Thermal Comfort in Naturally-Ventilated and Air-Conditioned Classrooms in the Tropics

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Abstract

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Designers use thermal comfort standards, such as *Thermal Environmental Conditions for Human Occupancy* by the American Society of Heating Refrigeration, and Air-conditioning (*ASHRAE Standard 55-1992*) and *Moderate Thermal Environments - Determination of PMV and PPD Indices and Specification of the Conditions for Thermal Comfort* by the International Standards Organizations (*ISO 7730-1994*), to design systems to provide a physical environment appropriate for thermal comfort. This thesis examines the comfort criteria of *ASHRAE Standard 55-1992* for their applicability in tropical classrooms. The Standard specifies exact physical criteria for producing acceptable thermal environments: minimum and maximum limits for temperature, air speeds, and humidity that are often difficult to apply, particularly in hot and humid tropical climates. The Standard's requirements are based in part on climate-controlled, laboratory experiments in temperate climates. The primary questions here ask: Are laboratory-based air-conditioning standards applicable in tropical climates? Does a different set of criteria exist for people accustomed to hot and humid climates than for those living in temperate climates? Preference for, or acceptance of, thermal factors beyond the prescriptions of the standard might suggest wider latitude for environmental control and air-conditioning set points.

Borrowing primarily from previous thermal comfort studies in office buildings and adapting them for the school setting, I used a variety of methods to collect the data: survey questionnaires, physical measurements, interviews, behavioral observations, and statistical analysis techniques. Hawaii serves as a case study where 3,544 students and teachers completed questionnaires in 29 naturally-ventilated and air-conditioned

classrooms in 6 schools. Concurrent measurements of the physical environment were made during each class visit.

The majority of classrooms failed to meet the physical specifications of the *ASHRAE Standard 55-1992* comfort zone. Analysis of subjective responses using the thermal sensation, preference, and other scales and environmental indices, found votes of more than 80% acceptability by both naturally-ventilated and air-conditioned occupants whether in or out of the comfort zone. Responses from these two school populations, suggest not only a basis for separate comfort standards, but energy conservation opportunities through raising thermostat set points and certainly by choosing to design optimized naturally-ventilated environments.

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The mystique and glamour of conducting a project in Hawaii was a difficult notion to dispel and dissertation funding was not forthcoming except from the University of California, Berkeley's Vice Chancellor's Research Fund which provided financial support for a portion of the field research expenses. The Vital Signs Project allowed a flexible schedule and the time off to work on this study, yet a burden that Bill Burke, Program Coordinator for the project, had to bear during my absences.

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I owe the debt of my intellectual sustenance and delight of investigative pursuit to Professor Cris Benton who guided the fine-tuning of this document - through his overall guidance as head of my dissertation committee and particularly on building evaluation methods and equipment (occasionally rescuing me during difficulties with the equipment in the field). I also thank the my advisors and other members of my thesis committee, Professors Ed Arens, Gail Brager and Robert Spear (Department of Public Health) who helped structure the research and provided hours of discussion towards analyzing and interpreting the data.

In 1992, discussions with Richard de Dear of Macquarie University helped form the research area about thermal comfort in the tropics; Rick Diamond of Lawrence Berkeley National Laboratory provided an overview and checkpoints for making the topic focused and doable; Marc Fountain launched me into the writing phase and offered thoughtful insights along the way; Alan Meier of Lawrence Berkeley Laboratory and Danny Parker of the Florida Solar Energy Center gave me regular updates and literature about schools and energy use; and Charlie Huizenga of U.C. Berkeley's Building Science Group provided computer wizardry enabling me to conduct the necessary statistical analyses.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Architects and engineers use thermal comfort standards, such as *Thermal Environmental Conditions for Human Occupancy* by the American Society of Heating Refrigeration, and Air-conditioning (*ASHRAE Standard 55a-1992*) and *Moderate Thermal Environments - Determination of PMV and PPD Indices and Specification of the Conditions for Thermal Comfort* by the International Standards Organizations (ISO 7730-1994), to design systems to provide a physical environment appropriate for thermal comfort. This thesis examines the comfort criteria of *ASHRAE Standard 55a-1992* for their applicability in tropical classrooms. The Standard specifies exact physical criteria (minimum and maximum limits for temperature, air speeds, and humidity) for producing thermal environments that are acceptable to at least 80% of the occupants. The Standard's criteria are developed in part from climate-controlled, laboratory experiments in temperate climates. The primary questions in this thesis ask: Are laboratory-based air-conditioning standards applicable in tropical climates? Does a different set of criteria exist for people accustomed to hot and humid climates than for those living in temperate climates? If so, these questions are important for schools undergoing renovation and construction and faced with the quandary of long-term energy costs associated with air-conditioning.

In the United States school facility studies on building conditions reported unsatisfactory environmental conditions in two-thirds of the nation's schools.[1] Many opportunities exist for potential savings on energy costs, as we build new schools, or retrofit old schools because of general disrepair. Schools, particularly those in hot and humid tropical climates, use natural ventilation -- an energy-conserving, passive cooling strategy. In more recent times, simple design techniques relevant for ventilation, daylighting, and solar control have been forgotten or abandoned in place of design practices dominated by air-conditioning systems. This issue of whether to air-condition schools has complex and far reaching design implications involving energy costs, policy decisions, and the well-being of school occupants. Such decisions require complete information about the standards that guide the design of air-conditioning systems and associated comfort in the school context.

This chapter introduces the three issues involved in this study: the *tropical climate*, the *standards* that architects and engineers follow to achieve comfort, and the *school environment*.

1.2 Codes and Standards in Design

The practice of architecture encompasses many issues -- one of the more significant is to ensure compliance to building codes and standards. Specifications from such standards provide for the health, safety and well-being of the building occupants. The designer's role is to apply these codes and standards in a manner sensitive to the built environment and the needs of the occupant. However, so many of our buildings are overheated, are overcooled, waste energy and leave the occupants dissatisfied. Through international standards for thermal comfort such as *ASHRAE Standard 55a-1992* (hereafter called *Standard 55*) and *ISO 7730-1994*, we have the opportunity to improve building performance and save energy because these standards go through steady cycles of revision and update.

While in many instances mechanical air-conditioning is vital, the trend toward sustainable building necessitates both industry and client to be more responsible in conserving resources. The demand for electricity from large commercial buildings contributes a significant load on local utilities, potentially increasing costs, creating power quality problems, or even necessitating construction of new generating plants -- all come at a price to the consumer and the environment.

One major significance of modifying the comfort standards lies in the potential for conserving energy through changing building design and careful temperature control. Nicol suggests that one quarter of all energy used in developed economies is used for indoor temperature control, a circumstance that could be achieved by reducing the indoor-outdoor temperature difference.[2] Similarly, after finding satisfaction with temperatures and humidities outside the ASHRAE comfort zone by Thai office occupants, Busch concluded that higher set point adjustments can potentially yield significant energy savings, particularly in the developing regions of the hot and humid tropics. "The energy savings could be significant: an increase of just 1°C in design room temperature in a large commercial building typically reduces cooling energy by several percent."[3] In aggregate, building systems (air-conditioning, ventilating, heating and lighting) add up to approximately 38% of the United States' annual energy use.[4] This statistic becomes important because of the influence that U.S. buildings have as models for the Pacific Rim cities now witnessing unprecedented economic development and construction of modern, air-conditioned buildings.

Also, the amenity of operable windows or workstation proximity to windows has been shown to improve office environmental satisfaction,[5] but these benefits are overshadowed by the fact that comfort standards have gradually claimed to be and are interpreted as applicable to *all* types of building regimes, whether mechanically conditioned or not. The debate about the applicability of the standards in buildings which are not air-conditioned, is one that de Dear recently found confirmation: " . . . when recently asked by a union official whether or not *Standard 55* was applicable to un-air-conditioned premises, ASHRAE's Technical Committee (TC 2.1) responsible for the standard openly declared that their comfort charts were intended for both HVAC and naturally-ventilated premises."[6] Do we hold naturally-ventilated spaces to the same standard as climate-controlled spaces? This question is addressed in further discussion by de Dear who challenges the assumption of the comfort standard's universal applicability on the basis that it ignores contextual differences or modifications in occupant behavior that might be instrumental in changing perceptions of comfort.[7] Additionally, the Standard contains prescriptions that limit the amount of air movement in spaces because of discomfort caused by draft. Application of such restrictions to naturally-ventilated spaces where high air movement is the only means to provide convective cooling, is an area that needs reexamination.

Recent proposals to modify the standard, recognize not only the quantitative but qualitative differences between naturally-ventilated and air-conditioned buildings.[8] The recommendations propose separate comfort standards based upon data supporting the model that prevailing outdoor temperatures can predict indoor comfort. This thesis examines thermal comfort responses in tropical classrooms, both naturally-ventilated and air-conditioned, to determine first the applicability of *Standard 55* and secondly to look at the results in the context of proposed modifications to the thermal comfort standard.

Subsequent discussion will refer to *Standard 55* for the remainder of this thesis, since *Standard 55* and *ISO 7730-1994* specify virtually identical conditions for thermal comfort.[9]

1.3 The Tropical Context

In the sprint toward modernization, developing countries in the hot and humid tropical regions are producing "glass box" buildings at a remarkable rate of construction. Many Asian countries, such as Malaysia and China (host to the world's tallest buildings by the year 2001), see tall buildings as a vehicle to launch them quickly and visibly into the global 21st century. The managing partner of Skidmore, Owings and Merrill (SOM), one of the nation's leading tall-building design firms, spoke of the opportunities in Asia, "We just got out the carpetbag, filled it full of renderings and went abroad."[10] Rarely mentioned in this quest, or in discussions of comfort, is the loss of vernacular design and associated passive strategies in naturally-ventilated buildings that allow the occupant a wide range of personal control and connections to the physical and temporal conditions of the outdoor climate.

SOM is not the only U.S. firm to transform the Asian skyline. Kohn Pederson Fox claims foreign clients comprise two-thirds of their business and will complete the Shanghai World Financial Center by 2001; half of projects from Kevin Roche's firm are located overseas in Singapore, Malaysia, China, Japan, India and Turkey; John Portman

& Associates have several projects in China and will complete a 55-story Tomorrow Square in Shanghai by 1999.[11]

The tremendous building boom is not only the result of wanting countries wanting new cutting edge designs, but also because of the region's overall economic transformation, fast growing economy, investment in infrastructure, and extensive energy resources. For example, gross domestic product (GDP) growth rates in Indonesia of 6 percent per year are expected to be sustained for at least the next several years. In 1996, GDP growth rates around the Pacific Rim were: Taiwan, 5.5%; South Korea, 7.5%, Singapore, 7.5%, Philippines, 6.5%, Thailand, 8.5%, Japan 2.7%, and Australia 4.8%.[12]

In cities such as Kuala Lumpur, Malaysia one has to wonder about the impact, in an already congested city, that the Kuala Lumpur City Center (KLCC) will have on the environment. Once completed the KLCC will enclose 60,000 people within 1.7 million square meters (over 12.4 million ft^2) each day.[13] Such showpiece projects, considered high architectural form, are held as models to be followed, even for less "demanding" building types such as schools. If there is a building type to be found that need not follow the sealed, air-conditioned archetype, it is the school.

1.4 Hawaii Schools as a Case Study

Schools in the tropics offer a setting to study non-temperate, non-office thermal comfort. Hawaii is a compelling location for such a study because it is the only U.S. state truly located in the tropics. At 21°N latitude, Hawaii is the southernmost state, located 500 miles further south than Miami -- a city commonly thought of as tropical. Although ideally situated for many alternative energy sources, Hawaii is currently 90% dependent on imported petroleum oil for its energy -- compared to the U.S. national average of 45 percent.[14] It consequently has the highest electricity costs in the U.S.[15] The majority of the 371 schools in Hawaii are more than 30 years old. Aging infrastructure, combined with a rising school-age population, and the trend toward year-round schooling, will require a program of renovation, expansion, or construction of new schools.

Many Hawaii schools face the quandary of whether to air-condition or not -- but the answers are not simple. Another opportunity is that it is indeed technically feasible to avoid air-conditioning, with properly designed buildings that feature cross-ventilation because of the constant, prevailing trade winds. In recent years, however, people have complained about Hawaii's increasingly hot weather and many have installed air-conditioners in their residences.[16] School building renovation is prone to take the route of air-conditioning, but the high costs of capital investment and operations kept this trend at bay. In a sense we are at a "fork in the road," where such decisions made in the early design stages of Hawaii's school expansion could chart distinctly different energy courses and contrasting directions for the architectural design of buildings.

1.5 Objectives

The primary objective of this research is to determine the applicability of the thermal comfort, *Standard 55*, to school settings in a tropical climate. In a case study carried out in naturally-ventilated and air-conditioned classrooms in Hawaii, the specifications and criteria of *Standard 55* are compared to the indoor classroom conditions and to perceptions of those environments by classroom occupants. To determine the standard's applicability, the study, the following specific questions directed this study:

- What ranges of thermal environmental conditions are found in typical tropical classrooms?
- Do the physical conditions generally comply with the standards?
- What is the relationship between measured indoor climate and the subjective comfort responses?
- Do classroom occupants find their conditions in accordance with the 80% acceptability criterion from *Standard 55*?
- How well do the prediction models of comfort match the observed subjective responses?
- Can the naturally-ventilated and air-conditioned data from Hawaii classrooms inform future revisions of the comfort standards?
- What are the perceptions of other non-thermal conditions such as air quality and dust?

1.6 Approach

The approach taken here is a field study which takes place in Hawaii, where there is an accessible collection of schools of various designs and conditioning regimes. Though climate-chamber studies have the advantage of controlling climate variables, field research is most appropriate for observing and evaluating a range of responses specific to naturally-ventilated environments. Data from field measurements will provide the basis for comparisons to the prescriptions of *Standard 55*. The general approaches taken in this study are:

- to characterize the physical environment of classrooms that represent two typical conditioning regimes, natural ventilation and air-conditioned classrooms;
- to compare measured physical conditions to the comfort zone specifications of the *Standard 55* for each classroom;
- to compare thermal comfort responses by the classroom occupants (subjective response) to criteria specified by *Standard 55*, using a variety of comfort scales and environmental indices;
- to compare subjective responses to predicted responses calculated by several, selected comfort prediction models;
- to compare the results with findings from other thermal comfort studies.

