct air movement questions

Roughly 35 percent of the subjects overall expressed the fact that they were 'bothered by the air movement'. The majority of these cases, not surprisingly, occurs at the higher temperatures where the fan speed setting is usually either 3 or 4. Here the non-thermal effects (such as wind pressure, eye dryness, thirst) become more noticeable. The data suggest a temperature (around 29°C) above which the inconvenience of the wind overrides the thermal benefit. Approximately 15% of the subjects wanted more air movement than they could get and 15% wanted less. There is no clear dependence of the air movement preference votes on temperature.

2.2.5 Comments from the subjects

We solicited comments from the subjects at the end of each experiment. The comments provide a good subjective indication of the pleasantness or discomfort the subject experienced overall. Comments were categorized as follows.

1. Transient thermal sensation (1=yes)
2. Overall comfort (0=no, 1=yes)
3. Thermal sensation (same as the ASHRAE scale)
4. Preference for the temperature (0=no, 1=yes)
5. Air movement (0= stagnant, 1=strong)
6. Preference of the air movement (0=no, 1=yes)
7. Asymmetry of air movement (0=no, 1=yes)
8. Loudness of the fan (1=yes)
9. Humidity (0=dry, 1=humid)

10. Controllability of the fan (0=no, 1=yes)
11. Setting of the furniture (0=bad, 1=good)
12. Lighting (0=bad, 1=good)
13. Others

Table 3 presents a summary of the comments received.

Table 3

CONSTANT WIND
(HIGH
METABOLISM)

			FAN	Activity	TA	Sensation	Head	L-upper	R-upper	L-lower	R-lower	Bothered (?)
		FAN	Level	Level		cold	comf	comf	comf	comf	comf	1=yes
		1=const				hot	W/C comf	W/C comf	W/C comf	W/C comf	W/C comf	2=no
	SUB	2=fluct.	1-4	H/L	ºC	(-3,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,2)
Preference for air movement												
Yes	79	1	3	H	28.9	0.0	1	2	1	1	1	2
Yes	59	1	3	H	27.2	0.0	1	1	2	2	2	1
Asymmetry												
Yes	49	1	4	H	30.7	2.0	2	2	2	2	2	1
Yes	55	1	3	H	28.4	0.0	1	1	1	1	1	1
Yes	60	1	2	H	27.0	-0.5	1	1	3	1	1	1
Yes	61	1	3	H	28.2	1.1	1	1	2	2	2	1
Yes	96	1	4	H	29.7	0.8	1	1	1	2	2	1
Loudness												
Yes	83	1	4	H	29.0	1.5	3	2	2	2	2	1
Controllability												
Bad	49	1	4	H	30.7	2.0	2	2	2	2	2	1
Bad	107	1	4	H	29.2	1.5	2	2	2	2	2	2
Bad	91	1	4	H	27.4	0.0	1	1	2	1	1	2
Bad	106	1	4	H	29.1	0.5	1	1	2	2	2	2
Good	79	1	3	H	28.9	0.0	1	2	1	1	1	2
Good	113	1	2	H	27.7	0	1	1	1	1	1	2
Good	81	1	4	H	29.0	1	1.0	1	1	2	2	2
Furniture												
Bad	49	1	4	H	30.7	2.0	2	2	2	2	2	1
Bad	107	1	4	H	29.2	1.5	2	2	2	2	2	2
Bad	55	1	3	H	28.4	0.0	1	1	1	1	1	1
Bad	57	1	3	H	27.1	1.0	2	3	2	1	1	1
Bad	53	1	2	H	28.0	0.1	1	1	1	2	2	1
Bad	94	1	4	H	29.9	1	2	1	1	2	2	1
Good	58	1	3	H	26.9	1.0	1	1	1	1	1	2

Light												
Bad	102	1	4	H	30.3	1	2	2	1	2	1	2

CONSTANT WIND (LOW METABOLISM)

			FAN	Activity	TA	Sensation	Head	L-upper	R-upper	L-lower	R-lower	Bothered (?)
		FAN	Level	Level		cold	comf	comf	comf	comf	comf	1=yes
		1=const				hot	W/C comf	W/C comf	W/C comf	W/C comf	W/C comf	2=no
	SUB	2=fluct.	1-4	H/L	ºC	(-3,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,2)
Preference for Air Movement												
Yes	79	1	4	L	29.0	-1.0	1	1	1	1	1	2
Yes	59	1	3	L	27.1	-0.5	1	1	1	1	1	1
Asymmetry												
Yes	49	1	3	L	30.9	1.0	2	2	2	2	2	2
Yes	55	1	3	L	27.9	0.0	1	1	1	1	1	2
Yes	60	1	2	L	27.2	0.0	1	1	1	1	1	2
Yes	61	1	3	L	27.9	0.0	1	1	1	1	2	2
Yes	96	1	4	L	29.6	0	1	1	1	1	1	1
Loudness												
Yes	83	1	4	L	29.0	1.0	2	1	3	1	1	1
Controllability												
Bad	49	1	3	L	30.9	1.0	2	2	2	2	2	2
Bad	107	1	4	L	28.6	1.6	2	2	2	2	2	2
Bad	91	1	4	L	28.2	-0.2	1	3	1	1	1	1
Bad	106	1	4	L	28.9	0	1	1	1	1	1	2
Good	79	1	4	L	29.0	-1.0	1	1	1	1	1	2
Good	113	1	1	L	27.2	0	1	1	1	1	1	2
Good	81	1	3	L	29.3	1	1.0	1	1	2	2	1
Furniture												
Bad	49	1	3	L	30.9	1.0	2	2	2	2	2	2
Bad	107	1	4	L	28.6	1.6	2	2	2	2	2	2
Bad	55	1	3	L	27.9	0.0	1	1	1	1	1	2
Bad	57	1	1	L	26.7	-1.0	1	1	1	1	1	1
Bad	53	1	2	L	28.0	0.0	1	1	1	1	1	2
Bad	94	1	4	L	30.1	2	1	1	1	1	1	2

Good	58	1	3	L	26.7	0.0	1	1	1	1	1	2
Light												
Bad	102	1	4	L	29.7	0	1	2	1	1	1	2

FLUCTUATING WIND
(HIGH METABOLISM)

			FAN	Activity	TA	Sensat ion	Head	L- upper	R- upper	L- lower	R- lower	Bothered (?)
		FAN	Level	Level		cold	comf	comf	comf	comf	comf	1=yes
		1=const				hot	W/C comf	W/C comf	W/C comf	W/C comf	W/C comf	2=no
	SUB	2=fluct.	1-4	H/L	ºC	(-3,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,2)
Preference for Air Movement												
No	30	2	4	H	27.9	1.5	2	2	1	2	1	1
No	15	2	1	H	27.8	0.0	1	1	1	1	1	2
No	47	2	3	H	28.9	0.3	1	3	1	1	2	2
No	80	2	3	H	29.2	1.5	1.0	2	2	2	2	2
No	13	2	4	H	31.1	1.7	2	2	2	2	2	2
Yes	4	2	1	H	27.1	0.0	1	1	1	2	1	2
Yes	84	2	2	H	25.0	0.2	1	1	1	1	1	2
Yes	46	2	4	H	28.3	0.7	1	1	1	2	2	1
Yes	7	2	4	H	26.4	0.0	1	1	1	1	1	2
Yes	11	2	4	H	27.4	0.5	1	1	1	1	1	2
Asymmetry												
Yes	30	2	4	H	27.9	1.5	2	2	1	2	1	1
Yes	34	2	4	H	29.1	1.5	1	1	2	1	1	1
Loudness												
Yes	12	2	3	H	27.4	1.0	2	2	2	2	2	1
Controllability												
Good	4	2	1	H	27.1	0.0	1	1	1	2	1	2
Good	119	2	3	H	26.2	1.5	1	1	3	1	1	1
Furniture												
Bad	34	2	4	H	29.1	1.5	1	1	2	1	1	1
Bad	67	2	1	H	26.1	-0.7	1	1	1	1	1	2
Bad	44	2	3	H	27.5	0.2	1	1	1	2	2	2
Bad	40	2	4	H	29.3	0.5	2	1	1	1	1	1
Light												
Bad	34	2	4	H	29.1	1.5	1	1	2	1	1	1

Bad	85	2	4	H	24.1	0.2	3	1	1	3	3	2

FLUCTUATING WIND
(LOW METABOLISM)

			FAN	Activity	TA	Sensat ion	Head	L- upper	R- upper	L- lower	R- lower	Bothered (?)
		FAN	Level	Level		cold	comf	comf	comf	comf	comf	1=yes
		1=const				hot	W/C comf	W/C comf	W/C comf	W/C comf	W/C comf	2=no
	SUB	2=fluct.	1-4	H/L	ºC	(-3,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,3)	(1,2)
Preference for Air Movement												
No	30	2	3	L	26.8	-0.2	1	1	3	1	1	1
No	47	2	3	L	27.9	0.2	1	1	2	1	2	2
No	13	2	4	L	28.5	-0.2	1	1	1	1	1	2
No	80	2	3	L	29.5	0	1.0	1	1	2	2	2
No	15	2	1	L	30.2	0.0	1	1	1	1	1	2
Yes	4	2	0	L	27.2	0.3	1	1	1	2	2	2
Yes	84	2	0	L	24.7	0.1	2	1	1	1	1	2
Yes	46	2	3	L	27.8	-0.6	1	1	3	1	1	1
Yes	7	2	4	L	26.7	0.0	1	1	1	1	1	2
Yes	11	2	1	L	27.4	-0.5	1	1	1	1	1	2
Asymmetry												
Yes	30	2	3	L	26.8	-0.2	1	1	3	1	1	1
Yes	34	2	4	L	28.8	1.9	1	2	2	2	2	1
Loudness												
Yes	12	2	3	L	27.1	-1.0	1	1	3	1	1	1
Controllability												
Good	4	2	0	L	27.2	0.3	1	1	1	2	2	4
Good	119	2	2	L	25.8	2.2	1	2	1	1	1	2
Furniture												
Bad	34	2	4	L	28.8	1.9	1	2	2	2	2	1
Bad	67	2	1	L	25.2	-1.0	1	1	3	1	1	2
Bad	40	2	3	L	28.7	0.2	1	3	1	1	1	1
Bad	44	2	3	L	28.7	0.0	1	1	1	1	1	2
Light												
Bad	34	2	4	L	28.8	1.9	1	2	2	2	2	1
Bad	85	2	1	L	24.5	0.0	1	1	1	1	1	2

There were ten comments concerning preference for fluctuating air flow from the subjects. Some subjects disliked it while others were favorable. However, even considering the unfavorable comments, only one subject out of five said that the wind bothered him/her. The highest temperature where favorable comments concerning fluctuating air flow were recorded was 27.4°C (the average of the measured temperature for each metabolism) and the lowest temperature where unfavorable comments concerning fluctuating air flow were recorded was also 27.4 C. There seemed to be no relation of temperature to the level of the fan nor the thermal sensation of the subject as expressed in the comments. Among the favorable comments, subjects said that the air movement felt like natural wind. For the constant fan speed setting, no subject discussed the nature of the air movement. Among the unfavorable comments, some said the fluctuations annoyed them and they could not concentrate with the air blowing. There were some comments regarding blowing hair from time-to-time. We cannot determine, however, whether this was caused by the fluctuations or simply the high speed of the fan.

Since the air movement was uni-directional throughout the test, some subjects mentioned the asymmetry of it. The interesting thing is that the number of the subjects who mentioned the asymmetry was two in the fluctuating fan experiment and five in the constant fan speed setting even though the total number of the subjects was larger for the fluctuating experiment than for the constant fan speed experiment. The fluctuations might bring produce a favorable change for the subjects and might reduce their perception of the asymmetry. Associated with the comments on asymmetry, subjects noted; 1. dryness of the eyes, difficulty finding a satisfactory velocity level, or that they want to have air movement over more of their body.

Some subjects mentioned controllability of the fan in the constant fan speed setting experiment. One reason was that there was a big difference between level 3 and level 4 in the velocity produced. At high temperatures, even the level 4 was not enough and that also contributed to a feeling of lack of controllability. One subject at each fan setting noted that the noise of the fan was too loud. Their preferred fan level was 4, the highest possible.

Table 4 presents the comments received.

Table 4

Comments from Subjects Using <u>Constant</u> 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 (?) & in a different position. It was hard to feel really comfortable because you have to stay in the same position. For me the partitions also make me feel confined & unable to see around me.- Thank you.
51	As an architecture student, having taken ARCH 140, I can appreciate the study of air movement & temp control. I spoke to you vaguely about the aspect of the project. I applaud the fact that you are studying the many dimensions of thermal comfort. In general, the experiment was quite efficient.
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 thermal comfort. 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 thermal 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 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 placed in 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. I may interested to know how the experiment was designed.
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; Fan's only (?). This slightly because the lamp was so hot. Interesting though.
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.
115	THANX, Hope we helped your research. Good luck!
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 temp.) 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.

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.

#9	I would like to know the results.
#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. I hope to hear how your project ends up.
#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 some what 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 to board 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. I would be interested in seeing the results.
#31	I enjoyed taking part in this controlled environmental experiment. Thank you.

#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. Anyway thanks a lot for the experience.
#33	I think the idea of this experiment is very good, but I think it takes too much time. $2^1/_2$ hour is a long time to be doing an experiment.
#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/spire(?). 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 air quality 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! I appreciated participating - curious what you are testing for? perhaps affecting right brain functions, due to svelling(?) + constriction of left nostril tissues, due to loss of oxygen level.
#35	It was pleasant to participate in the experiment. The researcher was friendly and fun to work with.
#36	None really(?), accept that 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 comfort 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. If the mark had been ahead, it would have solved it.
#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. I am curious as to why you did not read our temperature more frequently?
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.
74	I think it is an impressive product. I would like to know more about it. For example I have question weather this fan/device reacts to the room temperature, space available, distance from the objects and colors through sensory desire and reacts/throws air accordingly?
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.
85	The researcher should asked the people who would take part in the experiment to go to the washroom first before they start the experiment. If the people who take part in this experiment want to have a rest during the experiment, can they shut off the light??
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 my environment became more relaxed.

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.

3.0 ANALYSIS

3.1 Comparison with computer comfort model results

Table 5 presents predictions based on several well-known computer models of thermal comfort. The models were run for each subject's exposure and only summary statistics are presented here. The models are 1) J.B. Pierce Laboratory 2-Node Model (Gagge and Fobelets 1986) 2) Fangers PMV (ISO 1974), 3) Fanger's draft risk model (Fanger et al. 1986). Each model's input is derived from average values of the physical measurements for every visit.

Table 5

Comfort model results

Statistics	New Effective Temperature	Standard Effective Temperature	Predicted discomfort	Predicted thermal sensation	Gagge's predicted mean vote	Fanger's predicted mean vote
	ET*	SET*	DISC	TSENS	PMVG	PMVF
	deg. C	deg. C	scale units	scale units	scale units	scale units
Average	28.0	26.3	0.8	0.6	0.8	0.7
Maximum	31.3	30.1	1.9	1.3	1.8	2.0
Minimum	23.8	19.1	0	-0.5	-3.2	-16.4
Std Dev.	1.7	1.6	0.4	0.3	0.5	1.3
percent of measurements outside the comfort zone	83%	53%	38%	58%	74%	64%
	Fanger's predicted percent dissatisfied	Fanger's predicted percent dissatisfied due to draft	Operative Temperature and mean air velocity combined	Thermal sensation band of (-1 to +1)	Thermal sensation band of (-0.5 to +0.5)	
	PPD	PDF	Top	Percent of	Percent of	
	scale units	scale units	and Vel	Votes	Votes	
Average	24.5	14.6				
Maximum	100.0	34.3				
Minimum	5.0	0.0				

Std Dev.	18.6	5.7			
percent of measurements outside the comfort zone	60%	49%	72%	20%	49%

For each index, the percentage of the time that the index falls outside the comfort zone is given. In each case it is the warm side of the comfort zone. For ET* and SET*, the boundary is 26.2 deg. C., the upper boundary of the ASHRAE comfort zone. For DISC, the percent is the fraction above a scale value of 1. A person voting 1 feels that the environment is "uncomfortable but acceptable", 2 corresponds to "uncomfortable and unpleasant." For TSENS, the percent is also the fraction above a scale value of 1. Splitting it at 1 follows the assumption that the central three categories of the thermal sensation scale are comfortable and is the premise behind the ET* limits in the ASHRAE standard. If we split the scale at '0.5', we assume that the thermal sensation scale is mapped point for point by the PMV scale and the ISO 7730 (ISO 1984) limits on PMV apply. In the case of both TSENS and DISC, this would increase the percentage of points that are beyond the comfort zone. Both versions of PMV, PMVG and PMVF are split at a scale value of 0.5 following the ISO limits since the PMV scale is incorporated into the ISO standard. The percent for PPDF, Fanger's predicted percent dissatisfied and PDF Fanger's predicted percent dissatisfied due to draft are the fraction of values above 15% on each scale, the limit applied in ISO, and for draft, also in ASHRAE 55-92. The next entry in Table 5 combines the effect of operative temperature and air velocity as it is applied in ASHRAE 55-92 (See figures 5.3 and 5.4 in ASHRAE 55-92). The percentage in the table is the fraction of points falling above the air velocity limit, i.e. outside the comfort zone for a given operative temperature. It is interesting to note that points fall above the limits given by both figures in ASHRAE 55-92, not just the draft figure. The last two entries in Table 5 are the percentage of actual votes from the subject falling outside the comfort zone using the two conventional definitions described above. TSENS overestimates the number of people voting outside the band of -1 to +1 by nearly 40% while Fanger's PMV overestimates the number voting outside the band of -0.5 to +0.5 by nearly 25%. Overall, a strong majority of the environments produced by the subjects in this experiment, and considered comfortable to them using widely accepted measures of thermal comfort, would be restricted by existing comfort standards as being too warm.

3.2 Comparison with Fanger's draft limit.

Figure B13 shows a scatter plot of the air velocities produced in this experiment as a function of space temperature. There is an upward trend in the density of higher velocities chosen as temperature increases. The Fanger draft limit (Fanger et al. 1986, incorporated into ASHRAE 55-92) is shown for comparison. Clearly, the velocities chosen by our subjects exceed the allowable limits in the overwhelming majority of cases. Figure B14 shows the same data but with the constant fan speed experiment mean velocities separately identified with respect to the 1/f experiment mean velocities. There does not appear to be a significant difference between the operating modes regarding the choice of mean values by the subjects.

3.3 Analysis of thermal sensation for the entire sample, regressions and probits

Figure B15 presents a simple linear regression of thermal sensation as a function of air temperature. The slope of this line indicates that one scale value of thermal sensation corresponds to approximately 5 deg C. in air temperature. 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 deg C. Two important conclusions arise from this finding: 1) People are widening their comfort zone with air movement, and 2) People will 'include' more extreme environments in their comfort zone if they are in control of their environment.

Figure B16 shows a probit analysis of thermal sensation responses as a function of air temperature. The data are the same as in Figure B15, but the analysis method is more robust. The functional form of the fit follows the familiar 'dose-response' relationship that arises from assuming a normally distributed sample of subjects responding to a measured dose of the independent variable . The dose in this case is temperature and the response is thermal sensation vote. Each curve represents the percent of subjects voting at a certain level or higher. The leftmost curve represents a vote of -1 (the lower boundary), the middle curve represents a vote of 0 (the middle), and the rightmost curve represents a vote of +1 (the upper boundary). Again, the category width is 5 deg C. The ED50 point, that is, the dose level that produces a 50% response is 25 deg C. In the thermal comfort literature, this point is often called the 'neutral temperature' of the sample. It indicates the point at which the sample will be evenly divided between warm and cool response and is a useful measure for comparing populations. A neutral temperature of 25 deg. C is significantly warmer than what would be expected in a typical non-tropical population and much more akin to the neutral temperature found in tropical populations that are acclimated to warm conditions and naturally ventilated buildings. The analogy is clear.

3.4 The zone of likely use

The 'zone of likely use' is not intended to be a comfort standard. However, the concept is useful for defining the scope of energy consumption simulations and regulatory guidelines for alternatives to compressor cooling. From the results of this climate chamber experiment, we define the 'zone of likely use' to extend from 25 deg. C. to 29 deg. C in air temperature. Below 25 deg. C, cooling is not generally required while above 29 deg. C. non-thermal effects of air movement can cause significant discomfort. At the higher temperatures, discomfort can occur even though sufficient air movement is available for thermal cooling. The device providing air movement should be capable of at least 1.0 m/s at a distance of 2 m. People using the fan for cooling will most likely choose air velocities within the boundary defined by the angled lines in Figure B17.

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LIST OF FIGURES

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 B2-1

Home Environment

A number of characteristics related to your **home environment** are given below. Please indicate how IMPORTANT TO YOU each characteristic is by circling the number that reflects how you feel.

4 very important

3 moderately important

2 slightly important

1 not at all important

(circle one number for each item)

How important to you is:

1.	The type and levels of sounds?------------------------	1 2 3 4
2.	The lighting?--	1 2 3 4
3.	The temperature?--------------------------------------	1 2 3 4
4.	the humidity of air? ---------------------------------	1 2 3 4
5.	The indoor air quality?-------------------------------	1 2 3 4
6.	The ventilation and air movement?--------------------	1 2 3 4
7.	The colors of walls? -------------------------------	1 2 3 4
8.	The furniture and appliances? -----------------------	1 2 3 4
9.	The amount of space available to you?---------------	1 2 3 4
10.	The level of privacy?--------------------------------	1 2 3 4
11.	The feeling of comfort in your favorite chair?----------	1 2 3 4
12.	Opening or closing a window to be comfortable?------	1 2 3 4
13.	Turning a fan on or off to be comfortable?------------	1 2 3 4

Thank you very much for your time.