Specific methods included first assembling a subject sample by selecting student and teacher participants from specific classrooms at naturally-ventilated and air-conditioned schools. A combination of research methods such as interviews, observations, survey questionnaires, and physical measurements using laboratory-grade instrumentation and statistical techniques were used to collect and analyze data. All these techniques are commonly used in office thermal comfort studies (modified for the school setting) and are described in further detail in Chapter 4.

1.7 Organization of the Dissertation

Chapters 2 and 3 present background information about definitions of thermal comfort, past thermal comfort studies and the development of the comfort standard in the school context. Chapter 4 provides greater detail on the methods and equipment used to carry out the field study. Chapter 5 presents the data collected in Hawaii schools, followed by an analysis and discussion about the survey responses of students and teachers in Chapter 6. In the final chapter, I present the final conclusions about the applicability of *Standard 55* in a tropical climate and suggest directions for future work.

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2. Nicol, F. 1993. *Thermal Comfort: A Handbook for Field Studies Toward an Adaptive Model*. London, University of East London.

3. Lovins, A. B. 1992. Air Conditioning Comfort: Behavioral and Cultural Issues. Boulder, CO, E Source, Inc.

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5. In a study of 12 office buildings, 4 naturally-ventilated, 4 mechanically-ventilated, and 4 air-conditioned in Northern California, Mendell found the lack of a window near the workstation was associated with an increase in health symptoms. Further analysis found that distance to the window was less related to symptom prevalence than operability. Mendell, M. J. 1991. Risk factors for work related symptoms in northern California office workers. Berkeley, CA, Lawrence Berkeley National Laboratory.

6. de Dear, R., G. Brager, et al. 1997. Developing an adaptive model of thermal comfort and preference. ASHRAE Report RP-884. Sydney, Macquarie University.

7. *Ibid.*

8. ASHRAE RP-884 project assembled a database of quality controlled thermal comfort field experiments and evaluated thermal comfort using the adaptive

model, where indoor comfort is likely predicted by prevailing outdoor temperatures. de Dear, R. and G. S. Brager. 1997. "Developing an adaptive model of thermal comfort and preference," *ASHRAE Transactions*(Draft for Winter ASHRAE Meeting 1998).

9. ASHRAE 55-1992R and ISO 7730-1994 differ in they way thermal comfort is determined. ISO 7730 uses predictive indices, PMV and PPD that correspond to ASHRAE's 7-point thermal sensation scale. Although both are international standards, the ASHRAE Standard is one that is followed by most engineers, particularly in the developing countries of the tropics, i.e. Singapore, Malaysia, Thailand, etc.

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11. 1993. "Is bigger better?," *Asiaweek* **19**(29): 30-36. Pacelle, *op. cit*.

12. Pearson, C. A. 1996. "Pacific Rim Portfolio," *Architectural Record*(July): PR1-27.

13. 1993. "Is bigger better?, *op. cit*.

14. Royle, K. and C. Terry. 1990. *Hawaiian Design Strategies for Energy Efficient Architecture*. Honolulu, The American Institute of Architects-Honolulu Chapter.

15. A recent survey of commercial electricity prices, ranked Hawaii as the most expensive in the country $0.1717 per kwh on the Big Island. In comparison, California's PG&E charges its commercial customers $0.1286/kwh and Seattle City Light $0.0356. 1995. "Ranking of Electricity Prices," *Energy User News* **20**(2): 59.

16 During recent trips to Hawaii, I was struck by the number of families who have recently added air-conditioners to their homes, though I did not collect any statistical information on this fact.

CHAPTER 2

OVERVIEW OF PREVIOUS RESEARCH

2.1 The Thermal Environment

As organisms, humans must establish thermal equilibrium with their environment. Four environmental parameters describe the thermal environment: air temperature, radiant temperature, relative humidity and air velocity. The interaction of these four factors, combined with heat generated from human metabolic activity and the insulation value contributed by our clothing, create the conditions that shape the human thermal response.

Today, many people have come to understand, perceive, and expect the consistent and stable thermal qualities provided by mechanical systems. This has not always been the case. Prior to the establishment of an air-conditioning standard by the American Society of Heating Ventilating Engineers (ASHVE) in 1938,[1] the driving force of design of the indoor physical environment was proper ventilation for health rather than thermal control of the environment for comfort. In the 1930s through the 1960s, after the widespread acceptance of conditioned buildings, research focused upon creating optimum environments for thermal comfort. Researchers established ranges of comfortable temperatures for various climates: 21 - 27°C in the United States, 14 - 21°C in Britain, and 23 - 29°C in the tropics.[2]

The ranges of optimum temperatures prescribed by the *Standard 55* creates a zone of "thermal neutrality" in which building occupants should find acceptable. Thermal neutrality, a temperature which corresponds to votes surrounding "neutral" on a thermal sensation scale by a sample of building occupants, forms the basis of the current steady-state or "static" model of comfort[3] -- humans maintain comfort simply through the balance of heat flow with their immediate environment. However, questions about the conventional model, such as differences in comfort perceptions that might be explained by factors beyond the physics and physiology of heat balance, give rise to the "adaptive" model of comfort, where humans play an active role in creating their thermal experience.

This chapter focuses on the contributions of past field studies of thermal comfort and the applicability of the current thermal comfort standard in a tropical climate. The overview of literature is divided into three sections: 1) thermal comfort, beginning with definitions of comfort and indices, 2) *Standard 55* history, 3) studies in the tropics and 4) studies of temperature and performance in the school environment.

2.1.1 A Definition for Thermal Comfort

Before air-conditioning technology took hold, thermal well-being was not defined by a specialized word, "comfort." Many meanings have been attributed to this word, beginning with its root in the Latin derivation of *confortare*, meaning to strengthen greatly. *Merriam Webster's Collegiate Dictionary*, 10th edition, gives several definitions. The first, is that of assistance as in "accused of giving aid and comfort to the enemy." The second is that of consolation in a time of worry, "she was a great comfort to her grandmother in a time of grief." The third definition describes comfort as contentment -- a satisfying or enjoyable experience.

Eastern interpretations of comfort contrast with the Western definitions. Humans achieve well-being through the body's energy flow and the mind's serenity.[4] The word "comfortable," or *shu shih* in Chinese, translates to being suitable to a situation. However, there is no east-to-west or vice-versa translation for comfort in the thermal sense. Eastern thought seeks to establish inner harmony and balance, under difficult or adversarial conditions. Those cultivated in the martial arts, such as *tai chi* or *chi kung*, are able to move the body's energy flow, not only for serenity of mind, but for healing processes and well-being. This is most evident in the medical field where acupuncture, practiced along meridians of the body, is used to remedy a patient's malady and even as anesthesia for major surgeries. In design, the *feng shui* concept offers balance and harmony to believers. Although most practitioners consider this concept an alternative practice, a better understanding of how people conceive of their environment in relationship to themselves might play an important role in the success of environmental technologies and control.

In *Home*, Rybczynski traces the origins of comfort by examining the evolution of social and cultural factors that shape the experience of comfort in the home and our connections to nostalgic notions. Where traditions eliciting reminders or imaginative ideas of the comfort experience do not exist, many designers, such as Ralph Lauren, make their living creating interiors fashioned to "evoke atmospheres of traditional hominess and solid domesticity that is associated with the past."[5]

Comfort now has many layers of meaning, making a precise definition difficult and perhaps unnecessary. In his "Onion Theory of Comfort," Rybczynski describes comfort as the composite of all the layers, not just the most recent:

> It may be enough to realize that domestic comfort involves a range of attributes—convenience, efficiency, leisure, ease, pleasure, domesticity, intimacy, and privacy—all of which contribute to the experience; common sense will do the rest. . . . recognition <of comfort> involves a combination of sensations—many of them subconscious—and not only physical, but also emotional as well as intellectual, which makes comfort difficult to explain and impossible to measure.[6]

Arguing for environments with physical variations rather than static conditions, Heschong describes comfort in *Thermal Delight in Architecture* as a relationship between thermal contentment and human imagination. Presenting an example of how we as humans we are capable of recognizing, remembering, and adapting ourselves to most thermal experiences, Heschong writes:

> There is a basic difference, however, between our thermal sense and all of our other senses. When our thermal sensors tell us an object is cold, that object is already making us colder. If, on the other hand, I look at a red object it won't make me grow redder, nor will touching a bumpy object make me bumpy. Thermal information is never neutral; it always reflects what is directly happening to the body. . . . Our nervous system is much more attuned to noticing change in the environment than to noticing steady states.[7]

Comfort plays on our memory and expectations, and is defined by the thermal associations connected to a place or an object. Heschong continues, by reasoning about our need to identify with something that accounts for our state of well-being and laments the loss of thermal delight in buildings:

> On a lovely spring day we may identify the season itself with our wonderful sense of well-being, as has been done in hundreds of songs about the joys of spring. On a tropical isle that has an ever-perfect combination of balmy breezes, warming sunshine, and shady palms, we would probably come to love the island for providing us with such a fortuitous setting. But in a typical office building, to what can we attribute the all-pervasive comfort of 70°F, 50 percent relative humidity? The air diffuser hidden in the hung ceiling panels? . . . The engineer who designed the system long ago? The whole vast building itself? Most likely, we simply take it all for granted. Then thermal comfort is a constant condition, constant in both space and time, it becomes so abstract that it loses its potential to focus affection.[8]

McIntyre discusses the need for sensory and physical stimulation and makes a case for fluctuating interior temperatures to "counteract "thermal boredom" . . . It can be argued that achieving a steady optimum temperature is akin to finding the most popular meal in at the canteen and then serving it every day."[9]

Recognizing the difficulty of engineering steady-state conditions for the range of human activities, Fitch[10] in *American Building, The Environmental Forces That Shape It* raises the notion that humans might subconsciously have a need for thermal variation. He uses the example of a typist performing the same task all day, who might require a different thermal environment at 3 p.m. than at the beginning of the day. Environmental control must accommodate these needs within what Fitch terms "golden zone" of thermal balance. Environmental control and mechanical systems have the potential to provide comfort and efficiency for the range of human activities and endeavors. In practice, this is a challenging task, for we are not merely thermodynamic meters, but rather beings with variable needs, "tailored to our own psychic and somatic requirements."

2.2 Standard 55 History

Approximately 70 years ago the American Society of Heating Ventilating Engineers (ASHVE) formed the first thermal comfort standards. Based upon laboratory studies of unclothed subjects seated in front of a fan, the boundaries of comfort determined by these subjects, were set at temperatures between 19.4°C (66.9°F) and 24.4°C (75.9°F) at 50% relative humidity, and depicted on a Comfort Chart in 1924.[11] These new rules for comfort continued to evolve, taking into account clothing differences between the winter and summer seasons, and in the meantime implemented with air-conditioning installations, in office buildings and theaters.

In 1917, the first theater to install a year-round cooling system was the Empire Theater in Montgomery, Alabama. In 1928, the Milam Building in San Antonio, Texas was a landmark for office buildings, acclaimed as the tallest, most completely equipped building in terms of air-conditioning and by 1931, about 400 movie theaters were providing cool environments for their customers when it became clear that air-cooled environments were highly profitable.[12] In 1935, the Hong Kong and Shanghai Bank installed what was thought to be the largest air-conditioning system in the tropics.[13] Through the 1930s,comfort cooling by mechanical means took place primarily in industrial facilities, hotels, banks and theaters. In office buildings, air-conditioning promised the prospect of improved health, work efficiency, and comfort to its occupants.

In 1938, ASHVE set a comfort standard titled, “The Code of Minimum Requirements for Comfort Air-conditioning,” incorporating temperature, air movement, and relative humidity into one temperature index, called “effective temperature,” an index originally developed by Houghton and Yaglou in 1923.[14] Heating and cooling seasons had separate temperature and humidity limits, offering a comfort zone that shifted for each season. During the heating season, optimum indoor dry bulb temperatures were 21°C and relative humidity limit at 35%. During the cooling season, interior temperatures took into account higher outdoor temperatures, and allowed higher interior temperatures and humidity levels. For example during the cooling season, a 32°C outside dry bulb temperature allowed an interior effective temperature of 23°C. Though many buildings still used natural ventilation through operable windows throughout the 1940s, this decade marked a strong departure from the old because of new technologies such as the fluorescent lamp. After General Electric and Westinghouse provided fluorescent lamps for the New York World’s Fair and the Gold Gate International Exposition (San Francisco) in 1939 and listed the lamps in their catalogs,[15] building design embarked on a new frontier, with the promise of air-conditioned environments – because lighting was economical and considerably cooler than incandescent lighting.

In the 1960s, thermal comfort research focused on the thermo-physiological response. Auliciems in 1972 gathered a series of interpretations of comfort centered on the ”zone of vasomotor regulation” or “zone of neutrality,” which recognized the varying degrees of subjective comfort. Beyond the “zone,” an individual also experiences varying degrees of discomfort.

> Thermal discomfort arises when the thermal senses are excited, whether by the temperature of the environment or by the internal processes of the body to the extent of becoming subjectively disagreeable.[16]

In 1966, the *Standard 55-1966* replaced the 1938 “Code of Minimum Requirements for Comfort Air-Conditioning” and formally defined thermal comfort as: “the condition of mind that expresses satisfaction with the thermal environment.” In assessment, the condition of mind is determined by a subjective assessment of the acceptability of the environment. That is, of a group of people represented, 80% must find conditions satisfactory. Data from laboratory studies set comfort zone boundary limits at 22.7°C to 25.0°C ambient temperature, 20% - 60% relative humidity, and 0.05 to 0.29 meters per second air velocity. A further chronology of the development of the comfort standard is presented in the next chapter.

Since publishing *Thermal Comfort* in 1970, P.O. Fanger’s therrmodynamic equation to calculate thermal sensation has become the basis of today’s standards. The equation, derived from experiments with both American and Danish college-age students under the steady-state conditions of climate chambers, showed that in addition to the physical variables (air temperature, mean radiant temperature, air velocity, relative humidity), mean skin temperature and sweat secretion are strongly connected with thermal sensation. From his comfort equation, Fanger derived an index, Predicted Mean Vote (PMV) to predict the subjective thermal sensation on a standard scale.[17] For any combination of clothing, metabolic activity and set of environmental variables, it is possible to predict an outcome on the seven-point psycho-physical ASHRAE scale, where -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, and 3 = hot.