Figure B2-2

Comfort Study---------Questionnaire

1. Please write down the time: ______________________________

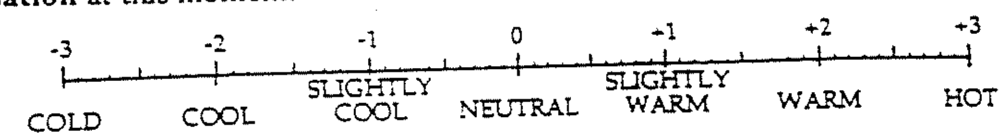
2. Please check (☒) the box that best describes your present **Thermal Preference**:

   - ☐ 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:



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:

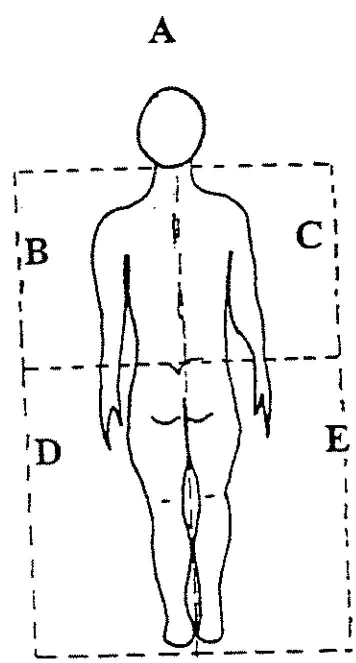
(A) Head
- ☐ comfortable
- ☐ warmer than comfortable
- ☐ cooler than comfortable

(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 B3

Consent Form ---- Comfort Experiment

June 15,1993

In this experiment, we will be simulating summertime conditions in a home.

If you agree to take part in this research, you will be asked to spend a few hours in the Controlled Environment Chamber in 272 Wurster Hall. Prior to the experiment, we will ask you to fill out a background survey. The background survey asks a few questions about your background and impressions of your thermal comfort in your home. In the lab, we will ask you to sit in a chair and read or listen to music. You will be given control of a remote-controlled fan and you can adjust it as you please to make yourself comfortable. We will periodically ask you to stand up and do some light activity and ask questions about how you feel and make measurements at your location. At the end of the exposure period (about 2.5 hours), we will pay you $20!

There is no benefit to you from participating in the research beyond the financial reward and couple of hours of peace and quiet! However, the research will benefit society by increasing our knowledge of thermal comfort. All of the information we obtain from you during the research will be kept confidential. Your name will only be on the paper copy of the background survey which will be locked in our laboratory. All data collected from you during the experiment will be labeled with a code. Your name or identifying information will not appear in any publication or report of this research.

Your participation in this research is voluntary. You are free to refuse to take part, and you may stop taking part at any time. If you have any questions about this research, you may call Tengfang Xu @ 642-2720 or stop by 272 Wurster Hall.

Participant:

I have read this consent form and I agree to take part in the research.

____

Print your name here

______________________________ ____________________

Signature **Date**

Figure B4

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	3rn 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 B5

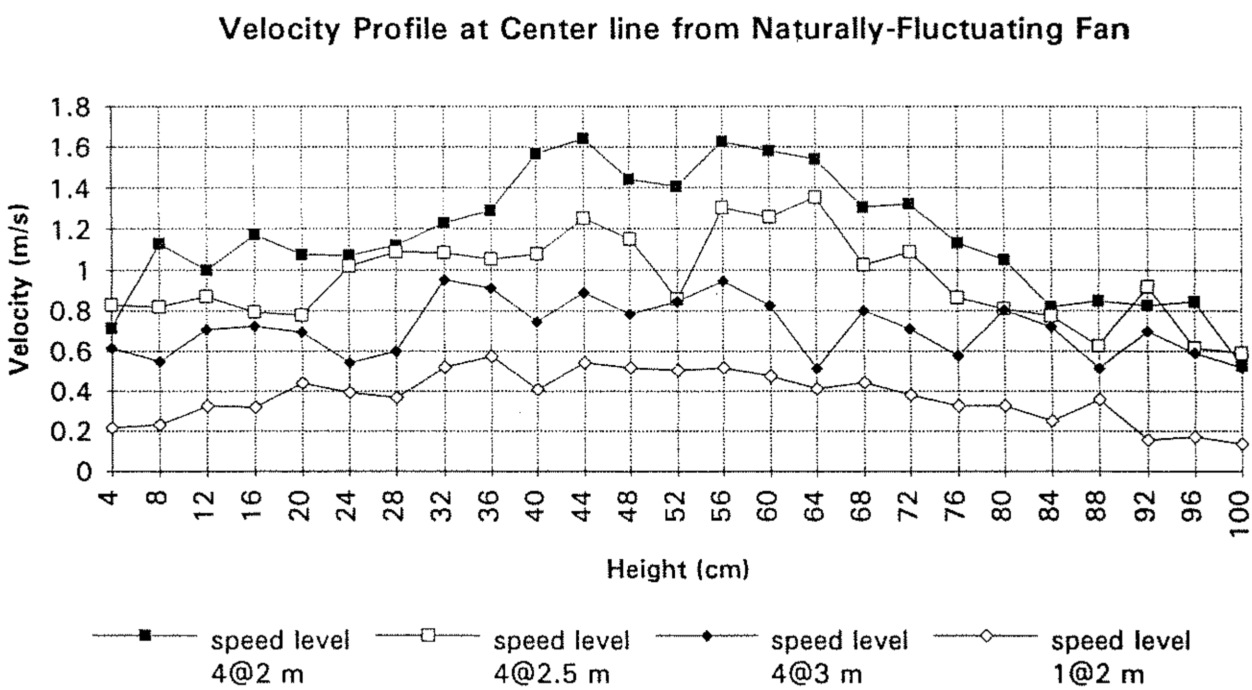

Velocity Profile at Center line from Naturally-Fluctuating Fan
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Velocity (m/s)
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Height (cm)
speed level 4@2 m
speed level 4@2.5 m
speed level 4@3 m
speed level 1@2 m

Figure B6

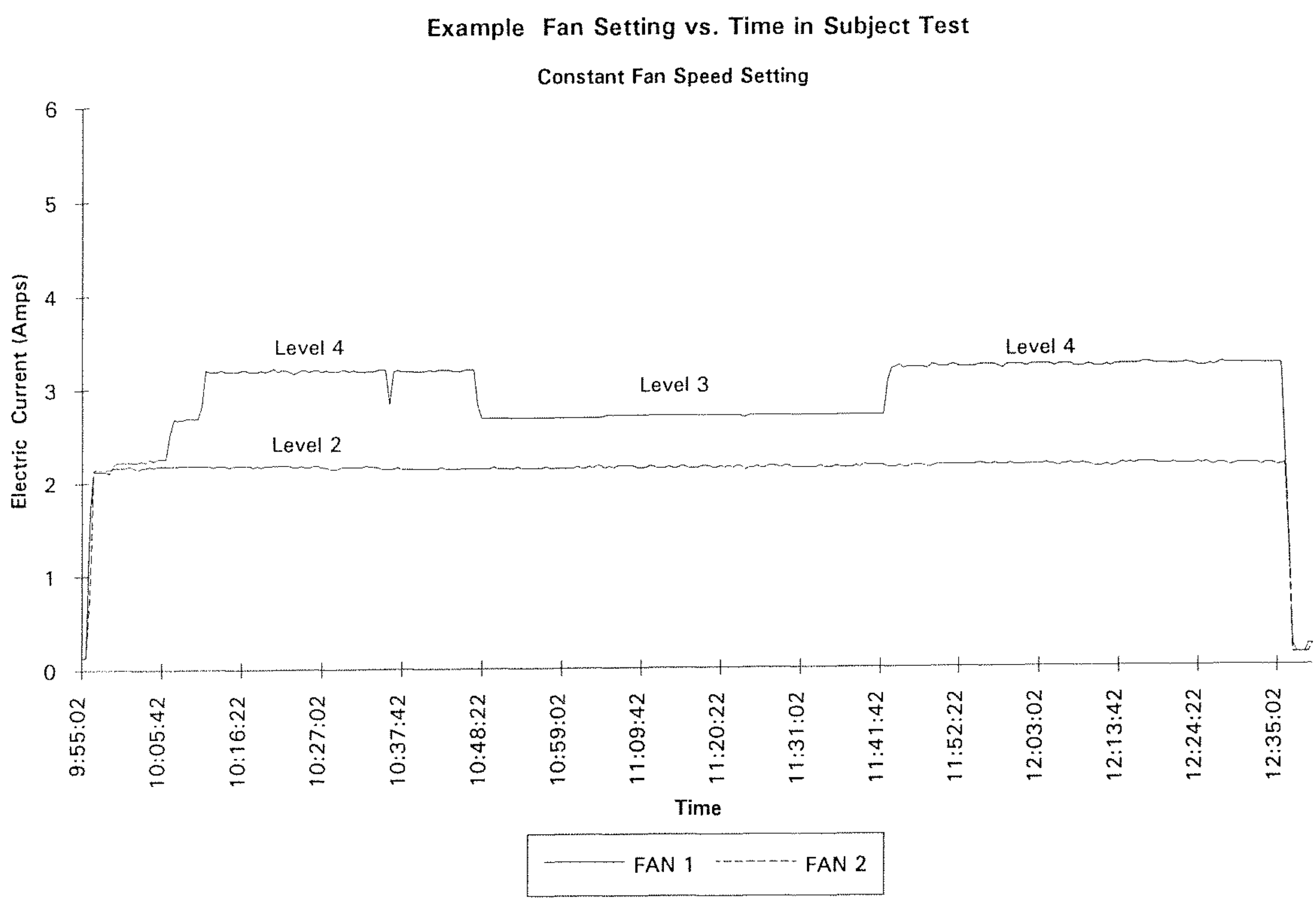

Example Fan Setting vs. Time in Subject Test
Constant Fan Speed Setting
Electric Current (Amps)
0
1
2
3
4
5
6
Level 4
Level 2
Level 3
Level 4
9:55:02
10:05:42
10:16:22
10:27:02
10:37:42
10:48:22
10:59:02
11:09:42
11:20:22
11:31:02
11:41:42
11:52:22
12:03:02
12:13:42
12:24:22
12:35:02
Time
FAN 1
FAN 2

Figure B7

Example Fan Setting vs. Time in Subject Test

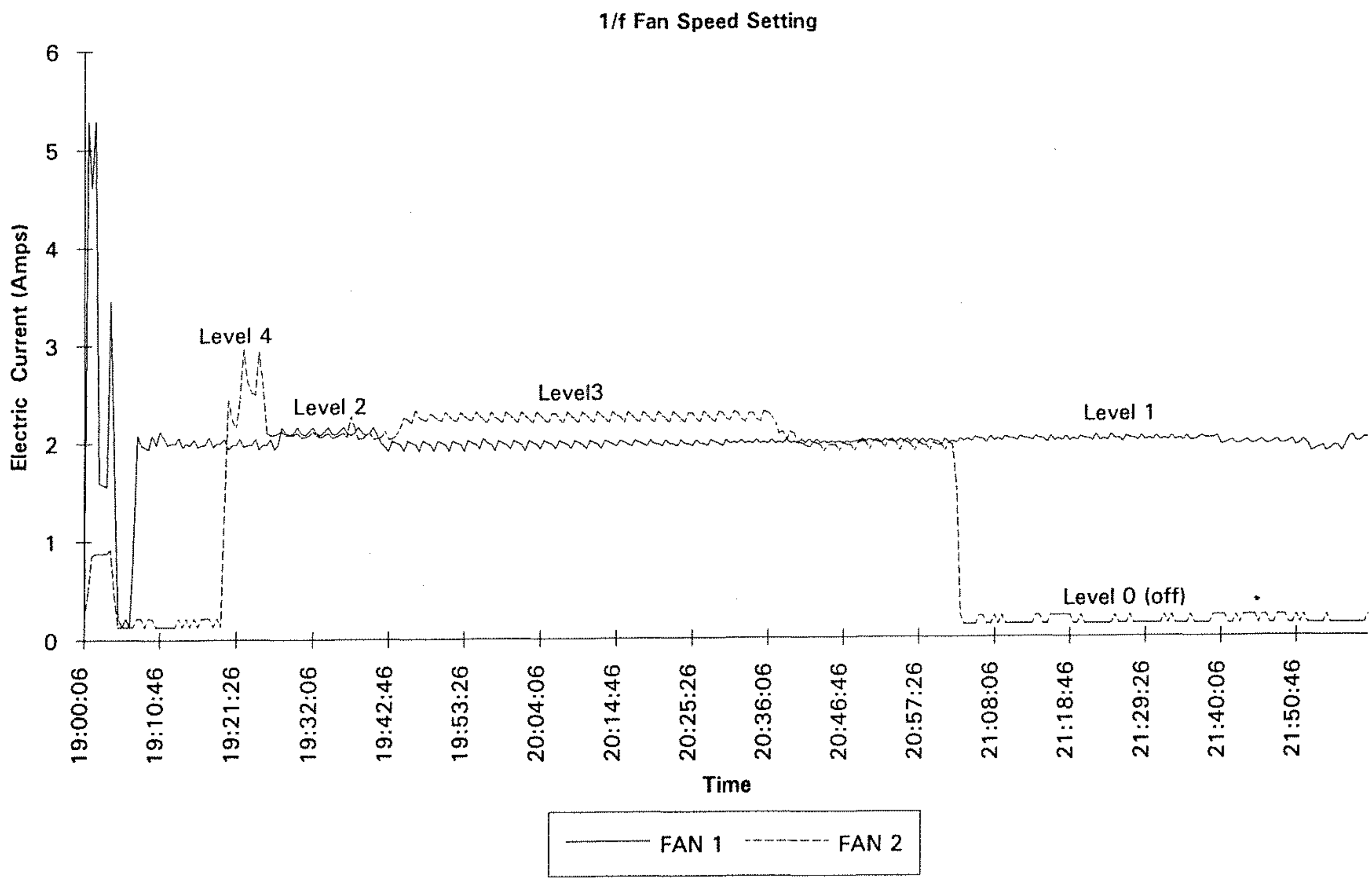


Figure B8

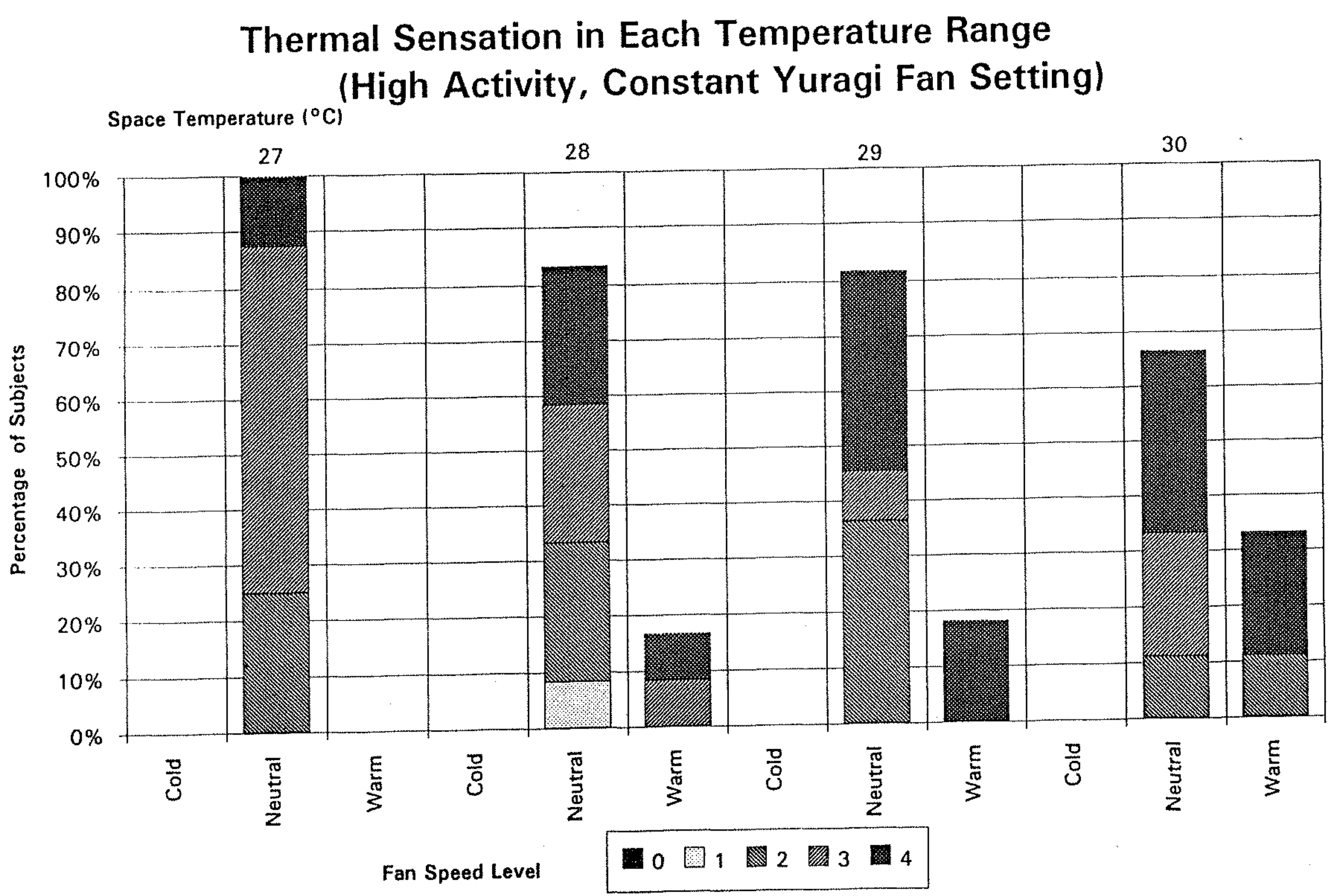

Thermal Sensation in Each Temperature Range
(High Activity, Constant Yuragi Fan Setting)
Space Temperature (°C)
27
28
29
30
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percentage of Subjects
Cold
Neutral
Warm
Cold
Neutral
Warm
Cold
Neutral
Warm
Cold
Neutral
Warm
Fan Speed Level
0
1
2
3
4

Figure B9

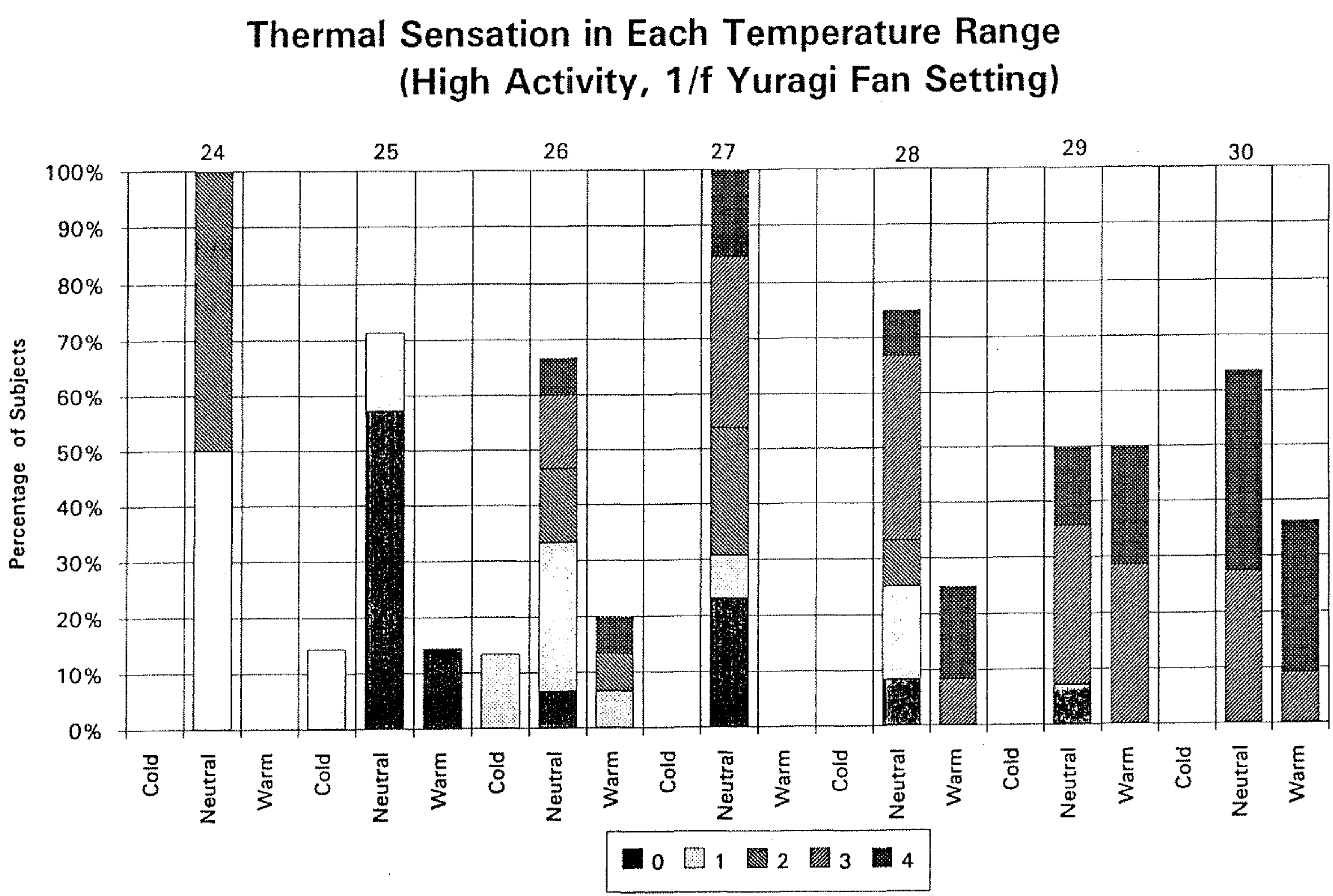

Thermal Sensation in Each Temperature Range
(High Activity, 1/f Yuragi Fan Setting)
Percentage of Subjects
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
24
25
26
27
28
29
30
Cold
Neutral
Warm
0
1
2
3
4