Standard 55-1974 replaced the 1966 standard and incorporated a new effective temperature, ET* in the standard's list of definitions. Here operative temperature (average of dry bulb and mean radiant temperatures), rather than dry bulb temperature, is used to bound the comfort zone between 22.0°C and 26.0°C. Additional bounds are provided by a humidity range of 20% to 60% and air movement of 0.35 meters per second.

In 1981, after research recognized seasonal variations in clothing, the *Standard 55-1981* divided the comfort chart into two zones, one for winter and one for summer. Temperatures of the winter comfort zone ranged from 20.0 to 23.5°C ET*, when people wear more layers of "winter clothing" and during the summer, slightly higher temperatures ranging 22.5 to 26.0°C, as people don lighter weight clothing. The upper boundary of the comfort zone for humidity was described in terms of dew point temperature (operative temperature) and not to exceed 16.7°C (also shown as 0.12 humidity ratio on the psychrometric chart). This boundary was explicitly driven by health concerns, stating, " . . . upper and lower dew point limits are based on considerations of comfort, respiratory health, mold growth and other moisture related phenomena."[18] Air movement limits were set at 0.15 meters per second during the winter, increasing to 0.25 meters per second during summertime conditions.

The limits of *Standard 55-1992* changed slightly from the previous *Standard 55-1981*, to allow more air movement than 0.15 meters per second in either season, but only if the occupant can control the source of the air movement. Humidity boundaries kept the lower dew point limit, but changed the upper limit to follow the 60% relative humidity line of the psychrometric chart. Again, the basis of the change to the humidity boundary was driven by "considerations of comfort, respiratory health, mold growth and other moisture related phenomena."

Because of recent amendments to *Standard 55-1992* (referred to as *Standard* 55 in this dissertation), the upper boundary humidity limits again changed from the 60% humidity boundary to follow the 18°C wet bulb line during the winter and 20°C during the summer. The key difference is that this boundary is no longer tied to non-thermal environmental factors such as microbial growth and respiratory health. *Standard 55's* basis is solely on "comfort considerations including thermal sensation, skin wettedness, skin dryness and eye irritation."[19] This point is critical to later discussions about naturally-ventilated environments in the tropics which often have hot and humid physical conditions that exceed the humidity limit of the Standard's comfort zone.

Returning to definitions of comfort, the current standard, *Standard 55* provides a definition of comfort: "thermal comfort: the condition of mind that expresses satisfaction with the thermal environment." The condition of mind is measured by people voting on a scale: "thermal sensation: a conscious feeling commonly graded into the categories cold . . . neutral . . . hot." And finally *Standard 55* sets an acceptability criterion, which translates thermal sensation votes into measures of acceptability: "acceptable thermal environment: an environment that at least 80% of the occupants would find thermally acceptable."[20]

2.2.1 Acclimatization, adaptation, expectation

During the past 25 years of research, defining comfort in terms of the standard's prescriptions and methodology has produced a debate between two approaches or models of comfort: the "static" and "adaptive" models. The two approaches not only contain different algorithms for calculating comfort zone prescriptions but have contrasting assumptions about the way buildings are designed and how environments are controlled. Ultimately, the models differ in their potential for conserving the way buildings use energy.

The rationale of the static model is based on various heat balance models, where the person is a passive recipient of thermal stimuli and the effects of a given thermal environment are mediated exclusively by the physics of heat transfer.[21] The assumptions imply that sensations of subjective discomfort are exclusively formulated by the magnitude of response to the thermal environment, such as shivering or sweating. Heat balance models such as PMV, ET* and SET* take into account only the four environmental variables (air and radiant temperatures, humidity and air velocity) and two personal variables (clothing and metabolic heat production), but exclude the influence of adaptive behaviors to the indoor climate by the occupant.[22] Both *Standard 55*and *ISO 7730-1994* use the static model with data from laboratory experiments in climate-controlled chambers as a basis for formulating the basis of their standards. Hence, these standards use laboratory-derived models to determine subjective responses to thermal conditions of actual buildings.

Looking beyond the thermo-regulatory responses to climate, the adaptive model approach considers a range of responses (behavioral, physiological, and psychological adjustments), building occupants undertake to achieve thermal comfort. The adaptive approach has a conceptually different basis than just heat exchange between humans and the environment. Nicol[23] discusses the range of actions that we may choose in order to achieve thermal comfort. These actions, or behaviors, in turn will modify internal heat generation, the rate of heat loss from the body, modify the surrounding thermal environment, or involve moving to a different environment.

At a website[24] describing a current ASHRAE sponsored project (known as RP-884) on the adaptive model of thermal comfort, de Dear explains how our expectations of indoor thermal environments, can influence our perceptions of comfort. Several behavioral and psychological processes provide the conceptual basis of the adaptive model. These adjustments, reactions, or responses performed by building occupants, are often assigned to three categories of adaptation:

1. **Behavioral Adaptation** - the manipulation or adjustment of clothing, body movement, or objects in one's immediate surroundings to create a more satisfactory state of heat balance for the body. Examples include adding or removing clothing, changing posture, opening or closing windows, adjusting thermostats, using fans, blocking or re-directing air from diffusers, or changing the blinds to block undesirable solar radiation.

2. **Physiological Adaptation** - the body's acclimatization or long-term exposure to thermally stressful environments (hot or cold). Physiological changes are those changes in the internal settings at which thermoregulatory responses occur. Such physiological responses include vasodilation, vasoconstriction, shivering and sweating.

3. **Psychological Adaptation** - psychological responses are a complex combination of factors outside the realm of the relationship between the six traditional variables which shape our awareness of the thermal environment. Thermal perceptions may be directly and significantly attenuated by one's past thermal experiences and expectation with what buildings offer technologically in terms of HVAC practice and architectural design.

Using a schematic developed by Auliciems (Figure 2.1), de Dear[25] describes the processes of the adaptive model. Occupant satisfaction with indoor climate is based upon the history of experience and the expectations that the occupant has had with similar buildings or spaces. Thermal history and expectation might then elicit behaviors which assist an individual in making adjustments toward thermal comfort. In reviews of recent thermal comfort studies, de Dear[26] also distinguishes between the responses from naturally-ventilated and air-conditioned settings, when looking at thermal neutralities.

Figure 2.2 depicts one effect of using this adaptability in thermal perception in terms of derived indoor temperature settings and their relationship with outdoor climate. The objective of diminishing the gradient between indoor and outdoor temperatures serves the purpose of reducing energy consumption in buildings and associated greenhouse gas emissions, lowering peak demand for electricity and constructing smaller cooling plants. The adaptive model would find success when optimum temperatures predicted by the model closely match the temperatures nominated by the building occupants themselves. Also evident in this figure is the relationship between the standard and indoor temperatures. Less stringent limits on interior temperatures would allow more latitude for indoor temperature settings, ultimately reducing energy consumption and saving energy costs.

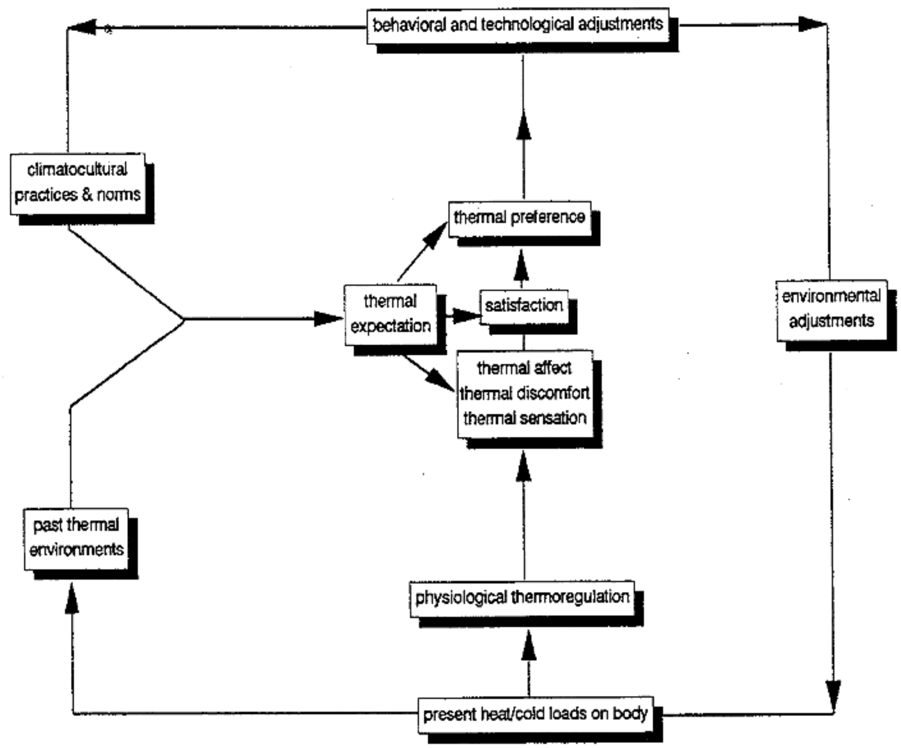

Figure 2.1 “Adaptive model” of thermal comfort (Auliciems 1981)

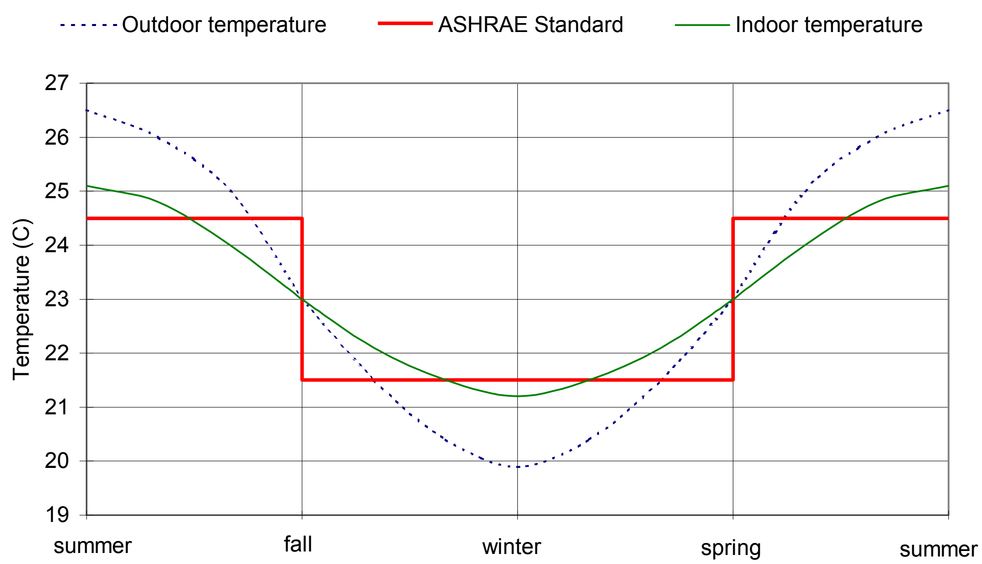

Figure 2.2 The adaptive model concept (©Macquarie University 1996)
(de Dear, http://atmos.es.mq.edu.au/~rdedear/)

Previous reviews by Auliciems[27] and Humphreys[28] of thermal comfort studies conducted in various climate zones around the world, indicate that indoor comfort temperatures are linked to the prevailing outdoor conditions. In ASHRAE RP-884, de Dear and Brager[29] compiled a database of data from recent field experiments (including more than 20,000 respondents) and categorized them, into three "classes" of experiments depending upon their methodology and instrumentation used. This level of quality control allows the data from a variety of building types and climates across the world to be compared in terms of thermal sensation, preference and acceptability between naturally-ventilated and air-conditioned buildings within the context of developing the adaptive model. The results of RP-884 are set forth by de Dear and Brager[30] in a proposal for a variable temperature standard is exclusively intended for buildings with HVAC systems.

2.3 Thermal Comfort Studies in the Tropics

A number of recent field studies in office buildings have expanded the database of thermal comfort to another climate - the hot and humid tropics. Studies in Bangkok, Singapore, various cities in Australia, and Jakarta[31] measured indoor climate parameters and subjective responses via questionnaires in both air-conditioned and naturally-ventilated environments (only air-conditioned office buildings in Townsville, Australia). The air-conditioned occupants, with the exception of the Jakarta study, had neutral temperatures consistent with their air-conditioned counterparts in mid-latitude areas of North America. Neutral temperatures for naturally-ventilated occupants however, were 3-5°C higher than the air-conditioned neutralities.

Busch[32] discusses the energy savings potential of taking advantage of this discrepancy in thermal perception. His conclusions assume that air-conditioned tropical office buildings might not need as much cooling energy because the tropical population showed a tolerance for warmer temperatures. For mechanically-cooled buildings, particularly in tropical developing countries, these findings have clear implications in terms of cooling savings.

In the adaptive model, the role of expectation is thought to play a significant role in the human response to the thermal environment. The difference between neutral temperatures in naturally-ventilated and air conditioned populations is in part explained by the different environments provided by each building type. With air-conditioning, we expect a static environment, stable temperatures, and in an approach that removes us from the ambient climate. In spaces without mechanical conditioning, the expectation is different. Such environments inherently require adaptability and a certain amount of human energy to achieve comfort, such as opening a window, turning on a fan, placing a paperweight on rustling papers or rolling down a shade to block the afternoon sun.

In Bangkok office buildings, Busch[33] distinguishes two populations by the conditioning regimes: naturally-ventilated and air-conditioned. After initially treating the entire sample as one population and finding a bi-modal pattern of responses, he later reasoned that acclimatization accounted for the discrepancies between thermal neutralities. Thai respondents from air-conditioned buildings had sensitivities and neutralities similar to other air-conditioned occupant office samples in both the tropics and temperate regions, but Thai naturally-ventilated respondents voted differently.

Most of the tropical studies carried out in the 1950s and 1960s[34] used acclimatized populations, that is people who had resided in the region and experienced the hot and humid climate for at least six months. These investigations tried to establish comfort zones for European residents living in the tropics, following a concern that the discomfort of the hot and humid tropics was a deterrent to establishing foreign communities abroad (a vestige from colonial days). Although subjects were acclimatized, most studies used European respondents rather than local residents. Several studies seemed to have a predilection for finding reasons to air-condition, with comments such as, " . . . the enervating effects of living in a tropical environment, which require adequate spells in a temperate climate."[35] Although these early tropical studies aimed for validation to provide air-conditioning, they did much to lay early ground work for the adaptive model by showing comfort associated with higher prevailing mean temperatures for acclimatized populations. For example, working with long-term tropical residents in Singapore, Webb[36] determined optimum working temperatures to occur at approximately 25.9°C, with the boundary for discomfort occurring at 28.8°C.