Figure B10

Thermal sensation voting VS Space temperature & Fan level (low activity, 1/f))

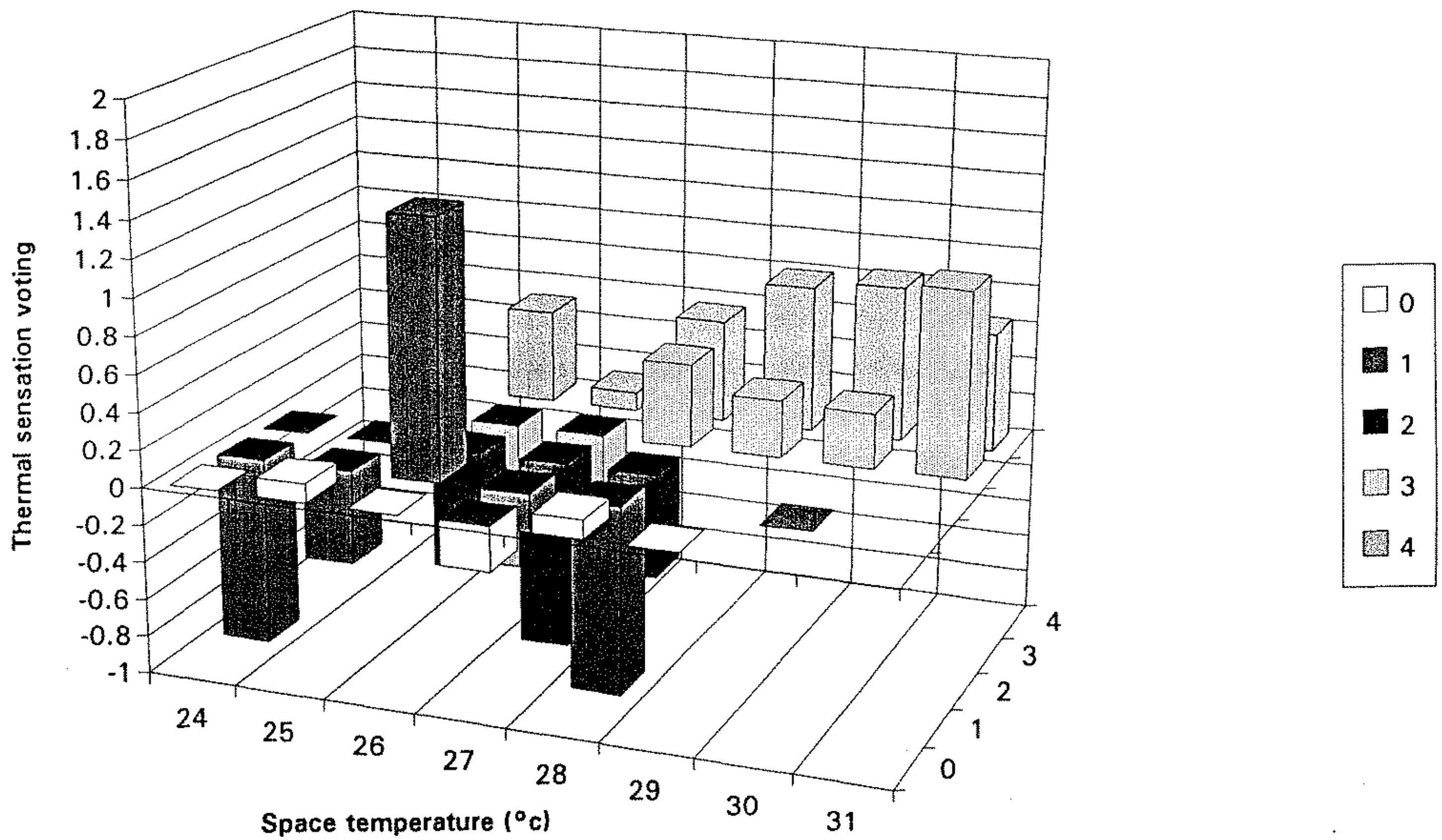


Figure B11

Thermal sensation voting VS Space temperature & Fan level (high activity, 1/f))

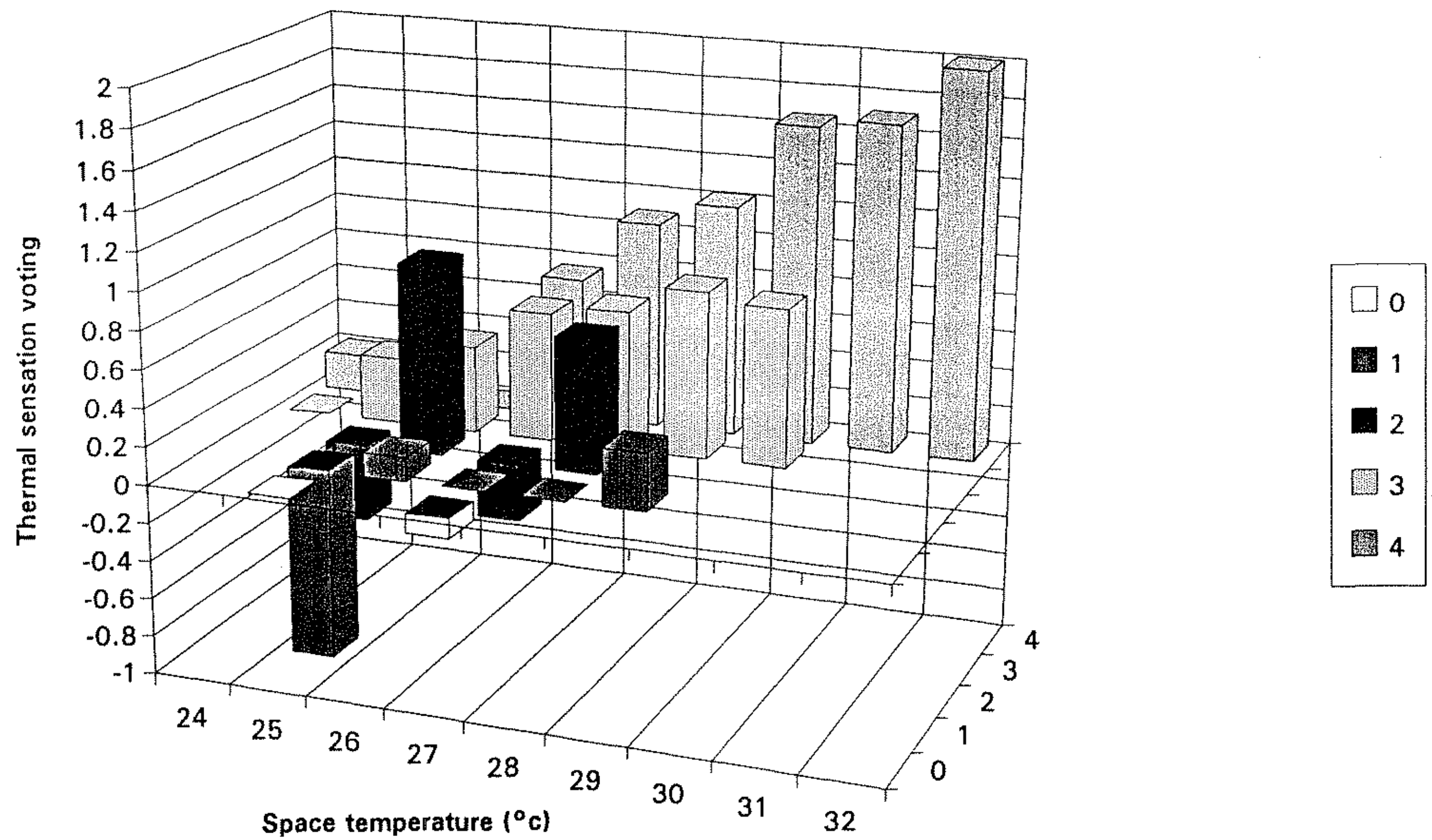
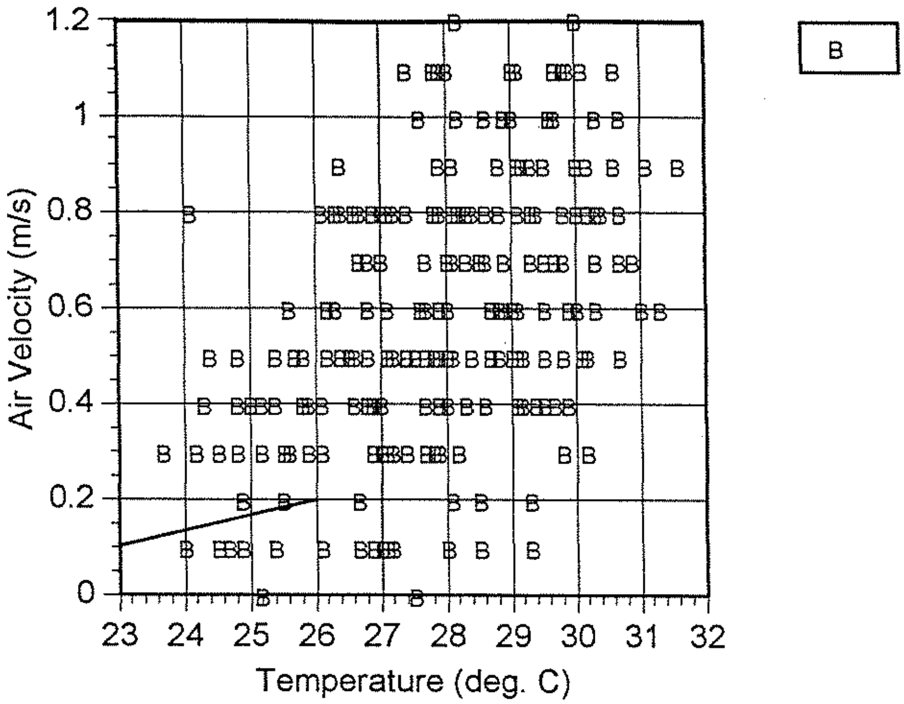


Figure B12

Air velocities as a function of space temperature



Air velocities as a function of space temperature (constant speed fan and fluctuating fan separate)

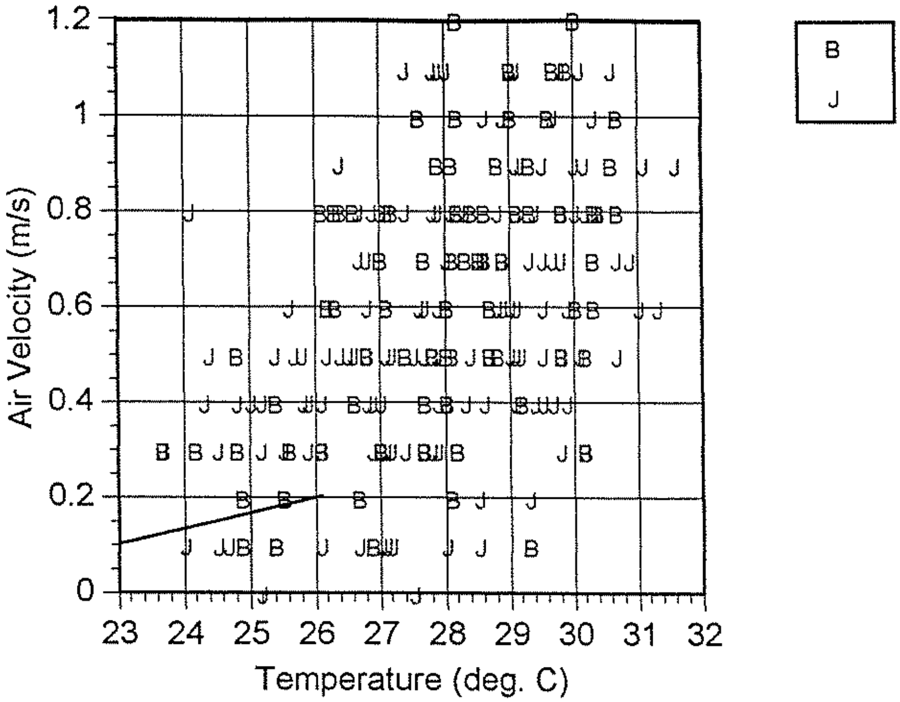


Figure B14

Thermal sensation as a function of air temperature

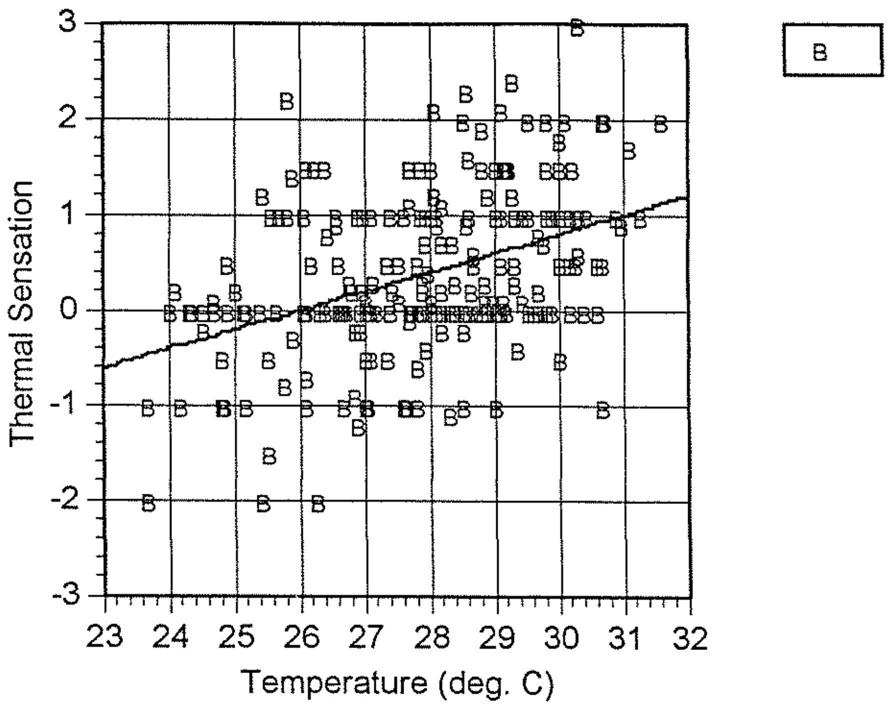


Figure B15

Probit analysis of thermal sensation response

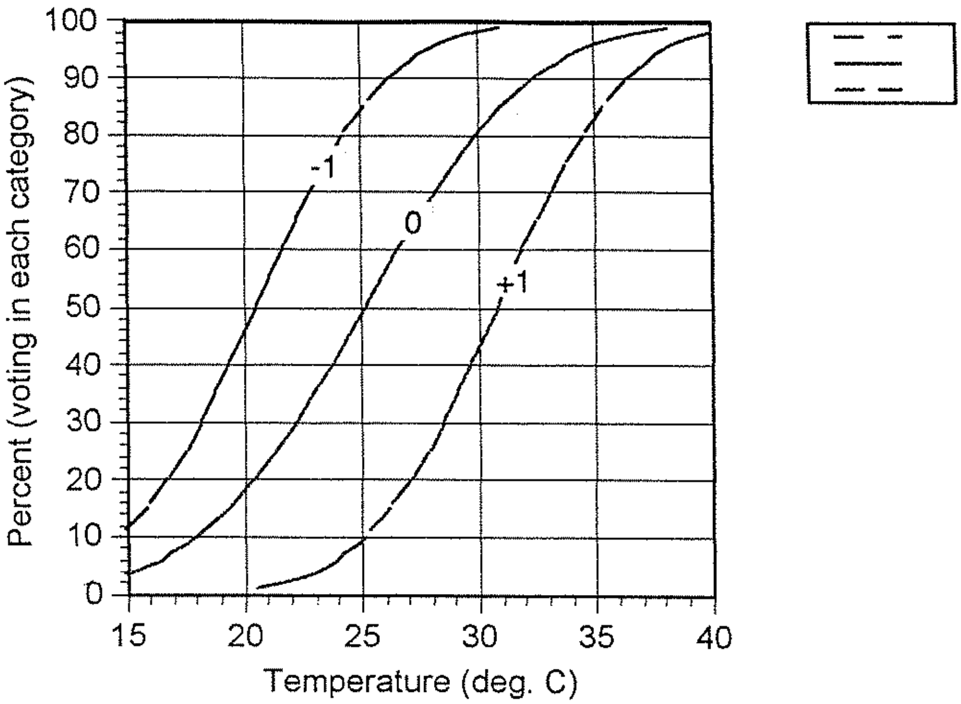


Figure B16

Zone of likely use

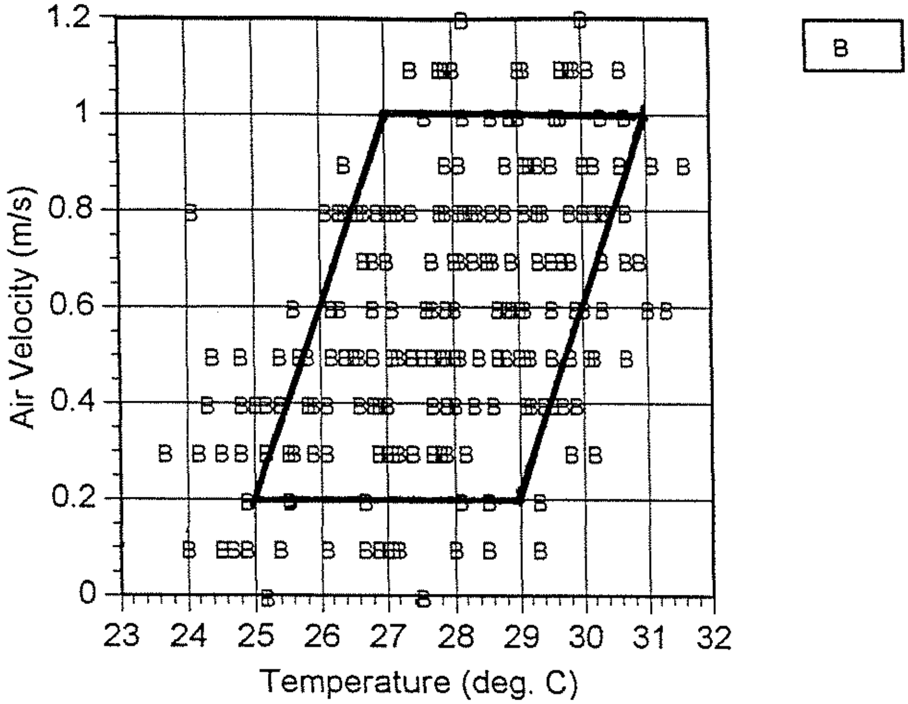


Figure B17

APPENDIX C

Laboratory Studies of Air Movement and Comfort:
Thermal Manikin Tests in Support of Human Subject Tests

Appendix C.

Thermal Manikin Tests in Support of Human Subject Tests

The manikin was tested in the controlled environment chamber under the same conditions as those of the human subject tests. The fluctuating fan was placed 2 meters from the chair, in the same surroundings and environmental conditions as the subject tests. The chamber temperatures were set at 26.5°, 28°, and 30.5° C. Fan speed level settings were 0, 1, 2, 3, and 4. The manikin was tested for back, side, and front air flow approach directions. The clothing insulation value was 0.55 clo. The padded chair shown in Photo 1 was used to represent an average residential type of seat. This test was done to obtain the manikin's thermal response to different levels of air movement and direction, both for the local body parts and for the whole body, in order to compare with the later results of the human subject tests. The physical data (segment temperatures, heat flows, and insulation values) cannot be obtained from the human subjects in such a study.

From this experiment we can see that the manikin was most influenced when air came from the front (Figure 1). The manikin response is represented by an equivalent still air temperature. We can also see that when air movement increased above level 1, the manikin was more affected by the wind direction changing from the back to the side than from the side to the front.

The lower body parts were not as sensitive as the upper body parts to changes in wind direction (Figure 2). This result is partly because the fan provided less velocity for legs and feet than for upper body. This result was also noted in the wind tunnel manikin tests, where the approach velocity was more uniform.

When the room temperature set point was 30.5°C and air came from the side, the manikin Predicted Mean Vote (PMV) values for all the fan levels was above +1 (Figure 3). This value is often used as the threshold for unacceptably warm conditions. When the room temperature set point was 28°C, the PMV values from the manikin were from +0.4 to +0.9. When the room temperature was set at 26.5°C, the PMV values changed from +0.4 to -0.4 as the fan speed increased from the 0 to 4 level . These results will be compared with the human subject votes.