Until recently, studies have rarely compared the effectiveness of the standard, both in terms of how existing conditions match the specifications by the standard and how acceptable people find their environments. Many of the air-conditioned buildings in three recent field studies, Townsville, Australia, San Francisco, and Bangkok,[37] did not meet the physical requirements of the ASHRAE summer comfort zone, yet more than 80% of the occupants voted the conditions acceptable by measures of their votes on the thermal sensation scale.

Field studies conducted in naturally-ventilated buildings are rare, probably because of the increasingly difficult task in finding naturally-ventilated-buildings. Such settings are necessary because they generally have a wider range of options for evaluating occupant control, such as operability of windows. Comparisons between thermal perceptions naturally-ventilated and air conditioned occupants are also integral to any discussion about the adaptive model (discussed in previous section). Although de Dear[38] reviews a number of studies that find higher levels of adaptive opportunity available in naturally-ventilated buildings, one needs to keep in mind that the "opportunity" might be even greater if those naturally-ventilated buildings were selected as "prime examples" with advantageous architectural designs (proper orientation for maximum cross-ventilation, appropriately sized windows, etc.), rather than including less-than-adequate buildings as a last resort.

More comfort studies are needed that control, as best as possible, for architectural issues of building design. That is, selected naturally-ventilated buildings (should a critical mass be found) should have similarities in orientation, age, proximity to external factors such as traffic, vegetation, etc. This study will take these factors into account in the selection of school buildings -- perhaps a slightly easier effort because of the larger numbers of naturally-ventilated schools available.

2.4 Thermal Comfort Studies in Schools

While a substantial database of recent field investigations exists for office buildings, a review of literature revealed no studies in the past 20 years that specifically look at comfort in the school environment. In the 1800s however, concerns about the thermal comfort and ventilation in classrooms were at the forefront of school design in Europe and subsequently New England schools.[39] Experiments in the early 1900s focused on ventilation and heating requirements in classrooms. The next chapter discusses the development of the standards (thermal, lighting, ventilation) and the physical environment of the classroom in more detail.

A number of school studies in the 1960s and 1970s[40] examined the effects of heat and cold stress on a range of factors such as behavior, comfort and task performance (e.g. memorization, reading comprehension, multiplication). These studies found reduced task performance, comfort, and motivation as a result of heat stress. Establishing direct influence on mental performance or learning capacity was less conclusive. Most of these studies used elementary school age children in temperate North America, European, and Australian climate zones and established the importance of thermal conditions to the learning environment, but also reflected the inherent difficulties in finding causal relationships between achievement and the physical environment.

Although the focus of this study will not attempt to assess the impact of the thermal environment on learning and student achievement, the literature contains a number of studies that try to establish such a correlation. Auliciems[41] reviewed a number of studies and found an important work by A. H. Seymour in 1936 that aimed to discover whether variations in temperatures between 13.0 and 15.5°C (study performed during the winter in England) would affect mental performance. For the performance tasks given (single figure addition tasks), Seymour concluded that conditions of 14.5°C were most suitable for classroom temperatures, and 12°C was the least suitable. Later in 1969, Auliciems' extensive winter study[42] in England schools established optimum temperatures for mental performance in the range of 15.0 to 17.8°C. From a thermal comfort point of view, this suggests that similar cool temperatures produced by air-conditioning might create improved learning environments. This study however, is performed in schools a heating regime during the winter season, where preferences for optimum temperatures might well vary from those occupants experiencing a cooling regime.

A series of moderate heat stress and behavior performance studies tried to determine an upper temperature limit for classroom temperatures. Holmberg and Wyon[43] children 9-11 years old in climate chambers and observational classrooms in Sweden with tested using eight indices: 1) posture, 2) clothing, 3) appearance, 4) concentration, 5) restlessness, 6) conduct, 7) perceptible response to heat, and 8) undesirable classroom behavior. Of the three temperatures tested, 20, 27, and 30°C, a marked and detrimental effect on classroom behavior occurred at 27°C (than at 20 or 30°C). Combined with performance results and spontaneous comments by students of feeling “tired” at 27°C, Holmberg and Wyon explained that “arousal decreased at the intermediate temperatures (27°C) and increased at higher temperatures.” The practical conclusion from this study implies that since a linear response was not found between temperature and behavior performance, we cannot assume that learning is lessened (or improved) by at temperatures.

In a project carried out from 1961 to 1963, McNall and Nevins[44] tested their hypothesis that “thermal environmental control (air-conditioning) or near the ‘comfort’ zone facilitates academic achievement of junior high school students.” Defining the differences between “learning” and “achievement” is a discussion that lies outside of the scope of this review, though both words can generally be used to describe mental performance. The authors used common standardized achievement tests to measure the academic achievement of the students from air-conditioned and non-climate controlled schools (term used to describe non-air-conditioned schools that contained heating systems) in Florida. Mean scores of the achievement tests were higher in air-conditioned schools than in naturally-ventilated schools, though not statistically significant. McNall and Nevins explain that further research is needed in controlling for the variables in such a study such as, student motivations, previous preparation of the students, and socioeconomic background – a task that has inherent confounding factors.

Wyon et al.[45] also looked at the effect of moderate heat stress on the mental performance of a group of 17-year old high-school students in a climate chamber setting with temperatures ranging from 20 to 29°C. Students performed tasks of sentence completion, multiplication, and word memory – but the results were not straightforward. Performance on tasks such as sentence comprehension requiring concentration and clear thinking, were worse at 26°C than at 23° or 29°C. Although the authors interpreted the counterintuitive data "as a lowering of arousal at levels of moderate heat stress corresponding to the limit of vasodilatory control just below the onset of sweating," other data also showed that certain tasks improved under heat stress, leading to an additional conclusion that thermal comfort is a poor predictor of the effect of heat on mental performance. Results such as these, though more assessments are needed, do not give any indication hot environments are detrimental to learning.

Although thermal comfort research began with concerns about the thermal environment in schools and hospitals during the early 1900's, during the past 20 years, research has focused primarily on occupants in office buildings. New investigations are needed about the physical environment in schools where indoor climate is undeniably one of the factors influencing the teaching and learning and emphasized by the following 1962 statistic.

> Young people attending schools of various educational levels constitute in developed countries by far the largest population group doing very similar work in similar conditions. It consists of almost a fourth of the total population of the (UK) country.[46]

Today, this statistic is true in the U.S. as well. The U.S. Census Bureau estimates by the year 2000, there will be 55 million school-age children, approximately 20% of the U.S. population.[47]:

Auliciems offers four hypotheses prior to beginning his 1969 study with school children in England. They are mentioned here as representative of the embryonic notions of the adaptive model and because of their applicability to looking at the effects of environment on comfort and work efficiency (task performance).

1. subjective thermal comfort is influenced by the meteorological environment;
2. optimum thermal environments exist for maximum work efficiency;
3. optimum thermal work conditions may be located at thermal neutral environments, or the zone of vasomotor regulation against cold or heat;

4. work efficiency is related to atmospheric conditions other than the immediate thermal environment.[48]

Auliciems found, “1) statistically significant relationships between outdoor climate conditions and observed thermal sensations - the most significant single variable was outdoor temperature, 2) optimum thermal temperatures were 15.0 - 16.5°C for maximum work efficiency, but the temperatures were not related to all types of work, 3) for certain tasks, optimum conditions for continuous work are located at neutral to slightly cool temperatures (on the thermal sensation scale), but are not subjectively considered as uncomfortable, 4) work efficiency was not clearly associated with non-thermal factors.” Although results from this school study reflect winter perceptions about thermal comfort, similar relationships between outdoor climate and perceptions about comfort might be found in warmer climates – one aspect which will be examined in this dissertation.

2.5 Ventilation Studies

Another standard, not directly related to thermal comfort but nevertheless important in the school environment, is *Ventilation for Acceptable Indoor Air Quality (ASHRAE Standard 62-1989* referred to later as *Standard 62)* which specifies ventilation rates required for acceptable air quality. Today, ventilation is viewed by many as the most effective strategy for dealing with indoor contaminants. Other methods, such as reducing source pollution, are often outside the control of the designer. Ventilation rates have been the subject of debate since the early part of this century and these debates still continue within professional societies. Recommended ventilation rates have ranged from as low as 5 cfm per occupant to the current rate of 15 cfm per occupant. Increased pollutant concentrations in office buildings seem to be associated with reduced ventilation rates to save energy in buildings with HVAC systems. Even with *Standard 62's* increased ventilation rates, incidents of health complaints associated with inadequate air quality have received wide attention in many office buildings and recently in several schools.

Symptoms of health effects might include eye, nose, and throat irritation, headaches, fatigue, coughing, and dryness of skin. In studies of building-related symptoms, these ailments are believed by the occupants to be caused by pollutants or elements within their work environment. In 1990, Lawrence Berkeley National Laboratory researchers, Mendell[49] looked at work-related symptoms of occupants in twelve California office buildings and found fewer health symptoms associated with naturally-ventilated office buildings in comparison to air-conditioned counterparts. Cousins and Collett[50] investigated the relationship between health symptoms and ventilation type in schools in Canada, classified school buildings into three groups by age and found results consistent with the California study - fewer health and comfort complaints in older buildings where ventilation is provided by operable windows and unit ventilators. Other school indoor air-quality studies[51] describe pollution control and ventilation problems in with HVAC systems.

For hot and humid tropical climates, the cost of air-conditioning is relatively high because of outdoor humidity exceeding 60 percent (relative humidity) for most of the year. To provide necessary ventilation, as well as humidity control, air-conditioning units are often oversized, resulting in greater energy use, potentially increasing undesirable drafts, and interior temperature fluctuations.

Successfully-designed naturally-ventilated spaces presumably assure airflow for thermal comfort and increased ventilation for pollutant control. Proper ventilation is particularly critical in schools where enclosed or poorly-ventilated classrooms can serve as an incubator of microorganisms and vessel for high concentrations of pollutants. Natural ventilation offers its own set of advantages including intrinsically lower energy costs, physical contact with the outside climate, and a high degree of personal control, such as operable windows.

The increased emphasis on energy conservation in the 1970's and consequent throttling of mechanical systems to save energy, plus the increased awareness of health problems related to indoor pollutants, such as tobacco smoke, formaldehyde, molds in ventilation systems, solvents, radon, and other substances, spurred research about health effects of such pollutants. While increased mechanical ventilation rates help with pollution dilution, *Standard 62-1989* also recommends maintaining relative humidity levels between 30% and 60% to reduce the growth of fungi, mycotoxins, and dust mites.[52] Recent work on health and comfort related to air quality has focused on the efficiency of mechanical systems at providing the proper number of cubic feet per minute to classrooms. This review of literature did not reveal studies that examined ventilation efficacy in naturally-ventilated classrooms. At the time of this writing, *Standard 62* recommends that spaces not exceed 1000 ppm for carbon dioxide. Current revisions to the standard, some of which include changes in outdoor ventilation requirements, offer new procedures to determine ventilation rates and suggest deleting the carbon dioxide guideline.

2.6 Summary

This chapter discusses several interpretations of the word “comfort.” General definitions- including non-thermal factors such as air quality, acoustics, illumination and anything else that might involve us in an experience that we could call, “comfort” are contrasted with the HVAC engineering definition which specifically narrows the equation down to six variables, by creating a thermal comfort standard which contains inherent assumptions that comfort can be supplied within a narrow band of conditions. The current comfort standards base these assumptions on the “static” model, in which humans respond as passive monitors to the thermal environment. The “adaptive” model places humans in active perpetrators of modifying their environment for comfort.

A handful of comfort studies have recently taken place in the tropics, mostly in office buildings and none using school settings. The review of literature also yielded two major questions: 1) how effective is a laboratory-based, air-conditioning standard (*Standard 55*) in a tropical climate? and 2) what opportunities exist in naturally-ventilated and air-conditioned school buildings for bringing new information to the comfort standard? These questions form the basis for this study.

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CHAPTER 3

SCHOOL DESIGN AND THE PHYSICAL ENVIRONMENT

3.1 Introduction

Over time, significant developments have shaped the design of schools. Rather than specific one-time events, they are a combination of pedagogical approaches, design traditions, and guidelines for the physical environment, spanning several decades. What began as rules-of-thumb related to daylighting and health in classrooms in the 1800s, later provided the basis for the formation of today's lighting, ventilation, and comfort standards. From a review of handbooks, treatises about early school design, and architectural journals featuring school projects, this chapter surveys approaches to school design over the past 200 years, examining the influence of pedagogical approach and the standards for the physical environment.

Although educational program and philosophy have been dominant issues in school design, school environments have also received attention. The basic approach to the physical environment has remained unchanged as a place vitally important a child's safety, health, psychological, and academic well-being. Early concerns about the spread of disease led to the need improve the physical conditions of the classroom in terms of air and daylight. School handbooks and treatises also offered guidelines about general principles of school architecture, specifications of furniture suitable for ideal posture, ceiling heights for ventilation, and proportions for classrooms. During the past 75 years, guidelines and rules-of-thumb gave way to formalized standards and codes, now set by research organizations, government, and state agencies.

The survey is organized as a chronology beginning in the early 19th century to 1900, then in half century intervals, 1900-1950, and 1950 - to present day. Each time period includes two-part discussion of: 1) the predominant pedagogical approaches and building designs and 2) the physical conditions and prevalent guidelines or standards.