Figure 1. Equivalent temperatures produced by the fluctuating fan at different levels and directions

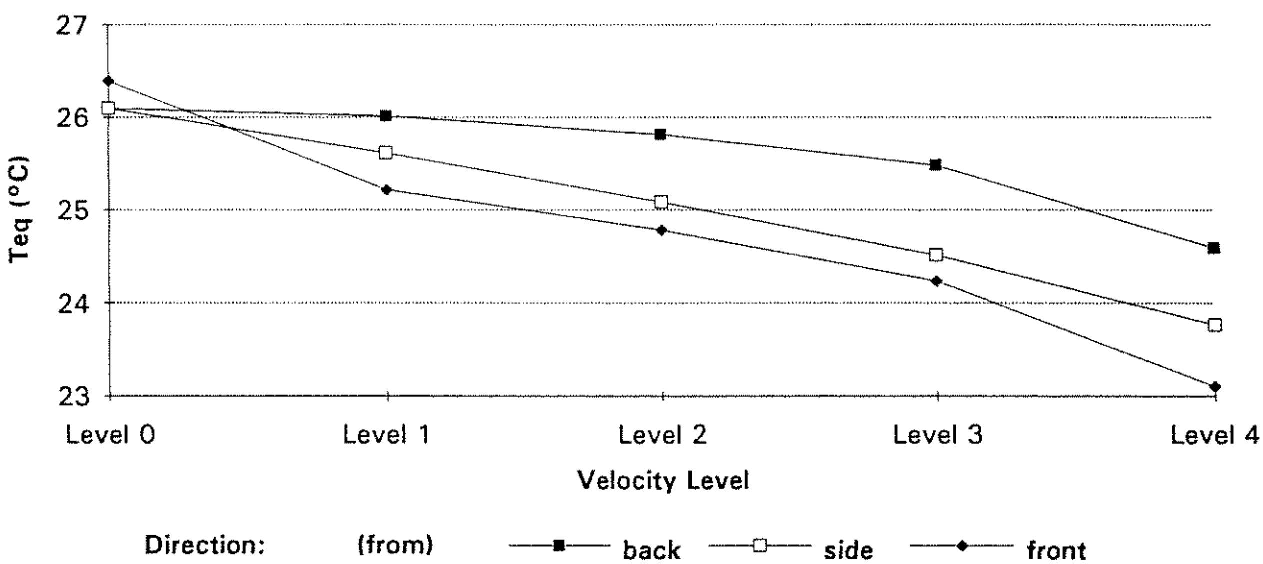


Figure 2. Equivalent temperatures affected by the air coming directions from the fluctuating fan on the different manikin parts (velocity level 4)

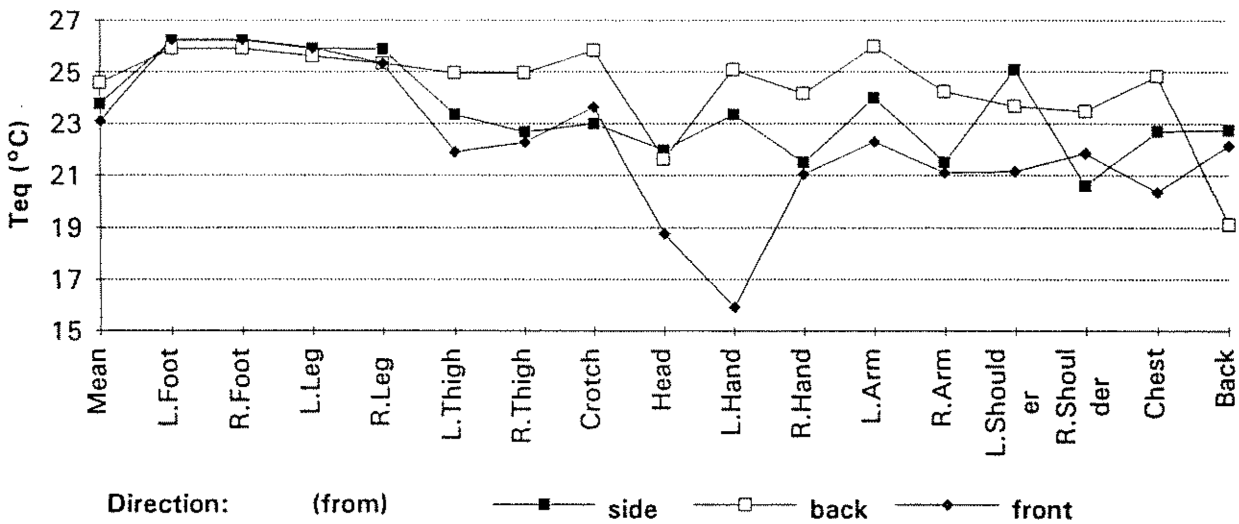
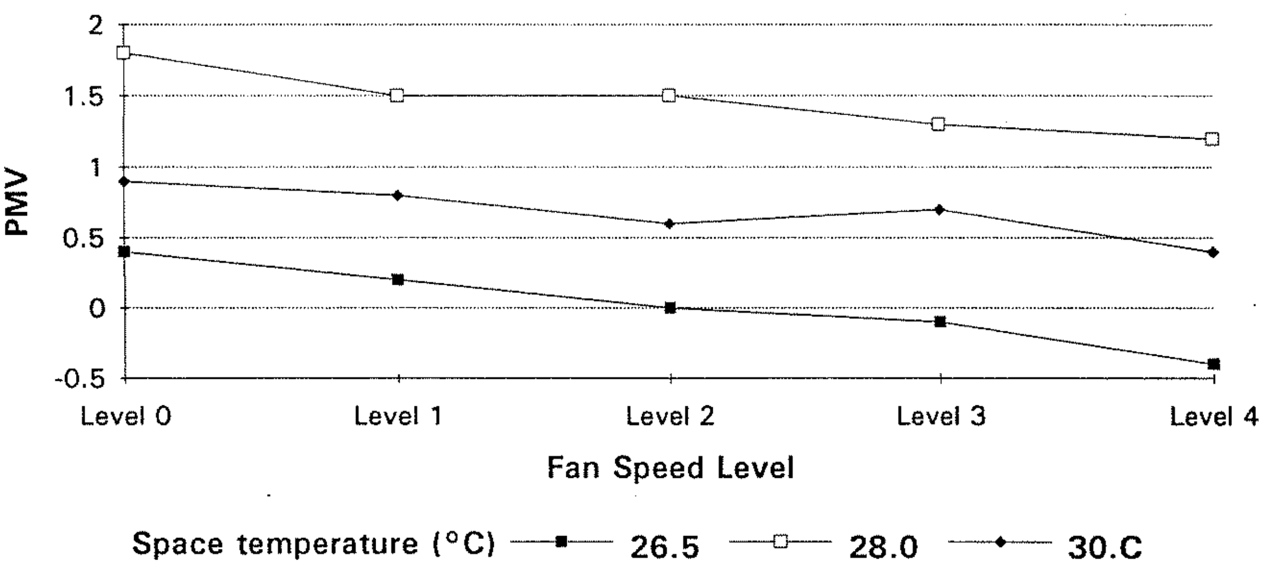


Figure 3. Manikin predicted mean vote (PMV) values vs fluctuating fan speed level for different space temperatures



APPENDIX D

Laboratory Studies of Air Movement and Comfort:
Thermal Manikin Tests in Support of Computer Comfort Modeling

Appendix D.1.

Wind Tunnel Tests of the Thermal Manikin Tests in Support of Computer Comfort Modeling

The purpose of the experiment was to characterize the effect of wind velocity and direction on clothing insulation, both for local parts of the body and for the whole body. To do this, a 16-segment thermal manikin was tested in the wind tunnel under uniform air movement conditions. The manikin was tested both with moderately lightweight clothing (still-air clothing insulation value equal to 0.55 clo) and in the nude. It was seated in a metal mesh chair thermally similar to the string chairs used in many past comfort studies (Photo 1). For each test, the manikin was allowed to come into equilibrium, a period of about 15 minutes.

Five levels of velocity were tested from 0.17 to 1.07 m/s, in addition to still air. The air movement produced by the wind tunnel was very steady, varying no more than 3% over the testing time at any of the velocity levels. The profile of air velocities along the vertical axis increased very slowly with height, with the velocities near the feet 13% lower than the mean value. This was considered a realistic representation of air movement found in a room. The air movements tested approached the manikin from different directions: side, back, and front.

Effect of changes in direction: From the results (Figure 1 and Table 1) we can see that the clothing insulation values in the lower body parts were not affected as much as the upper body parts by the changes in the air movement's direction. At velocity level 4 (0.73 m/s), the area-weighted total clothing insulation (I_t, in clo) for the whole body was 9.23% higher with the wind from back than from front. The lower body parts (foots, legs, thighs, and crotch) varied a maximum of 9% with this change of direction. In contrast, the insulation for the individual upper body parts (hands, arms, shoulders, chest, back, and head) tended to change over 20% with the same change of direction (Table 1). With the wind from the side, the total insulation value for all body parts was roughly half way between the values for back and front. For the nude manikin, the air layer insulation values (Ia, in clo) for the wind from the side were closer to those with the wind from the back than from the front (Figure 2 and Table 2).

The clothing insulation values changed with direction at air movements of 0.54 m/s and higher. For air movements of 0.33 m/s or lower, the clothing insulation did not respond to the changes of direction (Figure 3).

Effect of changes in velocity: As the air movement increased from still air to 1.07 m/s, the total (clothing plus air film) insulation value decreased from 1.37 to 0.82 clo (Figure 4 and Table 3). The largest decrease happened when the air movement changed from 0.33 to 0.54 m/s, with the total clothing insulation value decreasing 0.08 clo for per 0.1 m/s decrease. As air movement increased, clothing insulation values also changed more in the upper body parts than in the lower body parts.

In conclusion, these findings show that wind velocity effects on clothing insulation are significant enough that comfort simulation should incorporate functions of clothing insulation versus wind speed. The clo values developed here for both nude and clothed individual parts of the body provide the data to simulate people as combinations of nude and clothed surfaces. This will be possible in the multi-segment computer model now under development. Such a model is essential for realistically simulating human response to higher rates of ventilative air movement. Used as a design tool in conjunction with building energy simulation models, it should be able to predict the success of naturally- or fan-ventilated building designs to the level of confidence expected by building engineers.

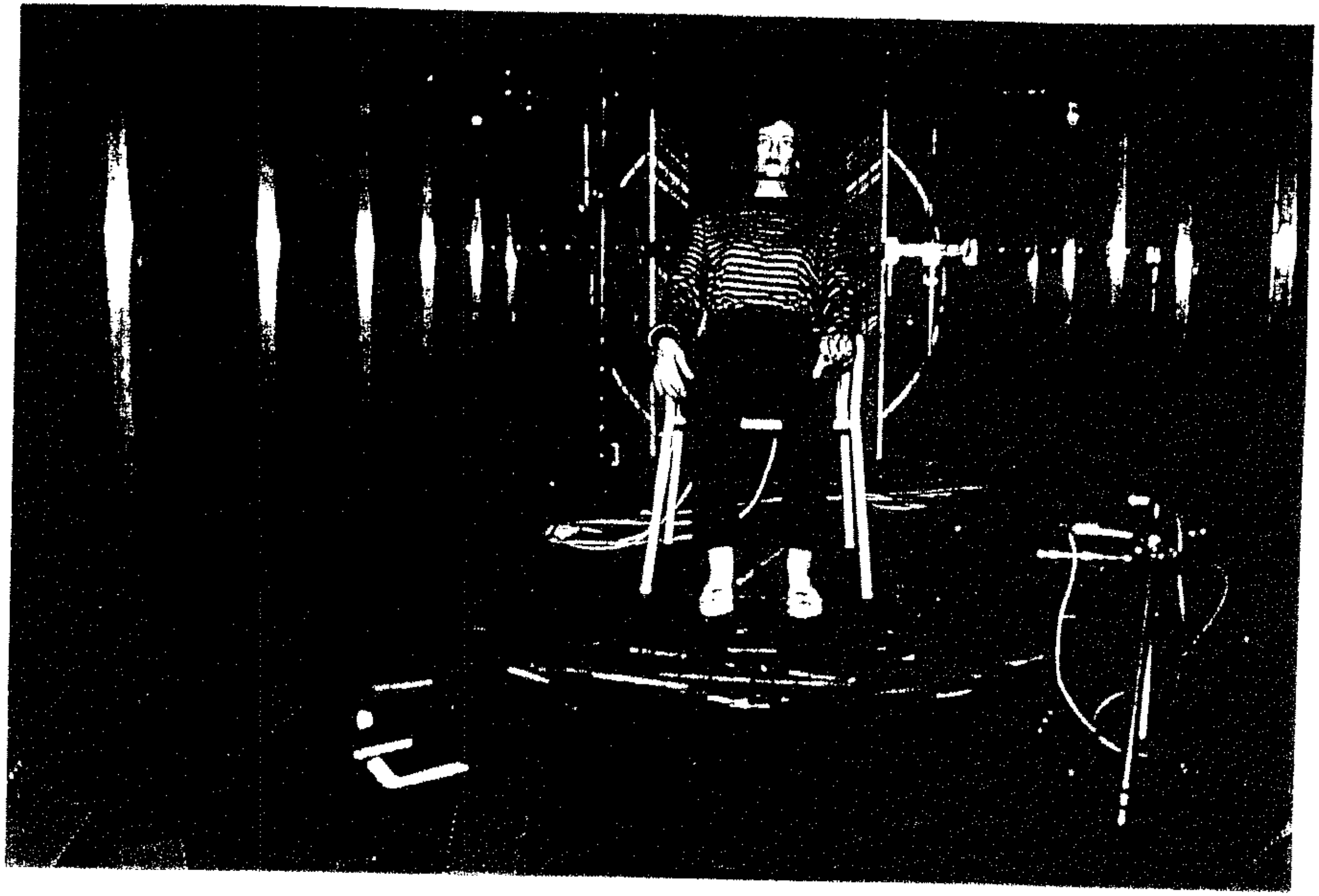


Photo 1

Figure 1. Air movement effects for different directions on the total insulation values (It) of different manikin parts at velocity 0.73 m/s

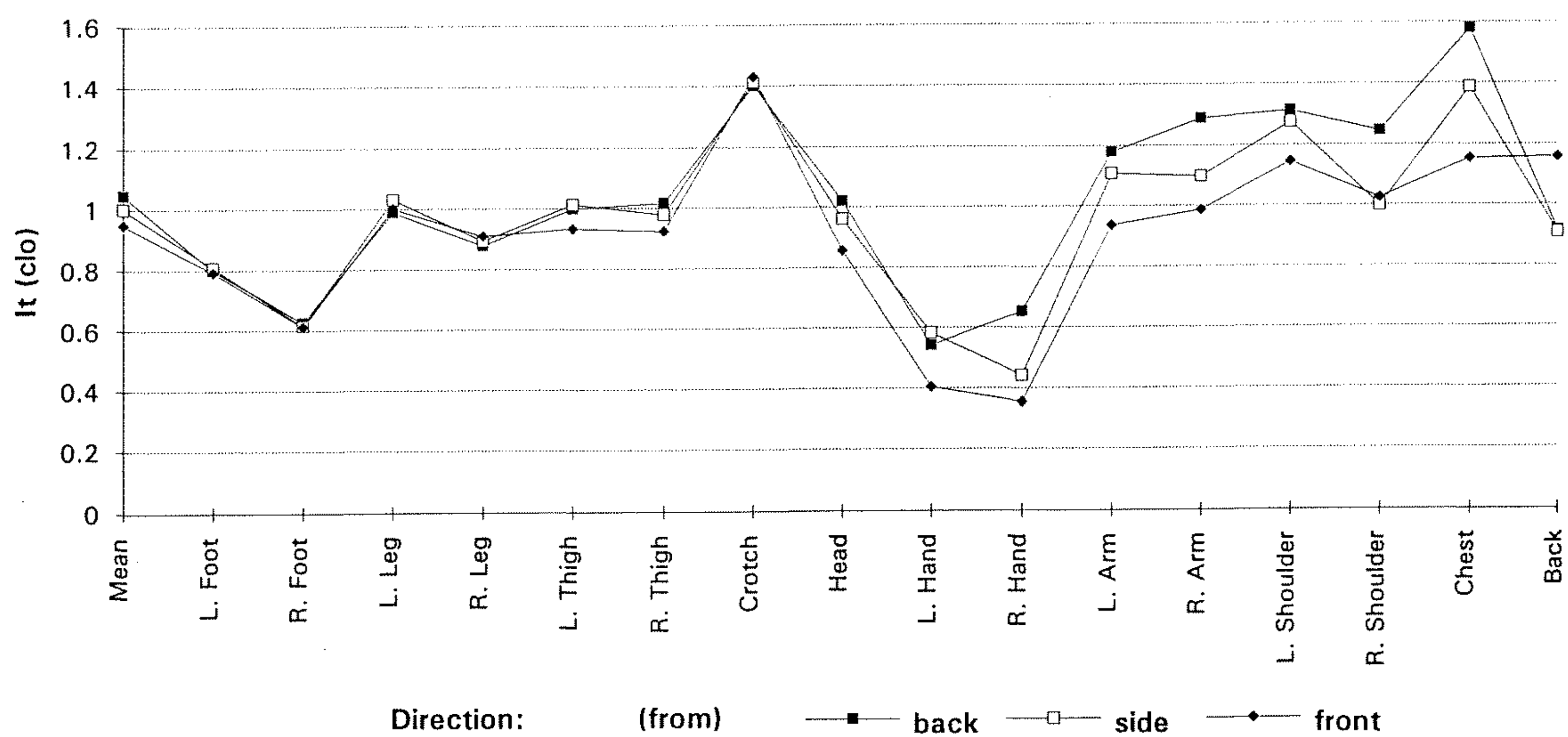


Table 1. Total insulation values (It) of the different parts of the manikin at velocity 0.73 m/s

direction	Mean	L. Foot	R. Foot	L. Leg	R. Leg	L. Thigh	R. Thigh	Crotch	Head	L. Hand	R. Hand
back It(clo)	1.05	0.80	0.63	0.99	0.88	1.00	1.02	1.40	1.02	0.54	0.65
side It(clo)	1.00	0.81	0.61	1.03	0.89	1.01	0.98	1.41	0.96	0.58	0.44
front It(clo)	0.95	0.79	0.61	1.00	0.91	0.93	0.92	1.43	0.86	0.40	0.35

direction	L. Arm	R. Arm	L. Shoulder	R. Shoulder	Chest	Back
back It(clo)	1.18	1.29	1.31	1.24	1.58	0.91
side It(clo)	1.11	1.10	1.27	1.00	1.39	0.91
front It(clo)	0.94	0.99	1.14	1.02	1.15	1.16

Total insulation value (It) decreases in percent (%) with the changes of the air movement direction

Body Part	Mean	L. Foot	R. Foot	L. Leg	R. Leg	L. Thigh	R. Thigh	Crotch	Head	L. Hand	R. Hand
(Itb-Its)/Itb (%)	4.31	-1.16	1.82	-4.27	-1.78	-1.26	3.68	-0.93	5.83	-7.60	32.45
(Itb-Itf)/Itb (%)	9.23	0.82	2.27	-1.25	-3.70	6.54	9.01	-2.17	16.00	25.57	45.92

Body Part	L. Arm	R. Arm	L. Shoulder	R. Shoulder	Chest	Back
(Itb-Its)/Itb (%)	6.00	14.76	2.90	19.69	12.21	0.73
(Itb-Itf)/Itb (%)	20.49	23.40	12.86	17.77	27.06	-26.54

Figure 2. Air movement effects for different directions on the nude manikin parts at velocity 0.54 m/s

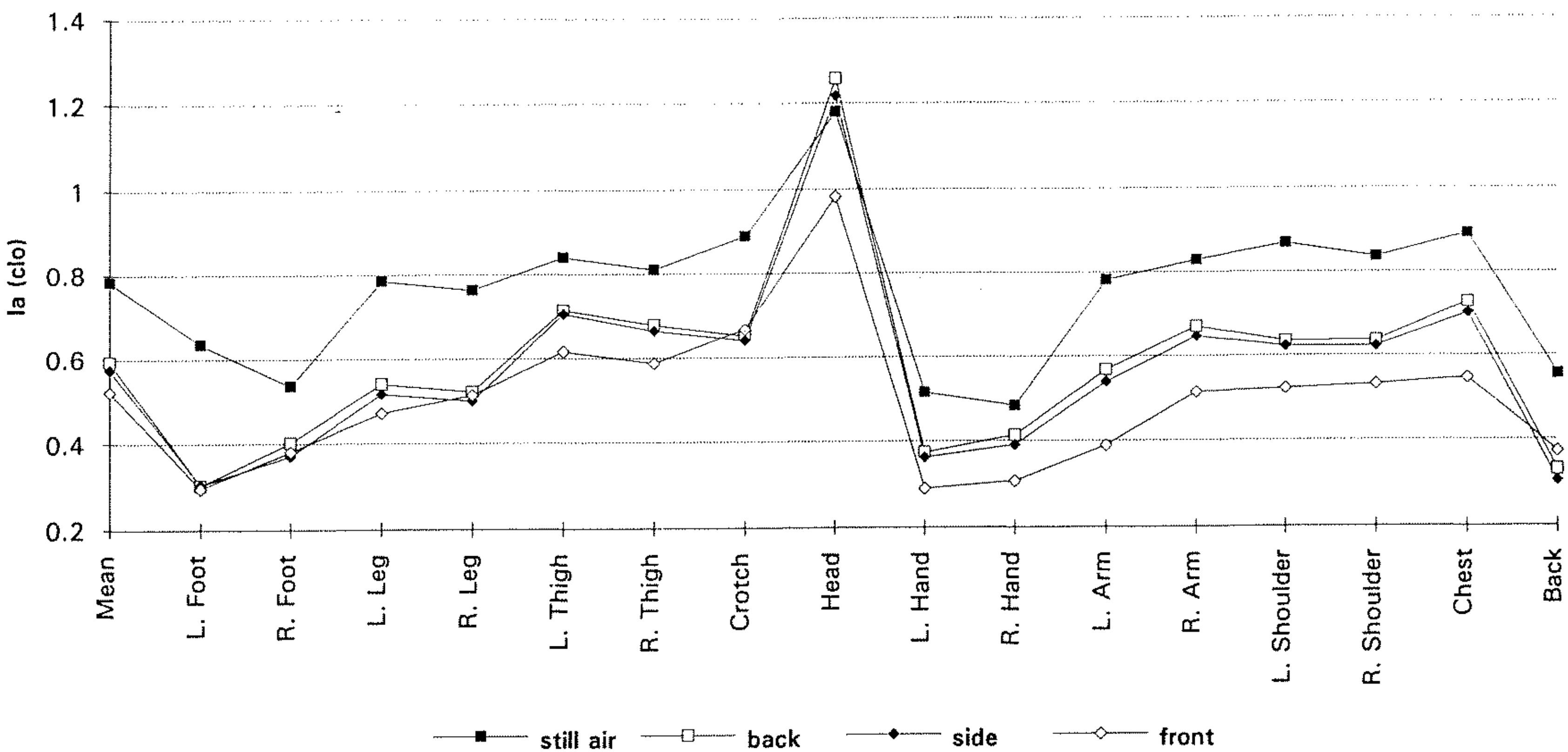


Table 2. Insulation values (Ia) of the different parts of the nude manikin at velocity 0.54 m/s

situation	Mean	L. Foot	R. Foot	L. Leg	R. Leg	L. Thigh	R. Thigh	Crotch	Head	L. Hand	R. Hand
still air	0.78	0.63	0.54	0.78	0.76	0.84	0.81	0.89	1.18	0.51	0.48
back It(clo)	0.59	0.30	0.40	0.54	0.52	0.71	0.68	0.65	1.26	0.37	0.41
side It(clo)	0.57	0.30	0.37	0.52	0.50	0.70	0.66	0.64	1.22	0.36	0.39
front It(clo)	0.52	0.30	0.38	0.47	0.51	0.62	0.59	0.67	0.98	0.29	0.31

Body Part	L. Arm	R. Arm	L. Shoulder	R. Shoulder	Chest	Back
still air	0.78	0.83	0.87	0.84	0.89	0.56
back It(clo)	0.57	0.67	0.63	0.64	0.73	0.33
side It(clo)	0.54	0.65	0.62	0.62	0.70	0.30
front It(clo)	0.39	0.51	0.52	0.53	0.55	0.37

Figure 3. Air movement effects for different directions on the total insulation velue (It) of the different manikin parts at velocity 0.33 m/s

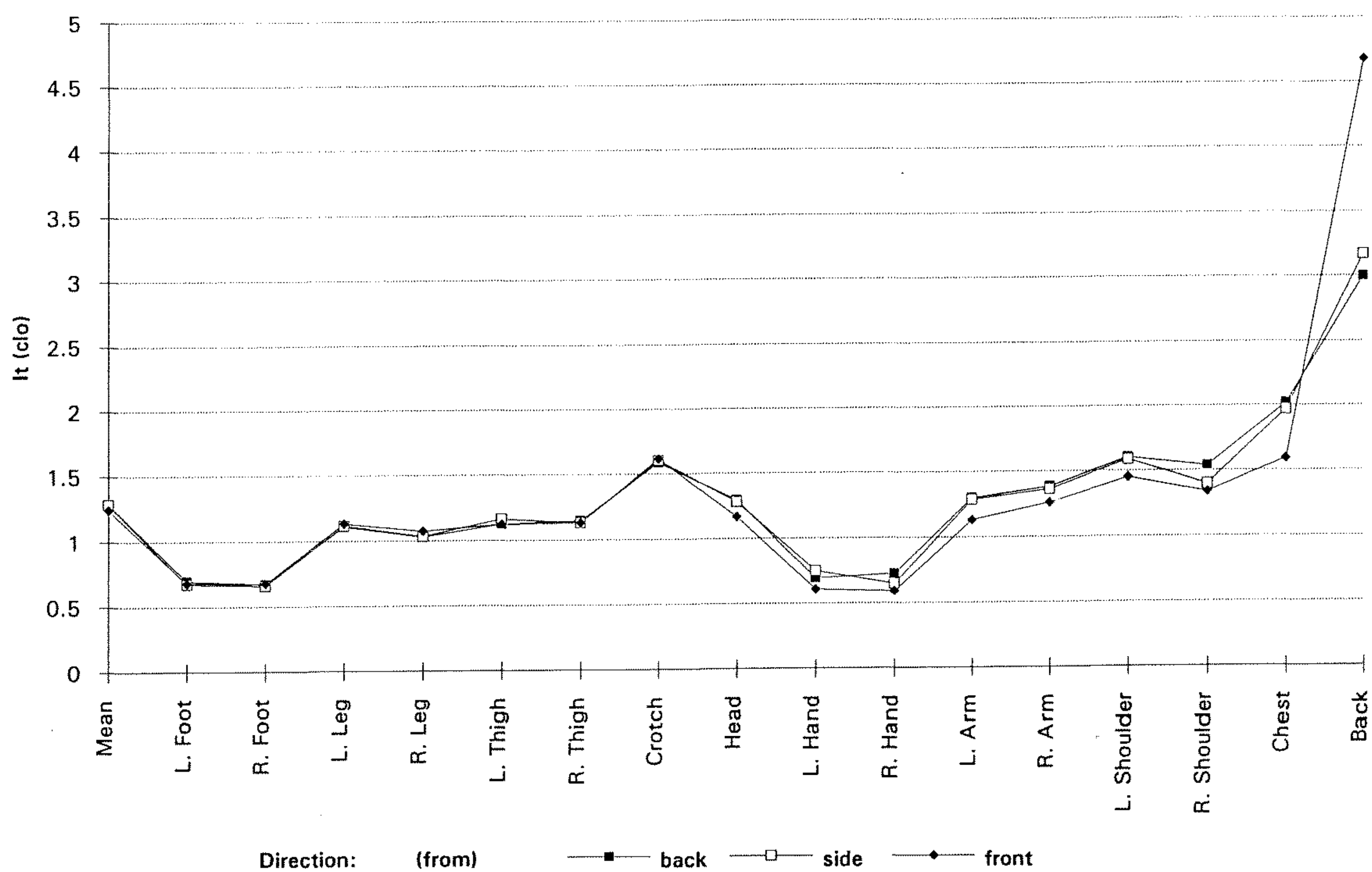


Figure 4. Effect of air movement from front on the total insulation values (It) of the different manikin parts

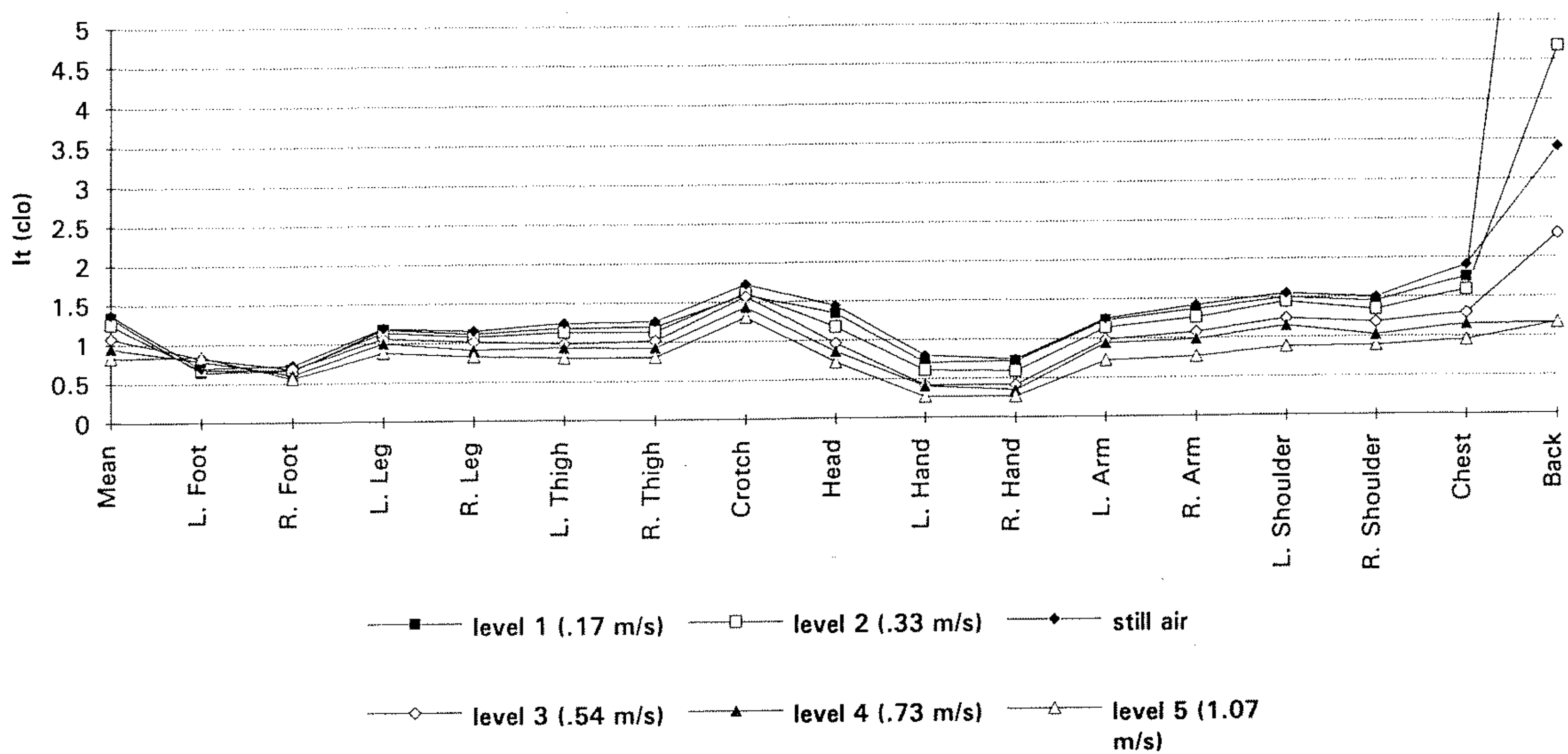


Table 3. Effect of air movement from front on the total insulation values (It) of different manikin parts

Body Part	Mean	L. Foot	R. Foot	L. Leg	R. Leg	L. Thigh	R. Thigh	Crotch	Head	L. Hand	R. Hand
still air	1.37	0.70	0.73	1.19	1.15	1.24	1.26	1.72	1.44	0.80	0.74
0.17 m/s	1.34	0.65	0.66	1.17	1.11	1.18	1.19	1.59	1.34	0.71	0.72
0.33 m/s	1.25	0.68	0.67	1.13	1.07	1.13	1.13	1.61	1.17	0.61	0.59
0.54 m/s	1.08	0.83	0.68	1.06	1.02	0.99	1.02	1.57	0.96	0.42	0.42
0.73 m/s	0.95	0.79	0.61	1.00	0.91	0.93	0.92	1.43	0.86	0.40	0.35
1.07 m/s	0.82	0.85	0.56	0.88	0.82	0.81	0.80	1.31	0.72	0.27	0.27

Body Part	L. Arm	R. Arm	L. Shoulder	R. Shoulder	Chest	Back
still air	1.25	1.41	1.56	1.50	1.91	3.40
0.17 m/s	1.23	1.37	1.50	1.44	1.76	11.11
0.33 m/s	1.13	1.26	1.45	1.34	1.59	4.68
0.54 m/s	0.99	1.07	1.23	1.18	1.30	2.30
0.73 m/s	0.94	0.99	1.14	1.02	1.15	1.16
1.07 m/s	0.72	0.77	0.88	0.89	0.95	1.17

Appendix D.2.

Chamber Tests of the Thermal Manikin Tests in Support of Computer Comfort Modeling

The manikin was tested in the controlled environment chamber in seated position on five different chairs. Three typical clothing ensembles were tested, in addition to nude. The manikin was also tested for the same clothing ensembles (including nude) in standing position. The tests were made in order to obtain typical clothing- and chair insulation values for use in computer comfort modeling.

A heavy clothing ensemble (#2, with 0.92 clo) was selected to represent winter clothing. A moderate clothing ensemble (#1, with 0.66 clo) was selected for transition seasons, and a lightweight ensemble (#3, with 0.55 clo) for summer. Chair types ranged from the types people use for doing paperwork at a table, to the sofa-like armchairs people like for watching television. A metal wide-mesh chair was used to determine clothing insulation values of the manikin in sitting position but without the insulation of the chair. A description of the three clothing ensembles and the five chairs is given in Table 1.

Table 2 shows the results of the tests. From the table we can see that when the chair changed from metal mesh to the soft-surfaced computer chair, the total insulation values (It) increased. The chair's effect on the total clothing insulation value changes with the insulation of the clothing ensemble. The chair's insulation effect is therefore not a constant value. When clothing insulation value increases, the insulating effect of the chair decreases. We can see from Table 3 that the differences in total insulation of the metal mesh and the computer chairs decreased from 0.15 clo for lightweight ensemble #3 to 0.07 clo for heavy ensemble #2.

From Table 2 we can get the results that with clothing ensemble #3, the padded swivel chair insulation is 0.23 clo and the sofa-like armchair is 0.38 clo. These values are higher than those of the computer chair and wood chair because the contact area between manikin and chair is greater for the more padded chairs. For all of the soft chairs, the insulation value provided by the thickness of the seat is relatively insignificant.

For the thicker clothings ensembles, the wood chair and metal mesh chair produced virtually identical total clothing insulation values. This is probably because the contact area between the hard manikin and the hard seat is very small. A real person would conform more to the wood seat and have greater contact area with its insulating surface.

Table 1: Description of clothing ensembles and chairs

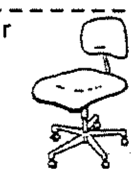
Clothing ensembles		
clothing ensemble #1	(1). bra + underwear (2). turtle neck shirt + lightweight sweater (3). pants (4). shoes without socks	
clothing ensemble #2	(1). bra + underwear (2). long sleeved silk shirt + heavy suit (3). heavy dress (4). shoes with long socks	
clothing ensemble #3	(1). bra + underwear (2). long sleeved shirt (3). pants (4). shoes with thin cotton socks	
Chair types		
mesh chair:	metal wide-mesh chair	
wood chair:	regular wood chair	
computer chair:	fiber cloth, soft surfaced chair	
padded chair:	padded swivel chair	
sofa chair:	sofa-like chair	

Table 2. Clothing insulation values for three different clothing ensembles and nude, five different chairs, sitting and standing

	Nude	Clothing ensemble #1		Clothing ensemble #2		Clothing ensemble #3	
	Ia (clo)	It (clo)	Icl (clo)	It (clo)	Icl (clo)	It (clo)	Icl (clo)
Standing	0.74131	1.34086	0.73	1.52311	0.95	1.328	
computer chair	0.86503	1.45521	0.75	1.63273	0.96		
wood chair	0.84823	1.34151	0.63	1.55589	0.89		
mesh chair	0.81938	1.34314	0.66	1.56168	0.92	1.22	0.55
padded chair						1.45	
sofa chair						1.6	

Table 3. Computer chair insulation changes with different clothing insulation values

	Icl (clo)	Ichair (clo)
clothing ensemble #3	0.55	0.15
clothing ensemble #1	0.66	0.11
clothing ensemble #2	0.92	0.07

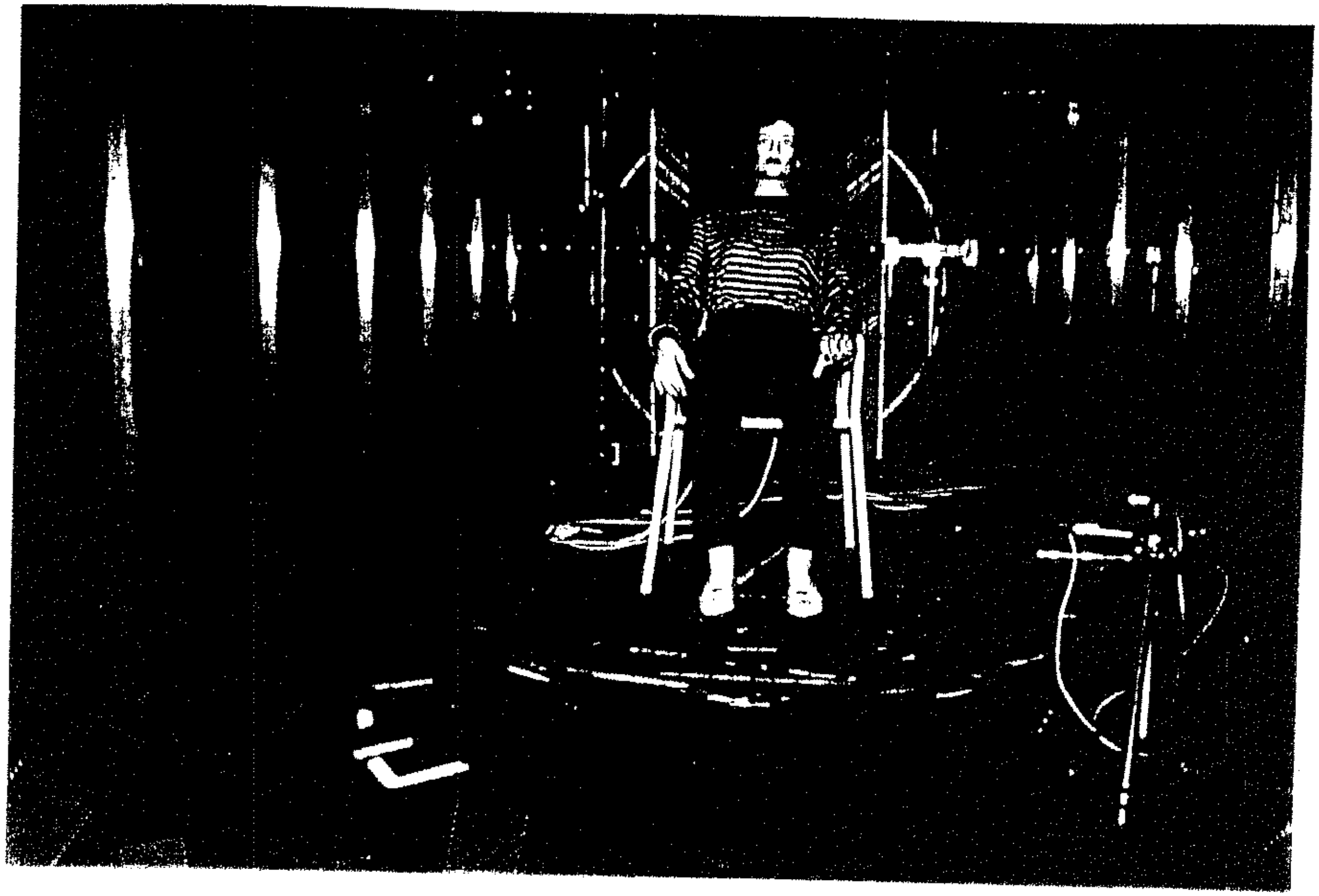


Photo 1

APPENDIX E

Indoor Humidity and Human Health: An Assessment of Health Implications of Direct Evaporative Cooling

by

Edward Arens, Anne Baughman, and Alison Kwok

INDOOR HUMIDITY AND HUMAN HEALTH:

AN ASSESSMENT OF HEALTH IMPLICATIONS OF DIRECT EVAPORATIVE COOLING

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INTRODUCTION

Standards for indoor thermal conditions and for ventilation have traditionally put limits on the amount of humidity permissable in interior spaces. Such limits are found in past versions of ASHRAE Standard 55 (Indoor Environments for Human Occupancy), Standard 62 (Ventilation for Acceptable Indoor Air Quality), and in most international standards. The values set for the limits have typically ranged between 60 and 80% relative humidity, although boundaries of absolute humidity have also been used. Although the reasons for the limits are often not explicitly stated, it is known that they were primarily set out of concern for the health effects that might occur should the humidity become too high.

Human health is not affected by high levels of humidity *per se*. Known health effects are primarily caused by the growth of biotic agents under elevated humidities, although humidity interaction with nonbiotic pollutants may also cause adverse effects. As best one can determine, existing limits have been set based on engineering experience with such humidity problems in buildings.

The position of any upper humidity limit has very large economic significance in hot-arid parts of the country where evaporative cooling is an energy-conserving option. It affects the need for billions of dollars of new peak electrical generating capacity that could be offset by non-compressor-based cooling. Such limits also have a direct effect on the viability of the evaporative cooling industry. 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.

A 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. The biological agents require appropriate conditions in the building for their germination, growth, release to the air, and transport to the human host. The non-biological agents are to varying extents influenced by humidity. Finally, the host's 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.