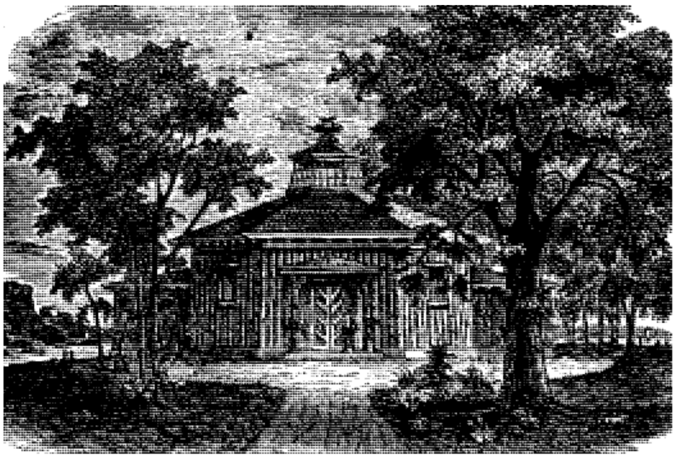
3.2 1800 - 1900 One-Room Schools to the Schoolhouse

3.2.1 Pedagogy and Design

During the early American republic, private homes or churches housed the first schools. In New England, education had its source with those raised in the Calvinistic tradition, the Pilgrims and the Puritans, who recognized the importance of elementary education for everyone. Laws enacted by the Massachusetts' General Court in 1642 and 1647 illustrate the religious background of early efforts, in providing that parents be accountable to the civil authorities "concerning their calling and implyment (employment) of their children, especially of their ability to read & understand the principles of religion & the capital laws of this country."[1]

During the early nineteenth century the typical building form for schools was the rural one-room schoolhouse (Figure 3.1), where one teacher taught every lesson to all the children attending that school. Teachers kept strict order and used strategies such as testing memory and listening to recitations. Students generally worked at their own pace, promoted to the next book or level only when the teacher judged the student ready. The wealthy hired tutors and the less affluent often sent their children to unmarried or widowed older women who held classes in their own homes.[2]

During this century, four educational systems imported from Britain included: 1) The Sunday School, a secular school taught on Sundays, with the goal of giving children who worked the other six days of the week at least the rudiments of learning; 2) School Societies, organized to offer education to those who could not afford to pay tutors; 3) The Lancastrian School, sometimes referred to as the monitorial or mutual system, was widely adopted by public schools in most of the large cities; 4) The Infant School, an attempt to get children into school at a very young age to delay their employment in factories and mills.



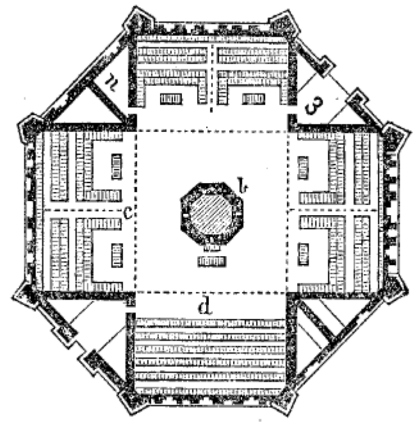


Figure 3.1 Eight-sided school house in Birmingham Meeting, Pennsylvania and typical plan.[3] This compact design provides lots of wall space for black boards and maps. A stove in the middle of the school heated the interior and the cupola served as a skylight and means of ventilation.

Lancastrian education, named after its founder, Joseph Lancaster an English Quaker, lasted only a short period in this country, from the beginning of the nineteenth century through the1830s. Though short-lived, it laid the foundation for subsequent American education and organization of the classroom. The system took on a military character where the teacher instructed a group of 50 "head" students, who in turn became monitors to drill 10 pupils, thus one teacher was able to teach 500 students. Students sat in rows by age and progress level in a large classroom, and often were divided into smaller groups under the direction of monitors. Among the system’s lasting marks was establishing a case for group instruction. Communities realized that it was economical to educate many, rather than individually or on a small group basis.

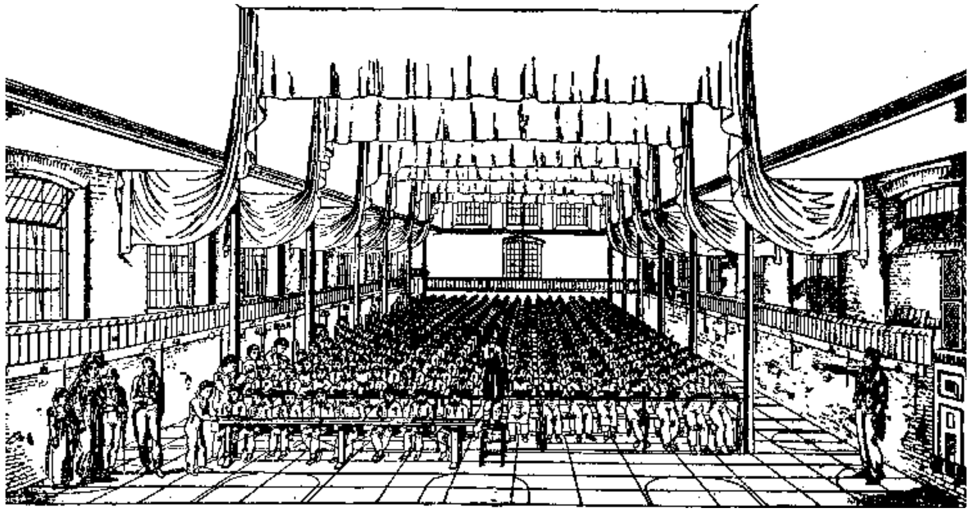
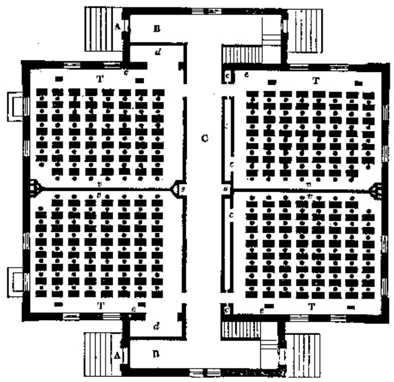


Figure 3.2 Lancastrian classroom, 1806 showing rows of students and semi-circular stations along the side walls for recitation exercises.[4]

In 1852, Massachusetts became the first state to require compulsory school attendance. Compulsory requirements spawned an energetic period of school building, particularly in the urban areas where grouping children by age into grade levels (with a teacher for each grade), gradually became the recognized educational approach. Subject matter such as history, geography, and composition expanded the course of instruction. This grading approach, the differentiation by ability and subject, called for a different type of school building. The Quincy Grammar School, built in Boston in 1848, is thought to be the first fully graded public school in the United States. [5] Its plan of twelve classrooms, assembly hall and principal's office, served as a design template for later projects in New England and established a degree of standardization in school building design. The 4-story building accommodated 600 students, usually 56 pupils to a classroom measuring 31' x 26' (approximately 15 ft^2 per child) containing desks bolted to the classroom floor (Figure 3.1).

Tyler street. Established, 1847. } QUINCY SCHOOL. { Erected, 1847. Cost, $60,210.18.

Figure 3.3 Quincy School and plan, constructed in 1847.[6]

3.2.2 Conditions and Standards

Poor conditions in schools were not unlike many of the problems we find in schools today. In 1854, Henry Barnard, Superintendent of Common Schools in Connecticut, wrote about the deplorable conditions of schoolhouses, enumerating some of the common problems related to building, construction, and general comfort of the students: “1) universally badly located, exposed to noise, dust and danger of the highway, unattractive, if not positively repulsive (resemble barns, sheds for cattle, or mechanic shops), built at the least possible expense of material and labor; 2) too small; 3) badly lighted, no blinds or curtains to prevent excess light falling directly on the eyes or reflected from the book; 4) they are not properly ventilated; 5) imperfectly warmed; 6) not furnished with desks and seats to promote the comfort and convenience of the scholars; 7) no blackboards, maps, clock, thermometer and other apparatus and fixtures; 8) no hooks and shelves for hats, no well for water, no sink, basin, towels, or toilets. Thus the comfort and health of the children are sacrificed.”[7]

Ventilation of building interiors was a prominent design consideration during this period. “Bad air” was thought to be a substantial threat to health. These concerns for health and hygiene prompted architects and planners to consider more carefully the effect of the classroom environment on schoolchildren. Children were considered less clean than adults and odors in classrooms were a tangible concern.

Standard practice for school design was generally a matter of individual recommendation based on experiments performed by engineers and medical officers, (usually from Europe), or more commonly upon experience and observation by school superintendents and professors of education. Research in the practice of heating and ventilation of Thomas Tredgold, an English civil engineer in 1808, Dr. D. B. Reid in 1833 in Edinburgh, and Dr. Billings (medical doctor) in the U.S. in 1884 investigated carbonic acid concentrations and health, and “impurities in the air to which proper ventilation would dispel.”[8] In early publications by the American Society of Heating and Ventilating Engineers (ASHVE), ‘sniff’ tests determined ventilation rates by calculations of the number of days children went without bathing and a judge’s vote on an odor scale. Open windows and doors ventilated the majority of school classrooms and plans describe the construction and placement of ventilating tubes, or ventiducts, which functioned to exhaust “impure” air.

Recommendations called for duct size of at least 15 inches square to ventilate the rooms at rates of 4-10 cfm per pupil, though Barnard noted that 5 cfm was inadequate.[9] Eventually, 30 cfm per student became the recommended ventilation rate to reduce odor to “barely perceptible” levels.[10] In 1888, the Commonwealth of Massachusetts passed a law requiring a supply 30 cubic feet per minute to each scholar and heat for the room to 70°F.[11] In 1895, at the first meeting of ASHVE in New York, mechanical fan ventilation was accepted as the best procedure for hospitals, schools and auditoriums,[12] thus marking the beginning of the technology that would later expand to include refrigeration and cooling of interior environments.

During colder months wood or coal burning stoves typically warmed the classrooms. In 1847, the School Committee of Boston sanctioned the introduction of the Chilson Ventilating School Stove into new schoolhouses constructed in Boston. Outdoor air to be warmed entered the stove beneath the fire-chamber, passed around the heated surface and flowed directly into the room (or through ventiducts to the rooms).[13]

What might be the earliest "comfort standard" is part of a regulation in 1845 adopted in most public schools in Rhode Island. Written by Henry Barnard, "Rules for the Care and Preservation of School Houses.," includes provisions for teachers and students to follow to maintain school property and the well-being of its occupants. Teachers were required to be attentive of and control classroom temperatures:

> As pure air of a proper temperature is indispensable to health and comfort, teachers cannot be too careful in giving attention to these things. If the room has no ventilator, the doors and windows should be opened before and after school, to permit a free and healthful circulation of air; and the temperature should be regulated by a thermometer suspended, five or six feet from the floor, in such a position as to indicate as near as possible the average temperature, and should be kept about 65 degrees Fahrenheit.[14]

Aspects of the school environment such as lighting in classrooms received less attention simply because of daytime attendance. Daylight, admitted through windows, was the predominate light during this period, although oil and kerosene lamps were available for darker periods. The rule-of-thumb for windows called for window areas to equal one sixth the area of the floor space. Daylight was thought to be the best if it was introduced from the left side of the pupils.[15] In England, the favored aspect for light was when it came into the classroom from the southeast and south, allowing daylight during morning hours and ensuring that sunlight not strike the windows before the hot part of the day.[16] For other hygienic factors, enclosed structures or sheds for toilets were located near the playground, but remained unattached to the one-room schoolhouse. In larger schools such as The Quincy Grammar School, students used the toilets located in the basement of the building.

3.3 1900 - 1950 Humanistic Approach

3.3.1 Pedagogy and Design

From 1900 to 1920, school enrollment doubled each decade under increased public pressure for more educational facilities. Educational philosophy changed toward emphasizing the child's individuality by encouraging the gradual unfolding of a student's unique personality. Courses in music, art, dance, and other forms of creative expression helped explore individual talent. It was perhaps the philosophy of educational theorist John Dewey (1859-1952) that most profoundly influenced programs and curricula of this century. Dewey’s ideas of learning by observation and discovery through inner experience, suggested that the individual has the ingenuity, (given ample intellectual space), to learn and make contributions to the “real world.” Many of Dewey’s “progressive” ideas challenged education practice of the time and eventually found their way into educational programs. This called for changes in school design, the most notable being the differentiation of the one-room classroom into separate rooms for each activity. By the early 1900s, classrooms were becoming bigger, chairs and desks no longer were fastened to the floor, and separate rooms formed to house kindergartners, hold assemblies, and provide manual training, such as woodworking for boys and domestic arts for girls. Space per student ranged from 40-80 ft^2 per pupil and by 1940 increased to 80-100 ft^2 per person, allowing more room to express Dewey’s individuality.

WWI provided the motivation to expand the traditional curriculum. When one-third of the men drafted for service were rejected because they were not physically fit, school facilities correspondingly expanded to provide swimming pools, gymnasiums, locker rooms, and large athletic fields. Instructional methods in science education changed from primarily religious and descriptive lessons to those encouraging students to use observation and reasoning skills. Again, school designs changed to offer specialized classrooms and laboratories to carry out these activities.

Mid- century urban school architecture settled on primarily a basic three- and four-story structure housing all classrooms and activity rooms under one roof (Figure 3.4). This solution could be cast in almost any historical style imaginable and incorporating substantial improvements in heating, lighting, toilet facilities, eating facilities, space per pupil, and fire safety codes.

Figure 3.4 Grover Cleveland High School in St. Louis, Missouri 1921.[17]
Note windows on all facades admit natural light.

As Dewey's pedagogy for personal development provided the framework for individual learning, it was the Open-Air Movement which set the stage for healthy school environments. Originating in Germany in 1904, "open-air-recovery schools" served as places where students who were physically ill could keep up with their school work, and also improve their health. The movement spread quickly throughout Germany and England, and in 1908 the first open-air school opened in Providence, Rhode Island, where most of the enrollees were tuberculosis cases.[18] Open-air treatment included just that, where rooms had essentially outside conditions because of wide open windows. Children ate regularly (the beginnings of our school lunch program) and teachers and nurses kept records of their menus, nutrition, and health. Open-air classrooms were thought to be most suitable if they were located in the upper stories of a building, above the dust level of the street, with southern exposure for maximum sunlight, and with windows pivoting to access the maximum amount of fresh air.