Humidity/health effects may be categorized as:

- Reactions to biological growth
  Dust mite allergies
  Fungus: allergens, pathogens, and volatile organic compounds (VOCs)

- Airborne spread of disease
  Viruses (common cold, flu)
  Bacteria (Streptococcus, Tuberculosis, Legionella)

- Interaction with air pollutants
  Off-gassing of formaldehyde from manufactured organic building materials
  Indoor ozone concentrations
  Acids produced from NO_x and SO_x

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, molds 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. Even if the surface humidity 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. The exposure of the surface to moisture may be intermittent, either seasonally or daily due to the operation of the building's mechanical system. 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 the case in the literature. *In vitro* 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 very building-specific, and are risky to generalize.

Broadly generalized biotic standards necessarily become very restrictive, in order to include all classes of problem cases. 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.

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

- hot-dry climates where thermal flows through the building envelope are inward and water vapor flows outward.
- hot-humid climates with interior cooling and/or dehumidification
- hot-humid climates without cooling or dehumidification
- cold climates where thermal 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: temperature, hygroscopicity, air movement
- water in cooling and humidification systems
- intermittency of operation in cooling systems
- moisture sources unrelated to the humidity in the interior air: 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.

SCOPE OF PAPER

The paper consists of the following:

- A review of the literature on humidity-influenced health agents, their propagation requirements, and the nature of their distribution to the occupants.
- A discussion of buildings and their mechanical systems, typical locations where humidity-related health factors develop, and types of operating conditions that cause health problems.
- Conclusions and recommendations about the: humidity/health implications for evaporative cooling of buildings in a hot-arid climate, and issues for consideration in the future development of indoor environmental standards for humidity.

The following two topics are not addressed in this paper:

- There is a substantial literature on the effects of *low* humidity on health, and that these effects (susceptibility to infection and irritation due to drying and cracking of mucous membranes, longevity of viruses and some bacteria, ..) are different from the high humidity effects. Low humidity health effects are probably better understood and accepted than the high humidity effects. In addition, there is an agreed-upon discomfort associated with excessively dry air, so a lower humidity limit appears in virtually all standards for comfort and indoor air quality. This aspect of humidity and health is not addressed in this paper, since we are looking at the upper limits permissable under summertime evaporative cooling.

- It should also be noted that there are two types of *comfort* effects related to high humidity, neither of which are addressed in this paper. The first type is *thermal* in that increasing atmospheric humidity reduces the body's ability to dissipate its heat through evaporation. This thermal comfort effect can be seen in the slope of the right-hand border of the comfort zone when plotted on a psychrometric chart. All points along this sloping border have equal heat dissipation potential and therefore give the same thermal sensation. The factual basis for these thermal comfort effects are pretty well established, and do not significantly affect the effectiveness of direct evaporative cooling as a way of providing comfort. The second type is *non-thermal*, in that the comfort effects are not caused by the body's inability to reject heat, but rather by some other sensation on the skin or in the nose. This type of discomfort could be used to prescribe the upper border of the comfort zone as plotted on the psychrometric chart, and is very important to the potential effectiveness of direct evaporative cooling. However, these effects are not well understood or agreed upon. Posited causes are: psychological sensations described as 'sultriness' or 'oppressiveness', mechanical effects of fabric drag across the skin, actual skin wettedness due to an adsorption phenomenon on the skin, and perception of worsened air quality in humid environments, whether or not there is an air quality problem. Data on these effects are sparse and the results contradictory.

The subject of humidity's influence on non-thermal comfort will be addressed in a subsequent review scheduled for 1994.

LITERATURE REVIEW: HEALTH EFFECTS OF HUMIDITY-INFLUENCED INDOOR POLLUTANTS

OVERVIEW

The primary influences of humidity on health are through *biological* pollutants. Such pollutants can be divided into two broad categories; pathogens and allergens. *Pathogens* are viable organisms that colonize the body and cause infectious disease. Most bacteria and viruses fall under the category of pathogens. In this case the species enters the body through the airway and colonizes in susceptible individuals, resulting in respiratory infection. Most pathogens are transmitted from person to person through aerosols formed when sneezing/coughing or from skin emanations (we shed about seven million particles per minute and each of these carries with it an average of four microbial cells (Binnie, 1989)). However some pathogens can form and spread within air conditioning systems, such as the bacterium, Legionella, which has been found in various building water systems such as cooling tower sump water and hot water heater storage units.

Allergens, on the other hand, cause an immune-system response in the skin or respiratory tract. The most common allergens associated with the indoor environment include dust mites, pollen, fungi, algae and insect emanations. Sensitization to an allergen can occur upon exposure to high levels of antigens, which provoke the formation of antibodies in an affected person. Re-exposure to the antigen can then trigger a larger immune reaction resulting in allergic symptoms. The allergic diseases which have well documented associations with indoor air quality include allergic rhinitis, which primarily effects the nasal area; allergic asthma and allergic bronchopulmonary aspergillosis (ABPA), which effect the lower airways and alveoli; and extrinsic allergic alveolitis, better known as hypersensitivity pneumonitis, farmer's lung or humidifier fever, which results from repeated exposures and can lead to recurrent flu-like symptoms. Rhintitis, asthma and ABPA are caused by reactions of antigens with a specific antibody (type IgE), and affect only those people with a genetic tendency to produce the IgE antibody. It is estimated that approximately 20% of the American population has the genetic tendency to produce the IgE antibody (Burge 1988) and it is estimated that 4% and 8% of the general population within the US is inflicted with asthma and rhintitis respectively (Goddish, 1989; Anderson and Korsgaard 1986). Extrinsic allergic alveolitis seems to be unrelated to IgE, but reflects other antibody-dependent mechanisms as well as cellular immune responses. Although there seems to be no genetic predisposition for this to develop, only a fraction of those at risk developed overt symptoms (Burge, 1988). In addition to allergens fungi also produce *VOC's* which have been implicated as a contributor to sick building type symptoms in microbially contaminated buildings.

Non-biological pollutants are the less-understood health hazard in buildings, both in terms of their prevalence and their health effects. Low levels of formaldehyde, ozone, oxides of nitrogen, and oxides of sulfur affect humans primarily through chemical irritation of the mucous membranes. Formaldehyde is released into the indoor air from building materials in ways dependent on atmospheric humidity. The irritation to the body from formaldehyde and NOx and SOx may be a function of humidity. Finally, the amount of ozone and NOx and SOx brought into houses from polluted outdoor environments depends on the rate of air exchange, which for direct evaporative coolers is much higher than for air conditioners.

DUST MITES

Introduction

Mites are considered to be one of the most important allergens in house dust, particularly in regions with high indoor humidities and moderate climates. The actual allergen is not the mites themselves, which are about 1/3 mm long, but dried fragments of their body parts and fecal excreta, which are about 10 -50 um in diameter but can break down into smaller fragments. One study found that more than half of the weight of mite allergens within a home were less than 5 um in length (Reed and Swanson, 1986). These smaller fragments become airborne when dust is disturbed and subsequently inhaled into the lower airways. Allergic reactions to mite allergens can then occur as a result of the formation of IgE antibodies for that portion of the population which are susceptible to IgE formation. 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; Murray et. al. 1985; Platts-Mills, 1989; Smith et. al. 1985). In most of these studies the patients were referred to the researchers by clinics and compared to control subjects randomly selected from the same or similar population base. Sensitization to mite allergens was demonstrated by a positive a skin prick test. In the study by Korsgaard, significantly higher concentrations dust mites were found in the homes of 25 and asthmatic patients compared to the 75 randomly selected homes (Korsgaard, 1983). Based on this study Korsgaard described sensitization as an important factor and estimated that about 60% of all cases of newly diagnosed cases of mite-sensitive asthma are due to heavy exposure to dust mites. A British Columbian study of the homes of 774 children with respiratory symptoms found that over 90% of these children lived in areas defined as "humid" (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 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) (Murray et. al., 1985). A five year study of 252 homes of dust-mite sensitive people in eight different regions of the US found that 83% of the homes had average mite densities greater than 100 mites/gm of dust, considered to be the threshold for sensitivity (Arlian, Bernstein et. al. 1992). However, one study of 30 homes in Oxfordshire, England detected no significant difference in the number of mites found in the homes of atopic and non-atopic participants (Hart and Whitehead, 1990).

High levels of dust mite allergens have also been correlated with atopic dermatitis (Korsgaard 1989, 1990). 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.

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 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.* A study of mite populations in eight different geographic regions of the US found that *D. pteronyssinus* and *D. farinae* were by far the most common species and that *D. pteronyssinus* tends to predominate in humid regions with moderate climates, while *D. farinae* is usually the predominate species in areas that have prolonged periods of dry weather (Arlian, Bernstein et. al. 1992). A study by Lang and Mulla of mite populations in four different climate zones of southern California found significant numbers of *D. pteronyssinus* and *D. farinae* in 14/15 coastal homes and 9/15 of the inland valley homes, with *D. pteronyssinus* dominating in the coastal region and *D. farinae* dominating in the inland regions (Lang and Mulla 1977).

Mites are relatively sparse in regions of low outdoor humidity, such as at high elevations and in the California desert (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 from direct evaporative cooling, the populations, particularly *D. farinae*, can become significant even with low outdoor humidities. A study of 190 evaporatively cooled homes in Tucson, AZ, detected mites within more than half of the homes, with *D. farinae* being overwhelmingly predominant species (greater than 98% of all mites recovered) (O'Rourke, 1993).

Environmental Requirements

Mites contain about 70 -75% water by weight and must maintain this in order to reproduce (Arlian, 1992). They do not imbibe liquid water but rather extract water vapor directly from unsaturated air (Arlian, 1992). Laboratory studies have found that optimal conditions for growth at 25-30°C are 70-80% RH for *D. pteronyssinus* and 50 - 60% RH for *D. farinae* (Lang and Mulla, 1978; Murray et. al. 1985). with population growth not occurring at 60% RH or below for *D pteronyssinus* (Lang and Mulla, 1978). Under optimal conditions mites live for three months, with the first month in three larval stages and ten adult mites can create almost 600 mites in six weeks (Brundrett, 1990). Active mites of either species cannot survive longer than 4-11 days at humidities below 50% RH at 25°C (Arlian 1982). However one of the dormant larval forms (protonymph) can survive for months at lower humidities and then evolve to the more active forms when optimal conditions return. These protonymphs tend to bury themselves within surfaces and are difficult to remove with normal vacuuming (Arlian, 1992). One field study which analyzed for the different stages of mite development found a higher number of protonymphs in one home when RH fell below critical levels (Lang and Mulla 1978). Most of the allergens are formed by adult mites during the active phase and thus the highest levels of allergens found in the environment usually correspond to the optimal humidity conditions

Laboratory studies indicate that mites are able to survive extreme temperature conditions for limited periods and that temperatures within the comfort range have little effect on their growth rate. Under laboratory conditions over half of *D pteronyssinus* survived for 12 days when continuously exposed to 34° C and 75% RH and 64% of *D. farinae* adults survived 72 hours at 2°C and 75% RH (Lang and Mulla, 1977). According to another study, mites are able to reproduce at 17°C, albeit more slowly than at 25°C (Murray and Zuk, 1979).

Mites subsist primarily on human and animal skin scales. It is believed that fungi of the genus Aspergillus are needed to dissolve lipids within the skin scales since they cannot be readily digested by mites (Flannigan, 1992; Hart and Whitehead, 1990). Consequently, conditions for mite survival may also need to be suitable for 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. 1987). However the overwhelming evidence from laboratory studies and field work suggest that relative humidity is the controlling factor. Mites have a high surface to volume ratio and are poikilothermal, that is their body temperature is identical to that of the surrounding environment (Anderson and Korsgaard, 1986). Thus 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 and not the absolute humidity. Arlian (1992) has demonstrated that the driving force for the uptake of water from the unsaturated air is the number of water molecules impinging on the mite's uptake surface. Arlian also performed laboratory studies which suggested that mites were able to maintain a water balance at 20°C and 79% RH, but died at 27°C and 56% RH (i.e. the same absolute relative humidity).

Field studies: Residential

Field studies within homes generally support the laboratory findings that indoor relative humidity is the most significant factor associated with high mite populations and mite allergen concentrations, and that temperature and outdoor humidity are not significant factors. In most of these studies live mite populations have tended to peak at humidities above 50% RH (Murray and Zuk, 1979; Smith et. al., 1985). For example, in the study by Murray and Zuk of homes in Vancouver, they found significant association between indoor RH and the presence of live mites, with the detection of mites occurring only when the RH was > 50% for at least part of every day during the month of collection. A direct correlation between mite population and RH was also found in the study by Smith of 20 homes of mite-sensitive children found, with mite populations peaking at RH of 50% or greater. A of 30 homes in the UK found that mite populations were most strongly correlated with indoor relative humidity and that bedrooms with humidities above 64% contained significantly more mites in mattresses than those with lower humidities (Hart and Whitehead 1990). In the study by O'Rourke (1993) suggests that humidities of 40% or greater were significantly associated with elevated mite levels. However, as with most of the other studies, this study does not indicate the time frame that this RH applies to (i.e. was the RH measured instantaneously at the time of sampling or was it averaged over some period of time?).

In some studies, samples from different homes within the same region and the same season exhibited wide differences in the concentration of house dust mites due to differences in indoor relative humidity. For example, in a recent study of 424 homes across the US, mites were detected in all climatic regions, with the greatest differences in mite population due to differences in the microenvironments between homes rather than regional climatic differences (Lintner and Brame, 1993). A four season study of 50 Danish apartments, all within the same region, found that the seasonal variation in dust mite populations in mattresses correlated with the indoor humidity and that some homes did not contain detectable levels of mite populations due to lower indoor humidities (Korsgaard, 1983).

Long-term studies have found seasonal trends that correlate with seasonal differences in indoor humidity. For example, a nineteen-month study of six homes in southern California showed a seasonal variation between species, with *D pteronyssinus* populations highest in July-Nov. and *D. farinae* more abundant Aug.-Dec. Both species were found to be less prevalent from late spring to July (Lang and Mulla 1978). In this study the monthly fluctuations correlated with indoor relative humidity, although the population increases showed a lag time of 1-2 months after conditions became favorable, while population declines correlated directly to decreases in RH to levels below the critical values for each species. A two-year study of 19 homes in Ohio also found a significant seasonal fluctuation, with highest densities of mites occurring during the humid summer months and lowest densities occurring during the dryer late heating season (Arlian et. al. 1982). One study by Korsgaard found that apartments which had a low absolute indoor humidity in the winter did not contain noticeable concentrations of mites in the summer and autumn despite the fact that the humidity conditions were high enough to allow for peak populations, indicated that in this case even the protonymph had not been able to survive through the dry winter months (Korsgaard, 1983)

Field studies have also analyzed for specific mite allergens and found that seasonal increases and decreases in allergen levels tend to lag behind changes in RH. A one-year study of 12 homes in central Virginia found mite populations and allergen levels lagging about one month behind increases in indoor humidity. However, while mite population decreased in parallel with falls in humidity, several months passed before a fall in allergen levels was detected (Platts-Mills, Hayden et. al. 1987). In the by Lintner and Brame (1993) of 424 homes across the US a distinct seasonal fluctuation of mite allergens was evident from both *D. pteronyssinus* and *D. farinae* species, with the *D. pteronyssinus* allergen peaking in July and the *D. farinae* allergen peaking in September.

Field studies suggest that the highest number of mites are most often found in mattresses, thick carpeting, and heavily used fabric-upholstered furniture. In a study by Arlian et. al.(1992), 77.5% of the samples showed the highest mite densities within the carpeted floor beside the bed, a heavily used family room couch/chair or within the carpeted family room floor, with the remaining samples showing the highest densities in the mattresses. Field studies also indicate that there tends to be less variation in mite population within bedding compared to other sites (Smith et. al., 1985; Murray and Zuk, 1979). In the study by Murray and Zuk, small numbers of mites were found in mattress dust in the winter even though RH fell below 50%. These higher counts in mattresses during the drier season may be explained by a temporary localized increase in humidity due to the moisture given off by the sleeper. Carpeting may also be a local site of increased humidity. Arlian (1992) studied the microenvironment of a carpeted floor and found that the relative humidity in carpeting was 9.6% higher than the ambient air 1-2 meters above the floor. This was attributed to the decreased temperature of the floor, which was 3.7°C (on average) lower than the ambient air. This study also found that long-pile carpeting contained significantly more mites than short pile carpets and tile or wooden floors (short-pile carpets did not contain significantly more mites than floors without carpets), which is in agreement with the study by O'Rourke (1993).

Field Studies: Office Buildings

Although carpets and fabric upholstered furniture are common features in offices there have been few studies in offices as well other non-residential buildings. The few studies of mite populations that have been conducted within commercial buildings have shown that the mite levels are generally low (Friedman, 1992). This may be expected since offices tend to be less humid than residences since many of these buildings use air conditioning; there are fewer internal sources of moisture (i.e. cooking, showering, etc.); and thick carpeting is not as common. It has also been suggested that mites tend to be more common on ground floors than upper stories and are rare in hotels for example (Reed and Swanson, 1986). However, one study of five office buildings in the mid-Atlantic region, did find moderate to high levels of mite allergens in the carpeting and chairs within one of the buildings (Hung et. al. 1991).

Remediation

The strong correlation between indoor relative humidity and dust mite population has led to recommendations to reduce indoor humidity to maintain levels below 50% RH. Some studies have indicated that remediation procedures such as high efficiency vacuuming or removal of carpets and covering mattresses with impermeable material may be useful in controlling mite populations . According to Platts-Mills, tenfold or greater reduction in mite-allergen levels can be achieved in many houses by using remedial methods, including hot washing all bedding at least every 10 days, and removing carpets and upholstered furniture (Platts-Mills, 1989). A few studies indicate that some of these remedial methods are not useful in removing mites, particularly vacuuming alone, since larval forms of mites stick to surfaces and are difficult to remove (Arlian 1992). A two year study of mites in 19 homes in Ohio found no significant correlation between the number of mite abundance and the frequency or thoroughness of cleaning, amount of dust, or age of furnishings or dwelling (Arlian et. al., 1982).

The use of electric blankets has shown to be successful in reducing mite populations in bedding by reducing local humidity (Hart and Whitehead, 1990). The use of air conditioning has also been associated with reduced mite allergen levels (Lintner and Brame, 1993). Humidification on the other hand may have a significant impact on mite abundance. For example one study found an average of 703 mites per gram of dust in six humidified homes compared to 197/gm dust in nine houses without humidification (Arundel et. al. 1992). Various acaricides have also been shown to be useful in reducing mite levels, including a fungicide that affects the fungus digesting lipids in the skin scales (Platts-Mills, 1987). Research is now under way on a promising new treatment using sulfated polyborate, which is being used commercially to reduce flees in carpeting and is not toxic to humans. This salt acts to desicate larval and adult fleas in the carpet and may be effective on mites as well (Fagan, 1993).

FUNGI

Introduction

Mold and mildew are common terms for used for fungi that colonize on building interiors under moist conditions. They may produce a characteristic musty odor and cause stains or damage to building furnishings and surface materials. Adverse health effects, such as allergic reactions, hypersensitivity pneumonitis and mycotoxicosis, can also occur when the spores, fragments of hyphal mat or mycelium, and metabolic byproducts of fungi become airborne. In general, less people are allergic to fungus than dust mites and animal dander. Flannigan (1991) cites a study by Beaumont in which many more respiratory patients with suspected allergy reacted to animal dander (34%) and house dust (44%) than to molds (3.4%)(Flannigan, 1991). However, allergic reactions are not the only concern. Some fungi, such as Aspergillus niger and A. fumigatus are both pathogenic and allergic and may infect the lungs, ears or eyes (Gravesen, 1979; Flannigan, 1992). In addition, metabolic gases produced by fungi contain volatile organic compounds (VOC's), which are responsible for the odor and have been implicated as a contributing factor for sick building type symptoms. A study of microbially contaminated buildings found that VOC's of the type commonly associated with indoor manmade materials were actually the metabolic by-products of the fungi growing in the buildings (Bayer and Crow, 1993). In this study, the gases produced by the fungi were analyzed by collecting samples from the building and incubating them within a laboratory at room temperature for 2-3 days. In a study of buildings with significant fungal growth, Morey (1988) found a high prevalence of symptoms associated with high levels of VOC's (i.e. headaches, nausea, etc.). Many studies have found an association between moldy buildings and adverse health effects; however, whether the specific causative agents are the airborne spores, their components microbial volatiles or mycotoxins has not been resolved.

Most fungi are saprophytic and originate outdoors, growing on a substrate of dead or dying plant and animal matter. The spores are 3 to 30 μm in diameter, are released in great numbers, and can travel suspended intercontinental distances. Airborne spores migrate indoors with ventilation air and set up colonies on surfaces where moisture and nutrient conditions are favorable. The fungi normally occurring in indoor air are most of the genera *Penicillium, Cladosporium, Alternaria, Aspergillus, Epicoccum* and *Aureobasidium* many of which originate from plants or soil (Nevalainen, 1993). Indoor concentrations are typically one fifth of those outdoors and range from 10 to 10,000 colony forming units (cfu) per cubic meter of air. Outdoor concentrations vary with the season, the time of day, local weather conditions, and whether the site is rural or urban. *Cladosporium* and *Alternaria* are the most common fungi found on decaying vegetation and show a strong seasonal activity, peaking in the summer. *Penicillium* and *Aspergillus* are soil fungi, more commonly found in urban environments, and remain relatively constant throughout the year. Once fungi have established themselves in a niche within a building they are often resistant and difficult to eradicate. Even under dry conditions spores are environmentally robust and can remain dormant and viable for years (Brundrett, 1990).