The methods of open-air schools took hold throughout the Midwestern states. In Chicago, the Elizabeth McCormick Memorial Fund in Chicago supported the construction of many schools, "stressing the importance of sunlight, fresh air, and cross-ventilation in promoting health, attendance and progress of students."[19] California's mild climate nurtured the idea of healthful environments through good ventilation, and open-air schools were no longer for children with illnesses (Figure 3.5). Expressing pride, educators described open-air classrooms, " . . . many of the best schools include a number of open-air classrooms, entirely open on the protected side with only an adjustable awning to be lowered in wet weather. Students clamor for these rooms and invariably make better progress in their studies, and are more healthful than those in the enclosed rooms, even where the most modern ventilating systems have been provided."[20]

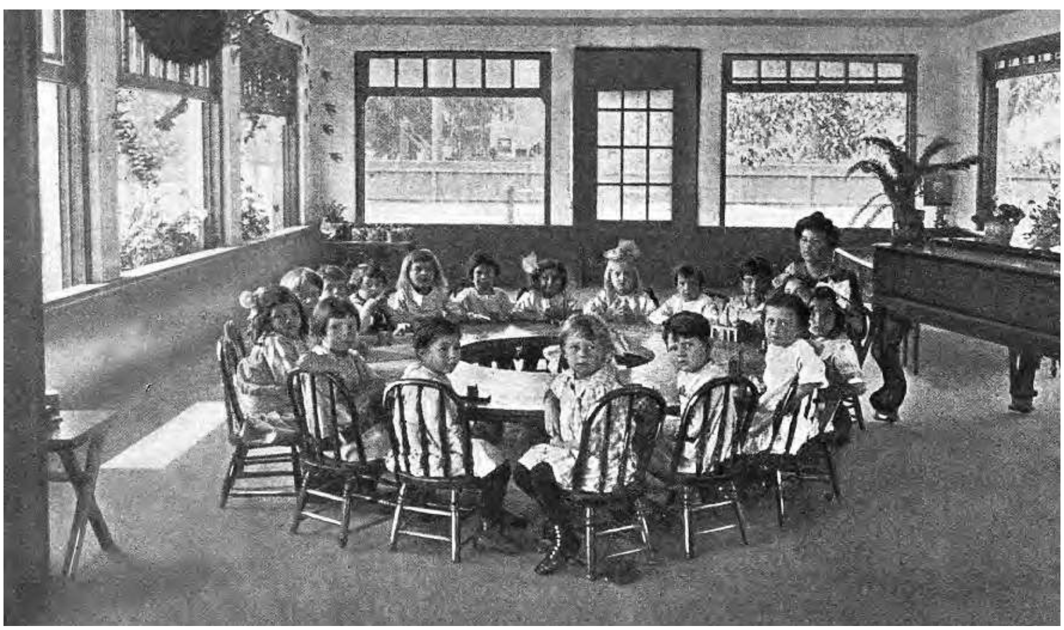


Figure 3.5 Open-air kindergarten, Fremont School, Sacramento, CA c.1920.[21]

Several notable exceptions to the multistory school building exemplify the influence of Dewey's philosophy and the open air movement:

Carl Schurz High School, Chicago, 1910 by Dwight Perkins displayed no ornament or historical eclecticism and is perhaps the earliest example of open-planning in schools where parts of the same school are differentiated to house various activities.[22]

Corona Avenue School, Bell, California, 1935 by Richard Neutra incorporated the first application in the United States of a sliding glass door, essentially combining indoor and outdoor classroom space.[23]

Crow Island Elementary School, 1940 in Winnetka, Illinois by Perkins, Wheeler & Will with Eliel and Eero Saarinen architects. The school was a radical notion for 1940, offering an informal, one-story setting that divided classrooms into separate wings giving each its own access to outdoor space - a striking contrast to the rigid organization of classrooms within a multistory Victorian structure. It received national historic landmark status in 1990.[24]

3.3.2 Conditions and Standards

Today's ventilation and comfort standards developed as an outgrowth from research about school fan ventilation issues investigations and laboratory experimentation on human physiology during the late 19th century. After the landmark ventilation law of Massachusetts in 1888, ten states enacted the same law and eight others mandated regulations (Figure 3.6) by 1912. Although many early investigations used school environments, attention turned toward improving office conditions because of an emerging new technology - air conditioning. With pressure from the medical community, engineering practitioners (belonging to ASHVE) performed detailed studies of human physiology during the 1920s. This work formed the first formalized comfort standard, "The Code of Minimum Requirements for Comfort Air Conditioning" in 1938.[25]

A list of such milestones shows the comfort standards (Table 3.1) and specifications for temperature, humidity and air movement set by ASHVE (which has since become ASHRAE, The American Society of Heating Refrigeration and Air-Conditioning Engineers). These standards, aimed at providing steady-state conditions, allowed a congruent move toward sealed building-designs, without operable windows. It marked a shift in our expectations of the physical conditions offered by air-conditioned and a naturally-ventilated buildings.

In the 1920s, most of the comfort cooling occurred in industrial facilities, hotels, theaters and auditoria. Large banking corporations could afford air-conditioning installations for their office buildings, and schools, for the most part, were left out of ASHRAE's research program, focusing primarily on thermal comfort of the office occupant. The first air-conditioned office buildings in the United States were the Milam Building in San Antonio, Texas in 1928, The Union Trust in Detroit in 1929 and Philadelphia Savings Fund Society in 1932.[26] Air-conditioning technology reached hot and humid tropical regions and by 1935, the Hong Kong Shanghai Banking Corporation boasted the largest air-conditioning installation in the tropics.[27]

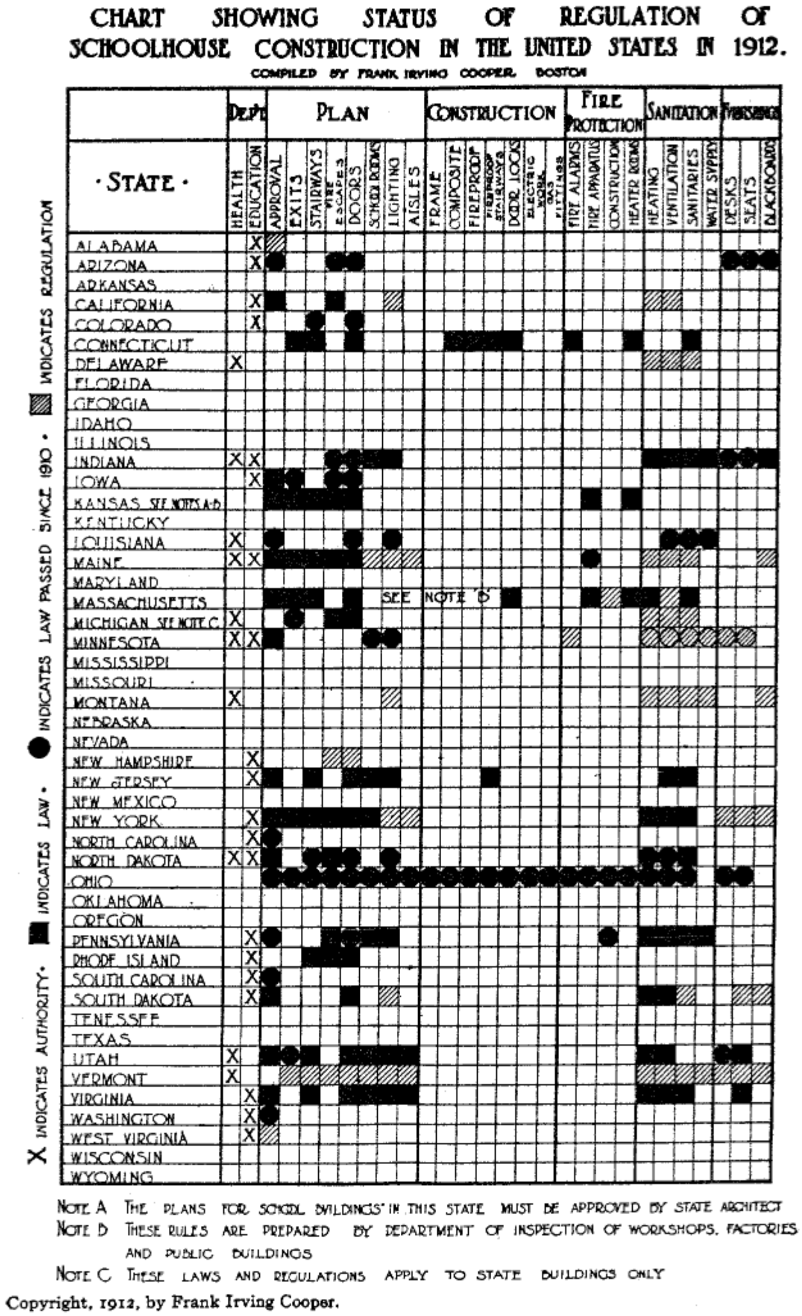


Figure 3.6 Regulation of ventilation in states by 1912[28]
(sixth column from the right)

Table 3.1 Timetable of comfort standards modified[29]

Year	Issuer	Temperature (mid-zone)		Air Velocity (max)		Notes
		°C	°F	m/s	fpm	
1888	State of MA	21.1	70	30 cfm		$500 penalty for failure to comply with ventilation of public buildings
1896	ASHVE	NA		30 cfm		Society reviews European standard
1915	ASHVE	18.8	65.8	30 cfm		Code of Minimum requirements for ventilation
1920	ASHVE	18.8	65.8	0.81	160	Synthetic Air Chart
1932	ASHVE	21.1	70	0.25	50	ASHVE Ventilation Standard
1938	ASHVE	21.1	70	0.25	50	Code of Minimum requirements for comfort
1966	ASHRAE	23.8	74.8	0.23	45	First Standard 55
1974	ASHRAE	23.8	74.8	0.35	70	Comfort velocity = 0.15 m/s
1981	ASHRAE	23.8	74.8	0.25	50	Uses Gagge ET*
1984	ISO	22.0	71.6	0.15	30	Adopts Fanger's PMV without modification
1992	ASHRAE	23.8	74.8	0.15	30	Adopts Fanger draft zone. Velocity = 0.15 m/s when turbulence = 40%

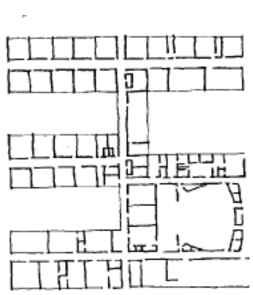
In the 1940s, space requirements for students increased, ceiling heights lowered to 9 feet from 12 feet, and light "from one side" was no longer a limitation because of advances in electric lighting technology. By the end of the decade, research focused on creating optimum classroom environments in terms of lighting and ventilation, setting the stage for the next generation of school architecture - a movement based on connecting the outdoors with the developmental needs of the student.

3.4 1950 - Present

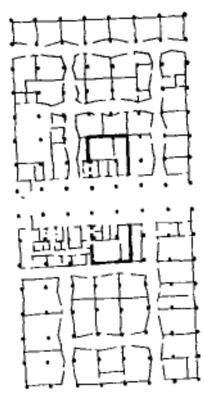
3.4.1 Pedagogy and Design

Educational theory and its connection to contemporary models of school architecture are not as easily categorized as in the previous fifty years of the century. The pupil-based approach of the 1950s was a turning point in both education and architecture. Programs designed to serve the post WWII baby boom offered flexible curricula providing activity-based programs for experiential learning. Building upon Dewey's legacy, Kurt Lewin (founder of American social psychology) and Piaget (French developmental psychologist), developed principles of cognitive-development through experiential learning, spurring the movement in curriculum development and teaching.[30]

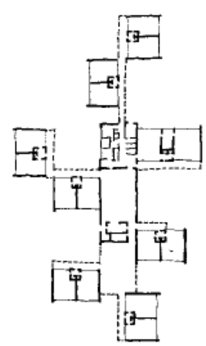
Again, school design and planning changed accordingly The frenzy of school construction during 1950s and 1960s focused on building open-plan classrooms to facilitate the variety of emerging instructional methods, such as team-teaching, large-group instruction, small group seminars, language labs, and the advent of television technology.[31] An important outcome of the new school designs was a differentiation of space, resulting in the separation of activities into several buildings. Still perimeter zone-bound by natural ventilation and to a lesser extent daylight, various organizational strategies created more connections with the outdoors (Figure 3.7). For example, the *Finger Plan* improved daylight and cross ventilation; the *Loft Plan* provided moveable interiors; and the *Cluster Plan*, isolated activities into separate buildings (e.g. detached gymnasium, cafeteria, and classroom buildings), connected by enclosed halls.



Finger Plan



Loft Plan



Cluster Plan

Figure 3.7 Organizational plans for school buildings[32]

The rapid growth expansion of schools in the 1950s spawned a systems approach to building schools. In 1962, the Schools Construction System Development (SCSD)[33] building system, developed by Ezra Ehrenkrantz and his team at Stanford University, focused on two primary school needs: 1) built-in flexibility to keep pace with rapidly changing and unpredictable needs of the user and 2) an improved learning environment. Prefabricated assembly systems including structure, partitions, lighting and ceiling were brought together on site and could ostensibly produce buildings readily responsive to needs as they change.

The success of such systems, decoupled from the specifics of the site in providing comfort depended to a large extent on the use of a controlled internal environment with air conditioning and non-operable windows. In some parts of the country, the trend of windowless schools became briefly popular, opening a new area of research into the psychological effect on learning of those deprived of the connection to the outdoors. Though these schools were short-lived, teachers enjoyed the benefits of additional wall space for chalk boards, educational displays and student work and some believed that classrooms without windows were less distracting for the students. Administrators appreciated reduced maintenance costs to replace vandalized windows. However, studies comparing occupants of windowed and windowless spaces found little statistical difference in occupant preference, performance, or health. One study investigated adaptations of office workers (of windowed and windowless spaces) in their workspaces and resulted in, "people's apparent strong need for contact with nature in some form . . . clearly indicating that people want to see the natural world . . ."[34] With no strong case for or against windowless buildings, the windowless "fad" dwindled to the general notion if a choice is possible, occupants should be given windowed spaces.

In the 1970s, the new concepts of the "community-school" and pedagogy of team teaching emerged, approaches that involved making school facilities available after hours for programs serving people of all ages in the community and internally, providing classroom designs that were open and spacious. Educators believed the open-plan concept would allow children to learn more effectively and that self-motivation and self-direction would prepare the individual for a fuller, more satisfying life. Team-teachers shared classrooms and teaching responsibilities. However, many teachers did not embrace the team-teaching concept or the idea of relinquishing control of their classroom domain. In some cases, walls were added to open-plan schools, creating more traditional classrooms, but resulting in awkward interior environments both spatially and also destroying the original design intent for lighting and ventilation.

3.4.2 Conditions and Standards

The firm of Caudill, Rowlett & Scott Architects, led by partner William Caudill, marked the decade of the 1950s with daylighting and ventilation research aimed at understanding and improving conditions in classrooms. Many of their school designs used scale models to study lighting levels and air flow in wind tunnel and sky simulation facilities at the Texas Engineering Experiment Station (Figure 3.8). For the most part schools built during this time purposefully used daylight through skylights, clerestories, monitors, plastic domes, and glass block. In many cases research changed window geometry and increased attention given to controlling daylight, preventing glare situations, and controlling solar gain (with the use of louvers, diffusing baffles, external vegetation). The American Standard Practice for School Lighting called for a minimum illuminance of 30 footcandles on the desk (with a range to 70 fc depending on the task). Figure 3.1 illustrates recommended lighting levels for classrooms over the past century.

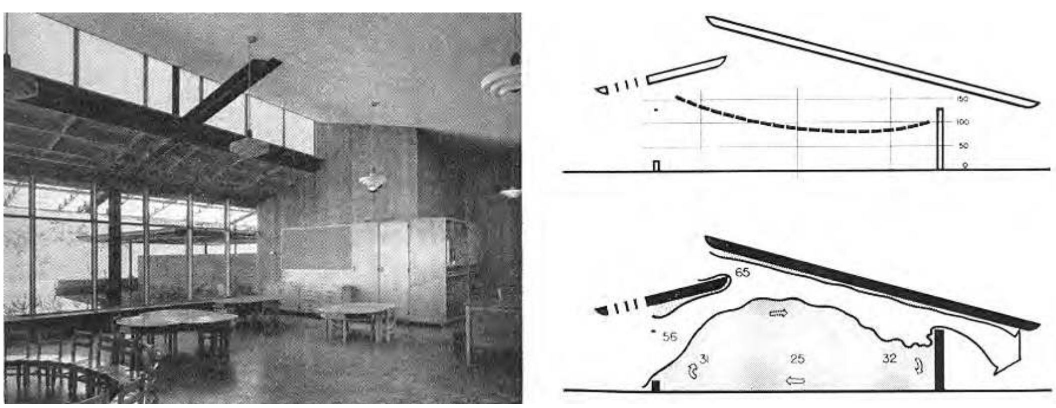


Figure 3.8 Testing for ventilation and lighting at an elementary school in Carmel by Caudill, Rowlett, Scott & Architects c. 1952 [35]

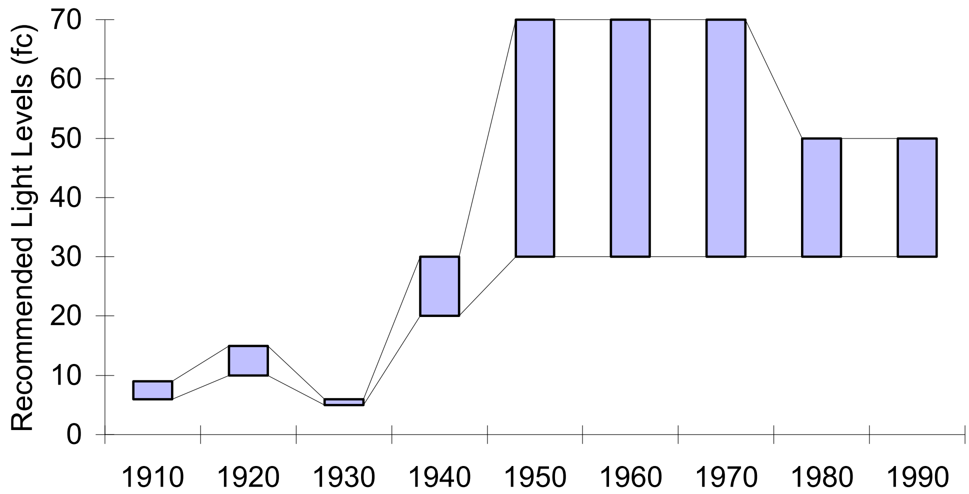


Figure 3.9 Recommended ranges of classroom lighting levels[36]

For schools that could afford air-conditioning, the rationale for doing so ranged from year-round climate control to cleaner and quieter classrooms. In addition, uniform illumination provided a means to eliminate the variable intensities of daylight.[37] Building design was increasingly driven by environmental technologies - the architectural artifacts included a reduced building perimeter, inoperable windows, minimized corridor lengths, and fewer stair towers. In similar fashion, engineers followed the guidelines of comfort standards developed for office environments (extrapolating for school activities. This begs the question: do conditions unique to the school context offer opportunities for saving energy?

The majority of today's school buildings are the products of a period when energy was inexpensive, thus energy efficiency of lighting, ventilation and cooling systems was of little concern. However, increased energy costs after the 1973 oil embargo led many school systems to adopt energy conservation policies, revamp operating procedures, throttle mechanical systems to save energy, seek alternative energy sources and design innovative buildings in order to cope with these issues. By the 1980s energy efficient design strategies had top priority in school design while research focused on monitoring energy usage to help reduce operational costs. Often these buildings formed less than satisfactory products - they do not provide the intended effect, at times seem to run "out-of-control," and rarely let the building occupants have any input.

Ventilation and air quality have been subjects of debate since the early part of this century. Today, the dialogue continues to be shaped by temperature requirements, advancing HVAC technologies, providing proper air exchange rates, and exhausting indoor pollutants. Recent studies about air quality and health in classrooms and their relationship to mechanical systems have led to a number of studies assessing indoor air quality by measurements of pollutant levels, ventilation rates, and HVAC diagnostics.[38]. This work primarily focuses on the efficiency of mechanical systems at providing the proper number of cubic feet per minute to classrooms. The review of literature revealed no work that examines ventilation efficacy and health symptoms in naturally ventilated and air-conditioned classrooms. *Ventilation for Acceptable Indoor Air Quality* (*ASHRAE Standard 62-1989*), specifies ventilation rates to provide acceptable air quality and recommends a ventilation rate of 15 cfm per person in classrooms.

Today, 75% of the nation's school buildings are in need of repair or renovation. A recent survey found 31% of our schools were built before WWII and 43% were built during the 1950s and 1960s (Figure 3.10).[39] A recent GAO report on the condition of schools in the U.S., estimated, " . . . one-third of the nation's schools (25,000) are in need of extensive repair or replacement of one or more buildings, affecting more than 14 million students. Even more students, 28 million, attend schools nationwide that need one major building features (e.g. plumbing, ventilation) extensively repaired, overhauled, or replaced or contain an environmental unsatisfactory condition, such as poor ventilation, heating or lighting."[40] Schools need $11 billion to comply with federal mandates of the next three years and an estimated $101.2 billion just to them into good condition.[41]

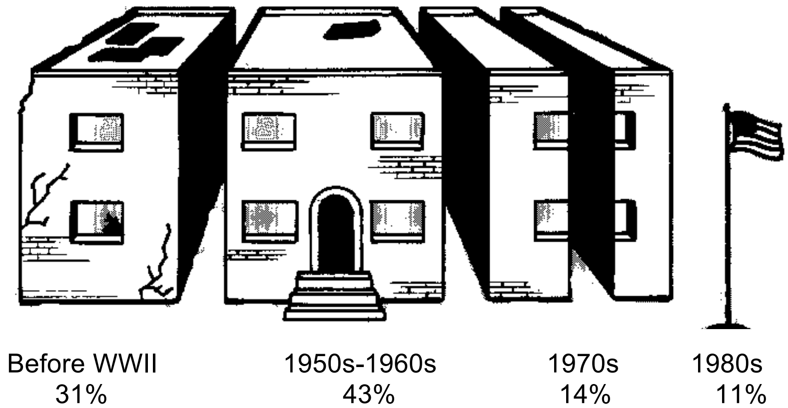


Figure 3.10 Age of existing school buildings in the United States[42]

Changes in demographics also influence the construction of schools. 47.5 million children now attend primary or secondary school, a figure which is expected to grow to 49.9 million by the year 2000, though the prediction may well be low because it does not account for new census data showing higher birth rates for minority populations.[43] With growing minority populations, the needs for special programs will increase, as will the efforts to reduce class size, resulting in the pressure for more space.

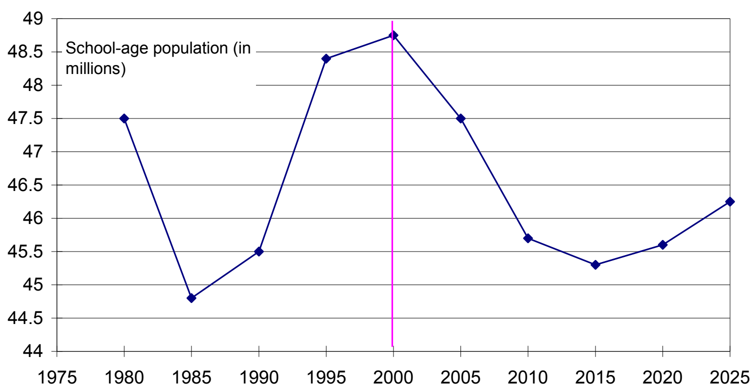


Figure 3.11 Estimates and projections of school-age population in the U.S.[44]

With new construction on the horizon, many school districts will face the question of whether to air-condition school classrooms - a decision with the potential for long-term operational costs. Architects and engineers use thermal comfort standards, such as ASHRAE Standard 55-1992 (see Table 3.1) to guide the design of systems that will provide a comfortable physical environment. How this standard performs in school environments is an area needing additional research, since most studies currently focus on the office thermal environments.

3.5 Future

3.5.1 Pedagogy and Design

Leading thinkers of educational reform advocate a "project-based" learning approach that allows students to work individually or in small groups on projects tailored to their own learning styles. This idea evolved from Howard Gardner's work at Harvard University which postulates that we have at least seven different kinds of intelligence and that we need to play to students' strengths and skills rather than centering education around test-taking. These ideas combined with the new computer and video technology, rising immigrant populations and the realization that many of our traditional school settings are inadequate to serve the needs of both teachers and students, will inevitably change the way we plan and design schools.

Some believe the future of our schools lies in the community. Recalling the community-school concept of the 1970s, many schools today stay open 14 hours a day to offer adult education classes in the evening, provide library and meeting facilities for the entire community, and host recreational activities year-round. Selim Iltus, architect and co-director of the Children's Environments Research Group at the City University of New York Graduate Center feels that community involvement is the key to schools of the future. . . . The school has to be seen as a resource for everyone."[45]

Others believe future of education lies in the growing impact of the private sector. The Edison Project, a profit venture, headed by the former Yale president, Benno Schmidt, hired four well-known architecture firms (Venturi Scott Brown & Associates, Frank Gehry Associates, William Rawn Associates, and Billes/Manning Architects) to come up with designs of schools which Edison would own and operate. Similarly, other projects prototypical designs for urban and suburban schools.[46]

3.5.2 Conditions and Standards

The question of what factors will define the environmentally sensitive school of the 21st century could be in the areas of energy efficiency, indoor air quality and health issues, occupant comfort, recycled building materials, working with the climate, or a combination of all of these. The efforts to achieve such building practices (air quality and rely to a large degree on current guidelines and standards such as *Standard 62* for ventilation and *Standard 55* for comfort.

3.6 Summary

This survey suggests that trends in education will always change. Architects must to be prepared to satisfy short-term needs, while keeping an eye on the possibilities for flexibility in the long-term. Comfort standards began their development in the schools. Now, controlled climate-chamber experiments have taken the place of those former field studies in classrooms. The current status of conditions in America's schools, combined with the rising school-age population, and trends toward year-round schooling, schools will need to be renovated or constructed in the near future. As an economical matter, few school districts have the financial resources to air condition new or existing facilities.

It is quite possible that natural ventilated schools might meet or exceed the engineering standards. In fact the practical point is, those schools using natural ventilation strategies may in fact bring their buildings closer to meeting the ideal comfort standard than schools environments without air conditioning. Before making such conclusions, additional work is needed to fill the gap in our knowledge about the physical environment and thermal comfort in schools. Thus, we return to the main thesis of this dissertation, the objective of which ascertains the applicability of comfort criteria of ASHRAE Standard 55-1992 in naturally-ventilated and air-conditioned schools in the tropics.

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CHAPTER 4

DESIGN OF THE STUDY: RESEARCH METHODS AND EQUIPMENT

4.1 Introduction

The methodology, equipment and research strategies described in this chapter return to my original question: how does *Standard 55*– the guarantee of producing comfortable and satisfactory thermal environments anywhere in the world, in any building type, perform in the hot and humid tropics? Evaluating comfort requires characterizing a subjective state of mind and the surrounding physical conditions that produce the comfort experience.

Toward this end, I use a variety of approaches to collect and analyze data, such as, interviews, observations, survey questionnaires, physical measurements, and statistical analysis common to thermal comfort field survey techniques. For example, in this experiment subjects respond to questions about their thermal environment, while data acquisition equipment simultaneously measure indoor physical conditions. Such data gathering and analysis techniques draw upon protocols used for office studies of thermal comfort and adapted for the school context. Since this work covers new ground, the methods derived for office settings are assumed to stand up in a school settings.

Prior to the start of the field study, I made two preliminary trips to Hawaii to interview school administrators and teachers, take spot measurements of classroom conditions, and preview potential schools buildings as candidates for this case study. Information gathered on these trips re-shaped the basis of my original questions and allowed me to prepare for field conditions that would otherwise have taken valuable time during the actual study. To “rehearse” the field process, I conducted a pilot test of the equipment, survey questionnaire, and protocol at a high school in Sacramento, California. This helped modify aspects of the questionnaire, such as developing clothing lists appropriate to high school students rather than office workers. For other nuances of conducting a study in a school setting (local customs, class schedules, length of class periods, busy times of the year for teachers and students, etc.), I relied on my past teaching experiences and the suggestions from participating teachers. The design of this study is outlined in this chapter beginning with a discussion of Hawaii climate conditions, descriptions of the schools and sample selected, and followed by an outline of research methods, instrumentation and field measurement protocols used during the field investigation.

4.2 Climate of Hawaii

Hawaii's archipelago stretches over many miles of the Pacific Ocean and although the islands have little land area, three other states are smaller-Connecticut, Delaware, and Rhode Island. With a total area of 10,380 square kilometers (6,450 square miles), Hawaii lies within the tropical zone (Miami is 500 miles further north), with the southern tip of the island of Hawaii at 18.0°N latitude to the northern coast of the island of Kauai at 22.15°N (see Figure 4.1). Like many Pacific island groups, Hawaii's geography contributes to a diverse range of climate conditions. Tropical rain forests against windward slopes of volcanoes receive up to 300 inches of rain per year, in contrast to regions shielded from the prevailing tradewinds, some dry enough to be classified as a desert.