Fungal growth is a prevalent problem in indoor environments. It has been estimated that 10-30% of commercial buildings are significantly contaminated by fungal spores. Studies carried out by the Healthy Buildings International (HBI) found that in over one third on the more than 400 buildings studies, the major pollutants included allergenic fungi, and in greater than two thirds, air supply systems were contaminated with dust, dirt and microbes (Binnie, 1989). The distribution of fungal species is an important indication of whether a building is contaminated by fungi. Studies by Miller of contaminated buildings found that such buildings had a distinct distribution of microbial species and that counts of total colony forming units alone were not sufficient to detect contamination (Miller, 1992).

Environmental Requirements

Fungi need carbon, nitrogen, sulfur, phosphorous, and water for their growth, as well as minute amounts of other nutrients. Typical construction materials that provide nutrients used by fungi include wood, cellulose, wallpaper, organic insulation materials, textiles (especially natural fibers) and glues, paints and motors that contain carbohydrates or proteins. Materials such as metal, concrete, plastics and other synthetic products cannot be used directly by fungi, however, these materials may collect organic debris on them which can then be used by fungi. One example of this is the frequent observation of growth on fiberglass duct lining (Morey, 1988).

Fungi acquire most of their nutrients through a solvent process and therefore require relatively high moisture levels for growth (Griffin, 1981). Since there is an abundance of available nutrients within buildings and always some fungal spores in the indoor air, the limiting factor for growth is usually moisture. Systems containing water such as water reservoirs of a humidifier favor growth of bacteria, algae, protozoa and certain types of fungi, especially yeasts. However, most fungi prefer the surfaces of moist materials instead of liquid water.

It is the moisture within the substrate that is the important factor rather the moisture of the ambient air. Temperature is not a limiting factor within the temperature range found in most buildings. Pasanen et al (1991) measured colony diameters on agar for both *Penicillium* sp. and *Aspergillus fumigatus* as a function of RH in the range of 11% to 92% with an incubation time of 15 days and found that fungal colonies can grow on wet substrates at even at low levels of atmospheric humidity. Their conclusion is that growth is dependent on surface moisture and independent of atmospheric moisture. They also found that both molds grew at all temperatures from 10 to 30°C, with *Aspergillus* growing fastest at 30°C and *Penicillium* fastest around 20°C.

The ability to grow on a substrate has often been attributed to moisture content (MC), which is equal to the ratio of free water in the material to the material's dry weight. Free water is defined as the water held in a porous material by Van der Waals bonds or capillary attraction, as opposed to water of hydration that is chemically bound to the materials. It is measured determining the weight of water lost when dried in an oven at 70°C or more. Block (1953) found in a study of a limited number of materials a common mold-growth-threshold value of MC = 0.1 that has been often quoted and used in the literature. Recently, Foarde et. al. (1993) found a critical MC of 0.055 to 0.065 for Penicillium growing in ceiling tiles. However, moisture content may not be the most appropriate measure of a substrate's potential to support fungus, because materials differ in how tightly they hold their free water. The availability of free water to mold hyphae can therefore be quite different for materials with equal MC. It has been shown that for biological purposes the more physically meaningful parameter is the ratio of the vapor pressure at the surface of the moist material to the vapor pressure of a pure liquid water surface. This in ratio form is termed the 'water activity' A_W, or in percent form the 'equivalent relative humidity' (ERH). (Griffin 1981, Flannigan, 1992). We will use the term ERH throughout the remainder of the paper.

Equilibrium Relative Humidity (ERH)

ERH can be visualized as RH if the atmosphere above a moist surface was confined to the extent that it had the same vapor pressure as the moist surface. Often there will be a gradient of vapor pressure from the surface into the air above. Then the relationship between EHR and RH is indirect.

Maximum growth for most fungi occurs at an equilibrium RH (ERH) of 95% to 100%, with theoretical limits for growth between 55% and 100% ERH. A few (xerotolerant) fungi can grow at ERH values as low as 65%.

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: (note Aw in this quote has been converted to ERH).

"Although all molds growing on surfaces in buildings grow most rapidly in pure culture at a high ERH...,...individual species can be classified as:

- Primary colonizers, which are able to grow at an ERH of less than 80% and also are referred to as xerophilic fungi because they are able to grow at lower ERH 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 ERH of 80-90%, e.g., *Cladosporium cladosporoides* and *C. sphaerospermum*

- Tertiary colonizers, which are only able to grow at an ERH more than 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* spp., at the less wet margins of the affected area. 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 ERH would be 96-98%. 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."

Growth of bacteria and yeast require ERH well above 90% and may breed in hyphal mats when large amounts of moisture are present. In dust, Flannigan detected increase of pseudomonas bacteria at high RH. However once the bacteria are present, survival in dust is higher at low humidities, dropping off relatively above 50% RH. Lidwell and Lowberry in 1950 found higher RH especially harmful to haemolytic streptococci and *Staphylococcus aureus* in dust (Flannigan 1992).

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

Remediation

Once a material has become contaminated with fungi it is almost impossible to completely rid it microbes and removal is usually the only alternative. A recent study of micribial growth in chipboard found that water-damage resulted in massinve growth and that even after drying the material still contained spores (Thogersen et.al., 1993). Use of biocides is discouraged, since most are toxic and continuous use may increase corrosion and encourage the development of resistant strains (Nevalainen, 1993) and bleach treatment has not been found to be is unsuccessful in cleaning contaminated dust liners (Morey, 1988).

Uttenbroek (date) suggested weekly average RH should not exceed 80% for flats in cold climates (even assuming that with some surfaces will be colder than air temperature). Hens (1990) also suggests 80% RH as the maximum limit, but in this case as the monthly mean. It is more often recommended that indoor humidity remain below 70% RH in order to avoid microbial growth (Morey, 1988; Miller, 1992; Nevalainen, 1993). Either way, the most frequent cause of indoor fungal contamination is usually a result of bad design, (leaks, exposed fiberglass insulation in ducts, glue in carpets, etc.) or poor preventive maintenance rather than high ambient humidity.

AIRBORNE SPREAD OF INFECTIOUS DISEASE

Human sources

Most viral and bacterial respiratory infections are transmitted between human hosts. This may occur either directly by touching an infected person (or animal) or with an object they have infected; or indirectly by inhalation of airborne contaminants expelled from the nose and mouth through sneezing, coughing and talking or from contaminants contained on flaked off skin. Most of these airborne droplets are large enough that they fall to the ground within about a meter. The smaller droplets quickly shrink through desiccation to form "droplet nuclei" between 0.5 and 5 um in diameter, which are small enough to remain suspended in the air for long periods of time (Laforce 1986). Droplets of this size are also small enough to penetrate deep into the lungs and if they contain viable organisms and are in sufficient numbers they will cause infection in susceptible hosts (Burge and Feeley 1991). Relative humidity can affect the desiccation process of the droplets which in turn affects droplet size and the viability of the airborne pathogens.

Although much work has been done in the area of aerosol science, there is little is understanding of the physical behavior of biological aerosols. At 80% RH or below, a 40 um diameter droplet of pure water will desiccate to a diameter of 10 um within 10 seconds, which is small enough to remain suspended in air (about the size of a fog droplet). According to Brundrett (1990), the effect that impurities within the droplet have on the desiccation process is insignificant at humidities of 70% or below. Thus if we assume that the organisms, which are relatively small (bacteria are typically about 1 um in diameter and viruses are on the order of 10 nm in diameter), also have little effect on the desiccation of droplets greater than 10 um, then even humidities as high as 70-80% RH should not have a significant effect in slowing the desiccation process and therefore would not inhibit the formation of droplet nuclei.

In vitro studies of the viability of airborne pathogens have indicated that effect of humidity varies from organism to organism, while the effect of temperature is not significant within the range of interest for conditioned environments. Some bacteria were found to have a window of relative humidity at which they died more quickly (Anderson et. al. 1968; Cox 1966, Brundrett 1990). E. coli strain jepp was found to have minimal viability in the range of 70 to 80% RH with viability increasing at RH values above and below this window (Cox 1966). Legionella pneumophila was found to have a minimal viability between 50 to 60% RH and at 30% RH (Hambleton et. al. 1983). Experiments on the bacterium pneumoccus showed a sharp decrease in viability in a narrow band at 50% RH with the aerosol in a broth resembling saliva (Brundrett 1990). A study of the survival of Streptococcus found that the change in viable count was insignificant for RH range of 0 to 92% (Flynn and Goldberg 1971). Field studies of airborne pathogen survival at high humidities are limited, however, studies at lower humidities indicate a higher rate of survival of airborne viruses at humidities below 30% (Green, 1985). In general for humidities above 50%

there is little evidence to suggest that one specific humidity level is better than any other in reducing the viability or number of suspended microorganisms.

Expelled droplets and skin flakes which settle out may survive in dust and transmit disease if re-entrained when surfaced 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). Also dust is less likely to become airborne at higher humidities. .

Although relative humidity clearly affects the disease agent there is no significant evidence to suggest a direct correlation between susceptibility to respiratory infection and humidity level (Burge and Feeley 1991). Studies have suggested a correlation between humidity and respiratory symptoms (Arundel and Sterling 1986; Strachan and Sanders 1989; Dales et. al 1991) however the relationship was no shown to be causative and source of disease is often not identified (Melia et. al. 1982). Also studies which use questionnaires to categorize homes as damp may be misleading since the perception of dampness may not necessarily correlate with high indoor relative humidity but may rather be an indication of surface dampness (Strachan and Sanders 1989).

Use of direct evaporative cooling may have an advantage in reducing the spread of infectious disease, in that since a high ventilation rate is required, any contaminants derived from an indoor source (other than the evaporative cooling system itself) would be diluted. 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).

Building Related Sources

Some biological contaminants are known to grow within conditioning systems, particularly systems which contain standing water, such as humidifiers and cooling towers. The most important example of such a contaminant is Legionella, one of relatively few environmental microbes that is pathogenic to humans. Legionnaires disease can lead to fatal pneumonia in susceptible hosts. Strains of Legionella have been isolated from a range of water bodies, particularly thermally polluted water such as in cooling towers and in natural ponds as well (Dennis 1990). It is commonly found in building drinking water, since it is less susceptible to the chlorine treatment intended to control coliform bacteria. Outbreaks of legionnaires disease are tied to injection of contaminated water droplets into the supply air stream. Control is primarily through keeping droplets from being formed. Examples are keeping cooling towers well away from air inlets, and avoiding standing water in the building duct system.

Hypersensitivity pneumontis, a disease characterized by reoccurring respiratory symptoms and fever, similar to pneumonia, has been directly associated with microorganisms growing in humidification systems, particularly cool-mist vaporizers (Hodges et. al. 1974). It tends to disappear when the individual is removed from the environment containing the offending antigen (LaForce 1986). Also, outbreaks of bacterial infections in hospitals and flare-ups of asthma have been associated with humidification systems (Covelli et. al. 1973; Airoldi and Litsky 1972; Smith and Massanari 1977; Solomon 1974) In all these cases the offending humidifiers have been of the spray or mist types that form aerosols in the airstream. No references to difficulties with steam humidification were found.

NON-BIOLOGICAL AIR POLLUTANTS

Formaldehyde

Formaldehyde is found in urea-formaldehyde foam insulation and in numerous other building materials such as plywood, paper and other wood products, furnishings, carpets and textiles. Most of these materials may also emit a wide range of other volatile organic compounds (VOC's). Formaldehyde's adverse health effects are due primary to its great affinity for water and its protein-denaturing property. The most significant effect of low level exposure is irritation of the mucus membranes in the nose and upper airways, which may occur at concentrations higher than 2-3 mg/m3. The long term effects of low level exposure are not known. WHO (World Health Organization) has set a maximum guideline of 0.1 mg/m3 to ensure sufficiently low formaldehyde concentrations in indoor air (Puhakka, 1993).

Since the 1970's concern for this pollutant has led to emission standards and products with significantly lower rates of formaldehyde off-gassing in North America and Europe. However these rates are usually based on a single average conditions and the effects of variable temperature, humidity and air exchange rate and aging have not been factored in. Laboratory and field studies have shown that all these factors may significantly effect the rate of formaldehyde off-gassing. Humidity has a significant effect, particularly on wood products, and tends to increase formaldehyde emissions since formaldehyde within binding resins is water soluble. Increased emissions occur due to both higher ambient humidities as well as the presence of water within the material itself, which may occur as a result of water damage. A study by Anderson et. al. (1975) of formaldehyde off-gassing from chipboard within a controlled chamber 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 referred to by Arundel et. al. (1992) of twenty homes, a significant correlation was found between the indoor relative humidity and the formaldehyde concentration in the air (Arundel et. al., 1992). Puhakka and Karkkainen (1993) studied 46 apartments in Finland and found that the concentration of formaldehyde released from chipboard 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. Short term effects were also noted and it was found that short term variation of the relative humidity within a period of 1-5 hours, as occurred when using a sauna or drying cloths, also caused increases in formaldehyde levels. This study also examined off-gassing of chipboard within a chamber and found that sealing chipboard on all sides with "reactive paint" significantly reduced off-gassing rates. One chamber study found that for some non-wood based products, such as gypsum board, the relative humidity was inversely proportional to formaldehyde off-gassing rates, however, the off-gassing rate of gypboard was only found to be about 1/5 of that for plywood (van Netten et. al., 1989).

In terms of direct evaporative cooling the effect of higher humidities on off-gassing rates may be offset by the high ventilation rates which will tend to dilute formaldehyde, as well as any other pollutants that originate indoors. However this effect is not directly proportional to the ventilation rate since the off-gassing rate depends on the concentration of the gas in the surrounding air and will tend to increase with higher dilution rates. The study by Anderson et. al., (1975) examined the effect of air exchange rate and found that the formaldehyde concentration decreased non-linearly with increasing ventilation rates (Anderson et. al., 1975).

Ozone

Ozone is well-recognized as a respiratory irritant and a significant problem in southern California, urban areas where the EPA standard for outdoor ozone concentration is often exceeded. Once indoors ozone decomposes quickly through heterogeneous reaction with indoor surfaces (half-life within a typical bedroom of less than six minutes (Mueller et. al., 1973)). Thus during episodes of high outdoor ozone levels the public is advised to remain indoors and reduce indoor infiltration as much as possible (i.e. be closing windows). There are also some indoor sources of ozone such as copiers and air cleaning equipment; however, under normal living and working conditions these levels usually do not reach high enough levels to be of concern.

A controlled chamber study found that the rate of ozone decay increased dramatically as either temperature or humidity were increased (Mueller et. al., 1973). However, direct evaporative cooling is again a unique situation because of its high humidity levels combined with high ventilation rates, which tend to increase the ratio of indoor to outdoor pollutant levels. The impact of direct evaporative cooling vs. refrigerated air conditioning was studied by Stock and Venso in homes in El Paso and Houston (1993) and they found that the average indoor/outdoor ratio ozone concentration was much higher in homes with evaporative rather than refrigerated cooling (0.7 vs. 0.1). Activated carbon filters have been shown to be successful in significantly reducing ozone levels (Mueller et. el. 1973) and it may be possible that these could be incorporated in to 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.

Sulfur and Nitrogen oxides

As with ozone, nitrogen and sulfur oxides are produced primarily from outdoor sources. However, nitrogen dioxide along with nitrous and nitric acids can also form indoors as combustion byproducts of unvented gas cooking stoves and heaters. Nitrogen and sulfur oxides can react with water on indoor surfaces to form acid aerosols, which are generally found in higher concentrations indoors (Leaderer et. al , 1993). Although these are common pollutants, surprisingly little work has been done thus far in determining the respiratory toxicity of these acid aerosols. However their acidic nature, reactivity and aqueous solubility suggest that respiratory damage is possible (Brauer et. al., 1993). 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 NO2 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 NOx and SOx are high.

BUILDINGS AND THEIR SYSTEMS

INTRODUCTION

This section discusses the specific conditions in buildings that cause health effects. In examining the processes that affect biological growth and propagation, one should be able to determine the propensity of different types of buildings and systems to health problems, and to suggest solutions.

As discussed in the sections above, the primary health problems related to higher levels of humidity are associated with growth on surfaces (solid or liquid), or with aerosols produced by spray humidity systems. The interpersonal transfer of biotic agents through the occupied airspace is not as extensively determined by ambient humidity.

The surfaces that suffer mold growth differ among building types. West and Hansen (1989) state 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, fungal contamination and dust mites are more commonly found on carpeting and furnishings within the occupied space. 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.

It is common practice to link the biological growth to the relative humidity measured in the human occupied space. This is done for ease of measurement, but is misleading. For example, field studies have shown that mildew can form as low as 10% RH in some cases (Pasanen, 1991) whereas in others RH values as high as 95% have not produced biological activity. Clearly there are other factors at work producing these observations. The habitat of the biota is on or in the surfaces of the building, and is only indirectly influenced by atmospheric humidity beyond the surface boundary layer.

For molds, the key issue for growth occurring on surfaces is the equilibrium RH or water activity. This parameter is influenced by the following processes:

- Surface temperatures relative to adjacent air humidity
- Hygroscopic properties of the materials
- Air movement at surfaces.

Although dust mites are not directly dependent on the ERH of the substrate, the fungi that some mites are said to depend on for digesting skin scales are. The mites live within textiles of furnishings and carpets in microenvironments buffered from and quite different from the space environment. O'Rourke in her studies of houses in Tucson observed mites most common 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 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 will allow water to condense onto the surface from the air. For a given type of material, the amount of water eventually absorbed (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 hygroscopic sorption 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 effects of air films at the surfaces, whose resistance (for a given air speed) is fixed. Thus it is that if a wall's solid materials have low thermal resistance, the resistance of the interior air film (under still air) will be relatively high, and a substantial temperature drop may develop across this film when the wall is exposed to a temperature difference. The wall's surface temperature may be higher or lower than the interior air; when lower condensation may occur on the surface as described above. This may be the situation in cold climates where the thermal gradient across walls 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 is not going to occur when the thermal and vapor gradients are opposite, as is the case in direct-evaporatively cooled buildings.

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 such effects are common. Interior mold growth 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. So cold climate effects are possible even in the tropics when nocturnal radiative cooling is high.

Humidity problems also occur in cold climates when low ventilation rates are used for energy conservation, and when there is inadequte exhaust of internal humidity sources.

In the Pacific Northwest, Tsongas IAQ 91, found mean RH in winter in 44% of newer (?) and 56% in older houses, 30 and 50% experiencing humidity problems respectively. Condensation problems on surfaces of outside walls. Few of these buildings had moisture exhausts, and the spot check rh measurements may have missed cooking periods where 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 are not applicable for 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 RH recommendations but.most of the effects cited have to do with inward penetration, by diffusion and infiltration, of warm humid air into mechanically cooled rooms. A major problem is that the most impermeable layer in the wall construction is a commonly-used vinyl wallpaper, which 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. However, Banks offered as a fundamental engineering principle that when RH > 65%, materials can absorb enough moisture to sustain fungal growth.

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 economiser cycle operation. It also can occur when cold air duct systems are turned off nights and weekends, and warm moist air can migrate in and condense on the chilled surfaces. Substantial deterioration 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 of air that had not been dehumidified to the cool interior. The problems were alleviated by providing a continuous system and controlling interior humidity levels below 70%.

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 much 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 will not reduce the mass temperature below the subsequent day's dewpoint temperature unless a humid airmass has moved in outside or much moisture is generated indoors.

EQUIVALENT RELATIVE HUMIDITIES RELATED TO SORPTION ONTO SURFACES

Moisture absorption processes

The amount of moisture adsorbed or absorbed by a material depends on physical and chemical characteristics of the material. In general, water can be adsorbed to surfaces by chemical or physical bonds, or absorbed and held 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. (However there may be an exception here with dissolved salts that I need to get a handle on!) Water adsorbed 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) categorizes three types of building materials. These are:

- *nonporous media*, in which condensation of liquid water can only occur at the surface, and where condensed water is physically bound. Examples are smooth plastics, glass, glazed surfaces, sheet metal.
- *hygroscopic porous media*, which have very small pores (microcapillaries). These pores are capable of exerting a powerful attraction on atmospheric moisture both because of the large surface area they make available for physical bonding, and because once the 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. These media swell and shrink as water is gained or lost. Examples are wood, natural textile fibers, clay.

- *capillary-porous media,* in which pores are clearly recognizable 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 (presumably), and packings of sand.

As a material absorbs moisture, it fills from the finest microcapillaries to the largest pores. Wong describes that, for wood exposed to very low humidities below 20% RH, 'moisture is held in a monomolecular layer bonded tightly to the finest pores and interstices. Between 20 and 80% RH, moisture is more loosely bound in polymolecular layers. Because it is located in microcapillaries, the vapor pressure is depressed. The energy level is primarily the latent heat of condensation or evaporation. At relative humidities higher than 80%, moisture is present in the large capillaries and pores and is relatively free for water molecules to leave the surface.' Therefore, at higher RH values, hygroscopic media have less surface vapor pressure reduction, and come more into equilibrium with the vapor pressure in the room. Their ERH also moves toward unity, since the material once totally flooded would have the surface vapor pressure of a plane sheet of water.

Data on the requirements of ERH requirements of biological organisms are being developed as discussed above. It is not clear whether there is at this time much information on the relationship between ERH and RH 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.

Moisture absorption on walls and duct surfaces

Study of mold growth on surfaces for bakery design done by Coppock and Cookson (1951). Non-porous brick had more condensation occur than porous brick, and mold growth began 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 brick caused mold growth above 80% rh perhaps because of nutrients in this paint. A glossy painted wood grew nothing at all in range 70-95% rh. Recommendation: for control on all surfaces keep RH below 70%.

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.

Foarde et al (1992) inoculated acoustical ceiling tiles with *Penicillium aragonense* and exposed them to RH levels from 33 to 97% RH for a two week period. As long as the moisture content 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 become established (as after a single flooding), then it becomes hydrophilic. Quoting Burge (1987): "Fiberglass-lined ductwork cannot be ffectively 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%. The preventative mechanism was not discussed.

Similar effects on fleas obtained with sulfated polyborate. In this case attributed to desiccation of the flea in its various stages. The surface treatment is typically renewed yearly as the compound hydrates.

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 as if 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 encourage air movement to eliminate mildew on the clothes inside. If this is not done, mildew is know to occur. The occupied spaces in Hawaiian buildings tend to be open and mildew not common. However, Aberg in Angola attributed a number of mildew problems to poor cross ventilation in rooms. It was not clear however whether the air movement was to remove internally generated moisture or to desiccate the surface. In addition, his study buildings often had the room surface temperatures cooler than the indoor air due to intermittent air conditioning, in which case the role of air movement is unclear.

There is not much literature on this subject. 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* also 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 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, both molds and mites, which tend to be most populous in carpets and carpet backings. There may be a small advantage to roughness in that it tends to trap particulate pollutants. It is often noted that pollutant levels are relatively low until disturbed by cleaning efforts. As with the topic of air movement within buildings, there is not much 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.

WATER IN ENVIRONMENTAL CONDITIONING SYSTEMS

Humidifiers: steam vs spray

Low-temperature , 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). They are generally not recommended in the literature. Steam humidifiers are recommended because they do not form aerosols.

Evaporative coolers: solid medium versus spray

There is a limited number of 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 with relatively low air flow so that the water evaporates into the air without creating an aerosol, biological contaminants should theoretically not become airborne. This seems to be supported by field observations (O'Rourke 1993; Macher 1990). The sump water used to wet the pads of evaporative coolers in California, though filled with bacteria and fungal material, did not spread into the occupied space. This is apparently because evaporative cooler pads (unlike cooling towers),do not produce aerosols.

Industry guidelines for evaporative coolers that use 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 (Pat Thomas, personal communication). This 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 consensus at the Denver forum on evaporative cooling). It is unlikely in any case that such a system would be applied to residences.

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 infect 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 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.

VENTILATION AIR EXCHANGE: COMPARISON OF ONCE THROUGH VERSUS RECIRCULATING SYSTEMS

In general, high rates of outside air ventilation should reduce the buildup of indoor pollutants.
Various studies of office buildings have shown less complaints when naturally ventilated. 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).

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

Only one paper was found addressing the problems of biotic factors in buildings in which the thermal gradient was inward while the humidity gradient was outward, as occurs in a direct-evaporatively cooled building. This paper, a field study of mites in a 190 houses in Tucson, Arizona, 96% of which were evaporatively cooled, showed populations of D 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 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 Tucson houses were direct evaporatively cooled by old swamp coolers, even though a substantial part of the summer (July through September) experiences a high humidity 'Monsoon' from the south where evaporative cooling is pushed to its capacity. Hofu Wu, who also worked in Arizona, wrote in an ASU internal report: 'During most of the warm, dry summer days, the large quantity of air exchange from the use of an evaporative cooler in a living space does not pose difficulty in maintaining human comfort. But later in the Arizona cooling season during periods of high humidity in the 'Monsoon' season, the added humidity becomes problematic for the occupants. Several pieces of ad-hoc auxiliary equipment [ceiling and other fans] can enhance the comfort range by providing higher air flow around the human body, although there is a limitation to the maximum air speed acceptable.'

Evaporative cooling produces indoor RH's of around 80% during operation. Wu measured substantial absorption/desorption effects in the furnishings and structure of the space during the cyclical operation typical of summer cooling. The moisture gained during the cooling period is evaporated during off-cycle periods. The absorption/desorption does not result in major changes in the space temperature under the ventilation rates typical of these systems.

California transition climates do not have the substantial monsoon period (July through September) experienced in Tucson and Phoenix where O'Rourke and Wu have worked. From this one might expect that indoor humidities would be lower and the potential for both molds and mites less.

ADDRESSING 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 are about 60%. 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.

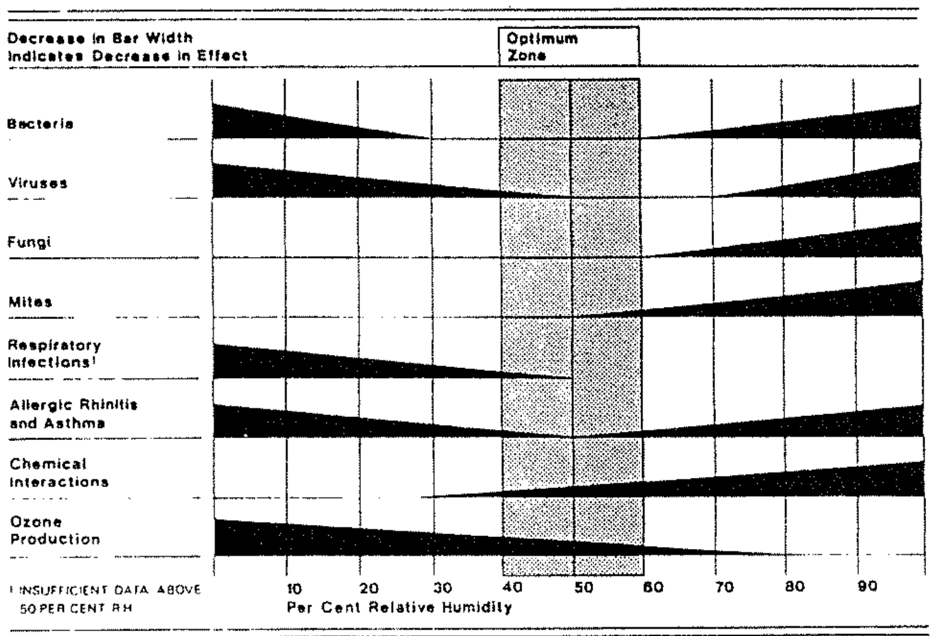
The current ventilation standard (ASHRAE Standard 62) is based on air change rates, with guidance language about humidity limits in the occupied space (60% RH) and in ducts (70% RH). (At time of writing, it appears as if the 70% requirement is going to be removed in the Standard 62 revision for being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

To directly address biological *health* influences, a standard should be expressed in terms of surface temperatures and humidities throughout the building and its mechanical system (ie walls and 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.

A recent figure by Sterling and Arundel has received wide circulation in the HVAC engineering profession (see below). It recommends upper and lower limits to humidity based on eight major environmental health factors. There is clearly a need for such a summary, because it has reappeared in numerous journals and conferences. It is also arrestingly drawn and easy to grasp, which must add to its appeal. It presents impact zones for various contaminants converging into a narrow recommended 'optimum zone' between 40 and 60% RH. The figure is the basis of the recommendation in ASHRAE Std.62-1989 that humidity in the occupied space should be between 30 and 60 % RH, and the paper in which the figure appeared (Sterling et al. 1985) is the only literature cited in the standard pertinent to humidity.

There are issues that may be raised with a figure that attempts to combine the influences of so many factors. One concern might be that it does not assign relative weights (severities) for the different health factors. Another might be that the practicality of the recommended humidity limits in various climates and building types is not assessed. In practice, these things need to be addressed. As an example, ASHRAE Standard 62 overrides (without explanation) the recommended lower limit of 40%, lowering it to 30%, although visually 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 judgement about the severity of the different health effects, differences that are not expressed in the figure; conversely the change may have been forced by practical reality.



Sterling/Arundel Figure

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 would be based on the factual substantiation of the health impact zones presented. For the higher humidities, these zones are linearly expanding areas beginning from a lowest RH point above which the effect has been observed. For the biotic factors, these lowest points are based on minimal numbers of selective cases. In some of these cases, RH is not a variable controlling the effect.

Starting from the top, 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 or its more recent versions (Arundel et al 1986, 1992). The mite recommendation (RH below 50%) is not explained in the the text which says mite populations increase above 60%. Although numbers similar to these may be found in other sources, they are just as often offset by higher numbers in other sources. The figures for allergic rhinitis are presumably based on potential for mites and fungal growth, although most of the discussion is about problems of mist humidifiers and of low humidities. The link between RH and the fungi listed is not made. The chemical interactions category (RH below 30%) is almost symmetrically offset by the ozone production categories (RH above 80% recommended); the relative importance of both these factors needs to be evaluated in light of the impossibility of controlling either of them through RH.

One may argue that for the purpose of setting humidity standards the figure is inadequate. It is important in encouraging good building design to identify the specific physical causes and solutions to health hazards and to regulate design practice to avoid them. It is also important to distinguish between the different health effects so that, for example, a building constructed without formaldehyde-producing materials might be exempted from humidity limitations imposed for that effect.

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 evaporatively 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 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, and 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 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 significantly affect the settling rate of dust particles to which bacteria are attached. The viability of these dustborne organisms also varies, with viability optima occurring throughout the range of RH. For each of the above considerations, there is little to suggest that any humidity between 50% and 90% is better than any other in reducing the viability or number of suspended infectious disease organisms.

The health impacts of non-biological health agents are hard to assess at this time. Formaldehyde is probably the most serious problem, and is exacerbated in some materials by higher humidity. It is being used less in building products and furnishings at this time, and the effect of this will have to be evaluated. Ozone is not a problem of humidity, but of the high ventilation rates associated with direct evaporative coolers in regions of high outdoor pollution. NOx and SOx are also of outdoor origin, but the severity of their effects on health may have a humidity component. These processes and their relative importances appear to be undefined.

Mites (in particular D farinae) are the most compelling reason to keep space humidities low. A number of field studies have found mites at RH's as low as 50%. In one instance, the RH within carpets has been found to be over 9% higher than the space RH, suggesting lower temperatures or local moisture production. It may be that mites (for those who are affected by them) should be controlled by other means having to do with cleaning, treatment or removal of carpets, and insulation of cooled floor slabs under carpets.

In general, molds become an issue only above 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%. Studies that reported problems at lower RH values appeared to have problems that could be corrected otherwise.

Evaporative cooling 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 is also benign in 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 should be systematically evaluated.

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

SPECIFIC NEEDS:

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 have grown.

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 scale.

In the litereature, intermittent moisture exposure is not addressed. 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 ERH and on organisms. Information is also needed on how such cycles are affected by the operation of the building and its mechancal system.

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 effective water-based versions suggests that typical indoor finishes can be less moisture absorptive than in the past.

For evaporatively-cooled building designs, smooth floors should be substituted for wall-to-wall carpets in the homes of mite-susceptible individuals. 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. This should also assist for cases where molds grow in carpet backing.

Carpet treatment with chemically absorptive salts such as borax reduces the ERH of the carpet substrate. This has the effect of killing fleas in all but cocoon stage over long-term periods. This may be an effective treatment against mites, and is currently under investigation.

In environments with high outdoor ozone [and NOx or SOx ?] concentrations, it might be advantageous to use activated charcoal filters as part of once-through ventilation systems.

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.

FUTURE PROSPECTS

The purpose of this review has been:

- to structure the issue of high humidities in buildings for a detailed examination useful for making building decisions,
- to assemble relevant evidence into the structure, and
- to give prelimary opinions of what is known and what needs to be known based on what is in the literature.

These opinions can become more definitive after the contents of this review are circulated among the various researchers in the field, and comments are received. One hopes that this formulation of the issue is useful in suggesting future research and in the upcoming standards deliberations.

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APPENDIX F

Proposed Addendum to ANSI/ASHRAE 55-1992: Thermal Environmental Conditions for Human Occupancy

PROPOSED ADDENDUM 55a to ANSI/ASHRAE 55-1992

(This foreword is not a part of this standard but is included for information purposes only.)

FOREWORD

After Board approval of the proposed ANSI/ASHRAE Standard 55-1992, a comment was received by the ASHRAE Manager of Standards regarding the rationale for the upper humidity limit of Figure 2. Because Standard 55 is a comfort standard, nonthermal environmental factors should not have been used in developing Figure 2.

The life of SPC 55-1981R was extended by the Standards Committee for the purpose of considering an early addendum to the standard. This addendum

- *(a) revises the standard so that nonthermal environmental factors, such as microbial growth and respiratory health, are not used and*
- *(b) provides consistency between the text, Figure 2, and the title, purpose, and scope of the standard.*

Note to Reviewers: Only the changes proposed are open for public review and subject to comment. Strikeouts indicate deletions and shading indicates new material, unless otherwise indicated.

Revise Figure 2: Change the upper humidity limit from 60% relative humidity to 20°C (68°F) wet bulb for the summer conditions and 18°C (64°F) wet bulb for the winter conditions. The Figure 2 legend was also revised by inserting "operative temperature" between "The" and "ranges" of the second sentence. See revised Figure 2.

Background Information: The revision of Figure 2 improves clarity and provides consistency with published reports.

Revise Subsection 5.1.2 (a) and (b): Change 60% RH to 20°C (68°F) wet bulb for the summer conditions and 18°C (64°F) for the winter conditions.

Text from **5.1.2 Operative Temperature** now reads:

...The acceptable range of operative temperatures and humidities for the winter and summer is further defined on the psychrometric chart in Figure 2. The coordinates of the comfort zones are:

(a) Winter: t_o = 20°C to 23.5°C (68°F to 74°F) at ~~60% RH~~ 18°C (64°F) wet bulb and t_o = 20.5°C to 24.5°C (69°F to 76°F) at 2°C (36°F) dew point. The slanting side boundaries of the winter zone correspond to 20°C and 23.5°C (68°F and 74°F) effective temperature (ET*) lines and are loci of constant comfort or thermal sensations.

(b) Summer: t_o = 22.5°C to 26°C (73°F to 79°F) at ~~60% RH~~ 20°C (68°F) wet bulb and t_o = 23.5°C to 27°C (74°F to 81°F) at 2°C (36°F) dew point. The slanting side boundaries of the winter zone correspond to 23°C and 26°C (73°F and 74°F) effective temperature (ET*) lines.

Background Information: The changes in **5.1.2 (a)** and **5.1.2** (b) are necessitated by revision of Figure 2.

Revise Subsection 5.1.3, to read:

In the zone occupied by people engaged in light, primarily sedentary activity (≤ 1.2 met), the humidity ~~shall~~ should conform with the limits shown in Figure 2; note that the upper and lower humidity limits are based on ~~considerations of dry skin, eye irritation, respiratory health, microbial growth, and other moisture related phenomena. It should be noted that temperatures of building surfaces and materials (e.g., windows, ductwork) must be controlled to avoid condensation.~~ the maintenance of acceptable thermal conditions based solely on comfort considerations including thermal sensation, skin wettedness, skin dryness, and eye irritation. (It should be noted that environmental factors outside the scope of this standard, such as physical, chemical, or biological contaminants, may also be partially dependent on indoor humidity levels during occupied periods. Refer to ANSI/ASHRAE Standard 62).

Background Information: The revised wording of **5.1.3 Humidity** improves clarity and provides consistency between this subsection and the title, purpose, and scope of Standard 55-1992.

Revise Section 8 to read:

To comply with this standard, the appropriate requirements of Section 5 shall be met under conditions not exceeding design conditions. For example, design conditions include the design weather conditions chosen by the engineer as appropriate for the intended use of the building. Design weather data are statistically based and established to explicitly acknowledge certain percentages of exceedence (i.e., 1% design, four-month summer basis, 29 hours of exceedence). This recognizes the impracticality of providing an HVAC system that can meet all loads under all weather conditions encountered in its lifetime. Thus, in practice, the requirements of the standard may not be met during the number of hours equivalent to the design weather data exceedence percentage or during excursions from the design conditions.

Background Information: The proposed change provides clarity about how Standard 55-1992 is to be used.

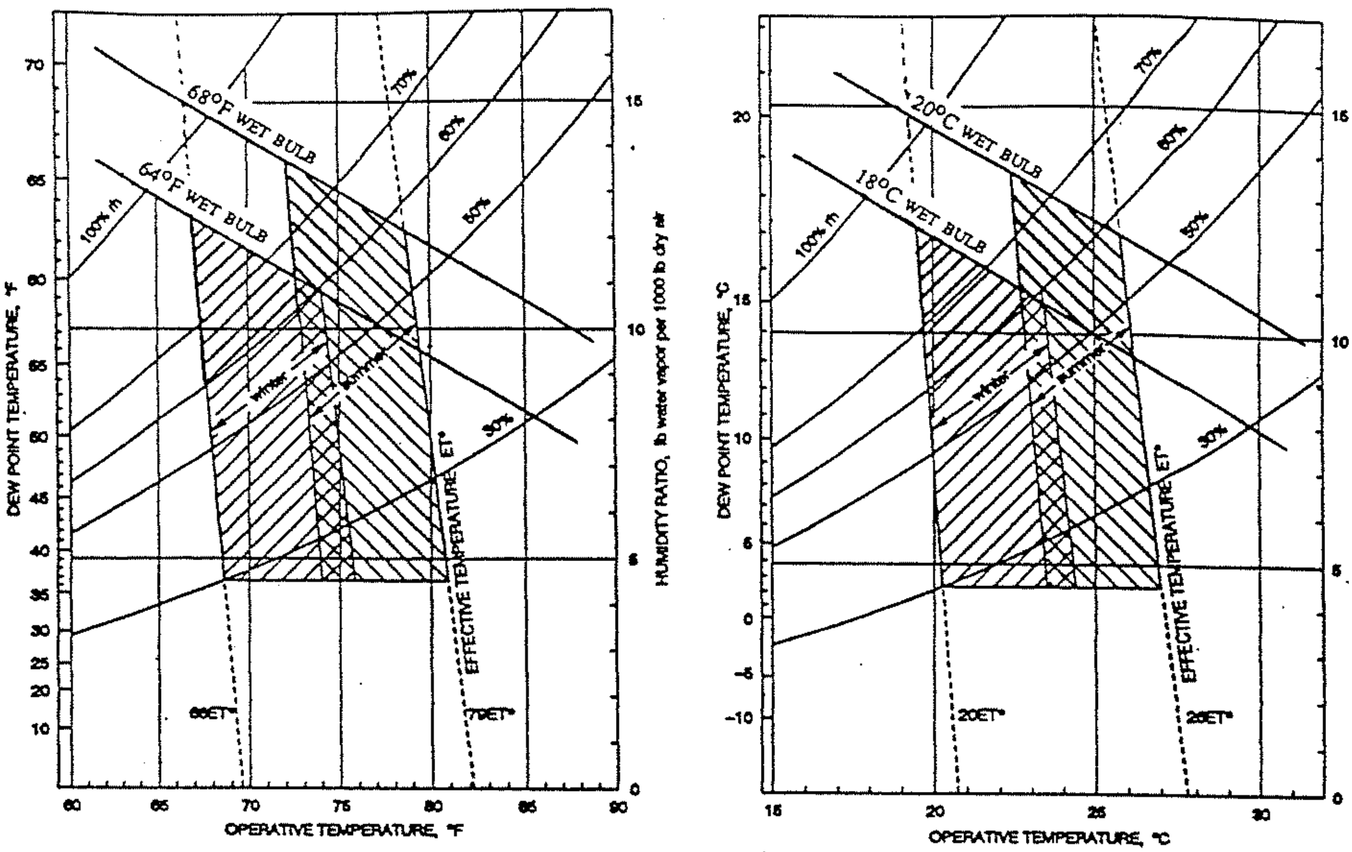

Figure 2 *Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during light, primarily sedentary activity (≤ 1.2 met). The operative temperature ranges are based on a 10% dissatisfaction criterion.*

<u>Revise Section 9 References by adding:</u>

ANSI/ASHRAE 62-1989, Ventilation for acceptable Indoor Air Quality.

<u>Revise APPENDIX A, Bibliography/Paragraph 5.1.3 to add:</u>

Anderson, I., G.R. Lundqvist, and D.F. Proctor. 1973. Human perception of humidity under four controlled conditions. *Archives of Environmental Health* 26:22-27.

ASHRAE. 1993. Physiological principles for comfort and health, Chapter 8, pp. 8.1-8.29, *ASHRAE Handbook—1993 Fundamentals*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Berglund, L.G. 1989. Comfort criteria in a low-humidity environment. RP2732-10. Palo Alto, CA: Electric Power Research Institute.

Tanabe, S., K. Kimura, and T. Hara. 1987. Thermal comfort requirements during the summer season in Japan. *ASHRAE Transactions* 93 (1): 564-577.

<u>Revise APPENDIX A, Bibliography/Paragraph 5.1.3 to delete:</u>

Green, G.H. 1979. The effect of indoor relative humidity on colds. *ASHRAE Transactions* 85: 747-757.

Morey, P.R., and J.E. Woods. 1987. Indoor air quality in health care facilities. *Occupational Medicine: State of the Art Reviews* 2: 547-563.

Morey, P.R., M.J. Hodgson, W.G. Sorenson, G.J. Kullman, W.W. Rhodes, and G.S. Visvesvara. 1986. Environmental studies in moldy office buildings. *ASHRAE Transactions* 92:399-419.

Background Information: Addition and deletion of above citations from APPENDIX A and Section 9 References are necessitated by revisions to 5.1.2 (a) and (b), 5.1.3, and Figure 2.