There are two seasons: "summer," between May and October, when the weather is warm and dry, with persistent tradewinds; and "winter," between October and April, characterized by cool, rainy periods and interrupted tradewinds.[1] While most people consider Hawaii's climate ideal, Hawaii is often warmer than the traditional comfort zone. Mean temperatures for the summer and winter seasons are 27°C and 22°C, respectively, with maximum temperatures during the summer season reach 34°C. Relative humidity ranges from 50-85% during the year.[2]

After reviewing climatological summaries of the hot summer and cool winter seasons, and class schedules of participating schools, I scheduled the first field survey during the hot season in the months of September and October 1995, and a second survey during the cool season in the months of January and February 1996.

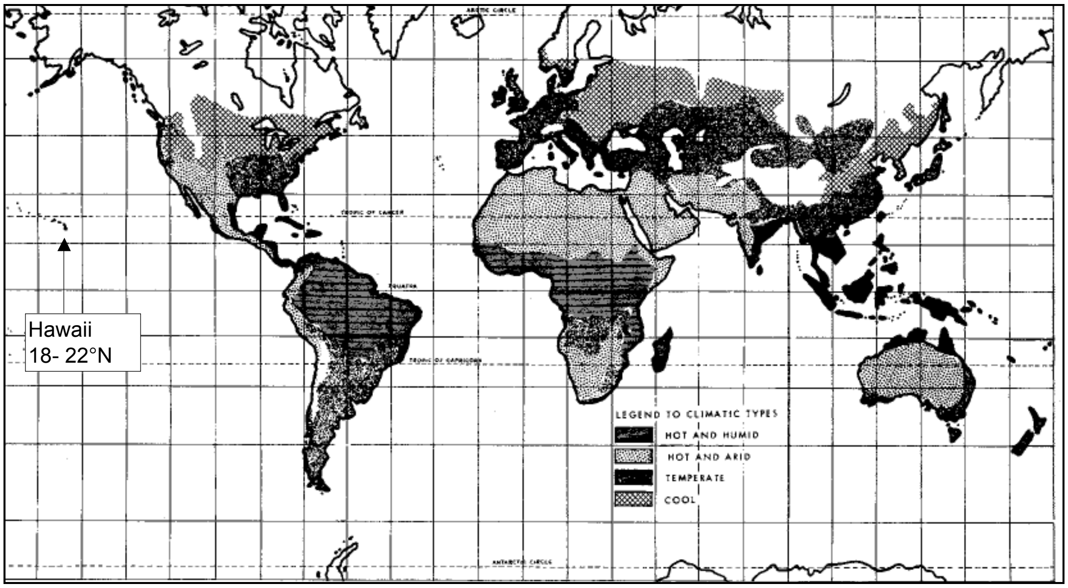

Figure 4.1 Map showing Hawaii location in the tropics[3]

4.3 School Buildings and Classroom Descriptions

Several criteria guided the selection of school buildings in this study. These criteria included a balance of air-conditioned and naturally ventilated classrooms; a mix of public and private schools; permission and accessibility granted by school administrators; the willingness of faculty to participate; project budget; logistics and time. Because of the technical equipment used and the nature of this study, science classrooms seemed the most appropriate rooms to conduct the field study.

Preparation for the study included compiling a list of candidate public and private high schools, meeting with school administrators and science department chairpersons to describe the objectives of the project, asking for volunteer participation (from teachers) and making spot measurements of temperature, humidity and air movement in candidate classrooms. Table 4.1 summarizes the six schools selected for the study. Buildings E_1 and E_2 are keyed as separate buildings, though they are on the same campus. All others represent different schools.

Table 4.1 Summary of the 6 school buildings and classrooms surveyed

School Code	Location	Year Constructed	# of Classrooms	Type of School	Ventilation Type	# of Subjects
A	Maui	1995	1	Public	NV	77
B	Hilo	1988	2	Public	NV	68
C	Maui	1995	1	Public	NV	20
D	Honolulu	1955	8	Private	NV	1035
E_1	Honolulu	1965	8	Public	NV	981
E_2	Honolulu	1965	2	Public	AC	182
F	Honolulu	1966	7	Private	AC	1181

4.4 Subjects

The subjects for the study were primarily high school students, polled during their regular science classes. School faculty also participated in the survey. Multiple classes took the survey, while teachers completed the survey with only one of their classes. Details summarizing the sample are provided in Chapter 5.

4.4.1 Recruitment Method

There is no precise way to specify sample size. Generally for statistical analysis, the more data the better - "Wider interval levels are more likely to trap population value; hence, more confidence can be placed in them.[4] But against this must be set the amount of work needed to complete the record, and the dangers of carrying the experiment on for too long a period-which can in effect reduce the coherence of the set.[5] Using sample sizes from previous office studies (ranging from 600 to 2,000 subjects) as a guide for studies of this sort (since there is no baseline to follow), the goal in this study was to achieve a minimum sample size of 500 subjects in air conditioned classrooms and 500 subjects in naturally ventilated classrooms for both seasons.[6]

Two basic forms of sampling are typically used in field studies: *transverse* or *cross-sectional* sampling, those that survey a large population once and *longitudinal* sampling, where the number of subjects is typically smaller and large amounts of data are collected from each individual. Most of the recent field studies used the cross-sectional approach. For example, Schiller et al. in 1988 gathered 2342 sets of observations in 10 office buildings in 2 seasons in both cross-sectional and longitudinal surveys; Busch in 1990 obtained 1146 data sets from different subjects in 4 buildings (cross-sectional); and de Dear et al. in 1993 surveyed 1234 subjects in 12 office buildings during 2 seasons (cross-sectional).[7] My choice of research design for this study was the cross-sectional method to follow similar data collection of previous studies and because it was appropriate for the school setting (tracking individual student responses from season to season had little practical value).

During my preliminary trips to Hawaii, prior to the start of the field survey, I recruited students and teachers in a series of meetings with school administrators and department chairpersons to explain the objectives, methods, and what their level of involvement would be over the two survey periods. The administrators and teachers responded with enthusiasm and voluntary participation, leading to a larger sample than anticipated.

Because the students participating in the field study were minors, the questionnaire used in the survey, went through a review process by the University of California's Committee for Protection of Human Subjects to assure compliance with federal regulations. Additionally, each school's administrators and teachers reviewed the questionnaire and procedures. Participation in the field study, which took place during a regular class meetings, was not made a part of a student's grade or any part of the academic work. To assure confidentiality, we assigned numerical codes to the questionnaires after subjects completed the survey and did not request participant names.

The students had no prior knowledge about the nature of the study. Several teachers informed their classes that a survey would take place during an upcoming week, but generally students were not aware of the survey until the day that I entered their classes. Each teacher introduced me as a graduate student from the University of California, Berkeley, conducting research on Hawaiian schools. The second visit during the cool season required coordination with teachers' schedules. Some of the students remembered the previous survey (4 months prior).

4.5 Indoor Climate Measurements and Equipment

The process of monitoring the immediate thermal environment of the subject has changed considerably in the past ten years because of the remarkable development of economical microprocessor-based instrumentation and data storage devices enabling easy collection of substantial amounts of data.

To synchronize the physical measurements with the subject votes, Schiller et al. in 1988 used a set of instruments (datalogger with a cassette tape, sensors at three heights, portable laptop computer) adapted to an actual office chair and took measurements by moving the "chair" into the desk space after the subject completed a comfort survey.[8] Busch in 1990 assembled instrumentation (datalogger with cassette tape and sensors) into what he describes as a "toolkit" in appearance, carrying the toolkit from workstation to workstation to measure within five minutes of completion of the questionnaire.[9] Recently implemented in an office comfort study by de Dear et al. in 1993, a mobile measurement cart (MKII) refined the chair concept and used an updated data acquisition system coupled with ancillary environmental parameters, such as illuminance in the horizontal plane.[10] All of these monitoring efforts require asking the subject to move from their chair so the measurements can be made.

The design of the indoor climatic measurement system for this study sought the least disturbance to the normal class routine, while still retrieving data accurately during each classroom visit. The equipment fit compactly on a laboratory tray or cart (Figure 4.2) with the sensors located at a height of 1.1 meters (43 inches) above the floor. The instrumentation remained stationary at a mid-location in the classroom for the duration of each classroom visit. From the previous studies mentioned, the *Standard 55* instrumentation specifications, and given the financial limitations of this study, I established the following set of criteria in the development of the classroom measurement kit:

1) **Multi-sensor data collection**. Dry bulb temperature, globe temperature, relative humidity, air velocity, and carbon dioxide sensors were to be connected to the data acquisition system and laptop computer;
2) **Location and position**. Although *Standard 55* specifies that measurements air temperature and air velocity be measured at three heights (0.1, 0.6, and 1.1 m) above the floor, I selected the 1.1 m height as the zone of the seated occupant that would most likely to be engaged by thermal variables, such as air velocity. A single location

was selected to represent the classroom environment as a whole, and the instrument kit did not move during the period in which the subjects completed the questionnaire.

3) **Instruments and accuracy**. Sensors measuring air temperature, mean radiant temperature, air movement, and humidity were to be accordance with the range, accuracy, and response time specified in *Standard 55*.[11]
4) **Portability**. Since up to 6 classroom measurements could potentially occur each day, it was essential to design a setup that could be easily transportable between classrooms in terms of weight, with the least possible chance to disturb the sensors, and with a quick set-up and connection to the data acquisition system.
5) **Visual access**. I needed a means for viewing real-time measurements to check proper functioning of the sensors and equilibrium of equipment during the measurement period, without the instrument panels or laptop screen being within sight of the subjects as they completed the surveys.
6) **Data retrieval**. All physical data collected from the sensors should be translated and downloaded to the laptop computer at the end of each day's classroom visits.

In accordance with these criteria, the organizing feature for the equipment assembly was a sensor mounting bracket (holding the temperature, globe temperature and relative humidity transducers) attached it to a small, telescoping monopod. This entire assembly connected to the data acquisition system, which served as a weighted base. The telescoping monopod allowed slight height adjustments to maintain the specified 1.1 meter height (Figure 4.2).

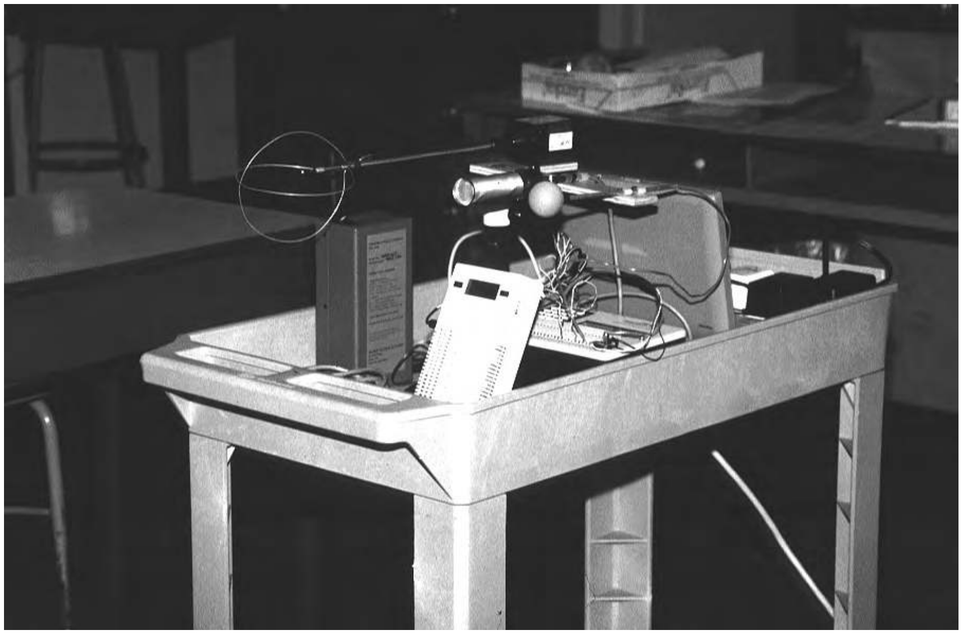

Figure 4.2 Equipment to measure indoor climate

Equipment and transducers chosen to measure the classroom environment included:

Temperature and relative humidity. The system applied a Campbell Scientific 207 transducer/probe measuring both temperature and relative humidity. This probe uses a Fenwal Electronics UUT51J1 thermistor and a Phys-Chem Scientific PCRC-11 RH sensor. The sensors are housed in a 41004-5 12 Plate Gill Radiation shield, surrounded by a stainless steel fine-mesh screen for protection against impacts. The temperature sensor's error is ±0.2°C between 0 -60°C, while the overall RH sensor accuracy is measures within 5% between 12 - 100% relative humidity.[12]

Globe temperature. To measure globe temperature, I constructed a globe thermometer using a 38-millimeter table tennis ball and type "T" thermocouple wire. The globe (table tennis ball) contained the bared, twisted and flattened tip of the thermocouple wire in its center, held in place by threading it through a metal tube. The globe is finished with matt grey paint for proper emissivity, with the goal of balancing radiative gains and convective losses for a particular environment (e.g. a particular air temperature, air velocity and mean radiant temperature of the surrounding surfaces in a classroom).[13] If dry bulb temperature, globe temperature, and air velocity are simultaneously collected, then mean radiant temperature may be calculated using the following equation from the *ASHRAE Handbook of Fundamentals*[14]:

$$\bar{t}_r = \left[(t_g + 273)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} (t_g - t_a)\right]^{1/4} - 273$$

where,

$\bar{t}_r$	=	mean radiant temperature, °C
t_g	=	globe temperature, °C
V_a	=	air velocity, m/s
t_a	=	dry bulb temperature, °C
D	=	globe diameter, m (0.038 m for 38 mm table tennis ball)
ε	=	emissivity (0.90 for matt grey globe)

Air movement. The kit used an omni-directional, temperature-compensated anemometer from TSI to measure air velocity. This transducer functions as a heated element that is kept at a constant elevated temperature (relative to ambient temperature) by means of control electronics. As airflow past the sensor increases, more electrical power is required to maintain the sensor at the elevated temperature and is then translated into an air velocity measurement. This anemometer does not have a fast enough response time to accurately estimate turbulence intensity in indoor air flows. A guard made of baling wire formed a protective cage around the tip of the anemometer to protect the sensor from accidental bumps in the classroom environment.

Data acquisition system. The "heart" of the kit is the Campbell Scientific 21X datalogger which controls the timing and sequence of sensor-polling through a designed to process the signals and relay data to a laptop computer for display and storage. Once the data collection sequence begins, the datalogger polls the sensors at 1-second intervals, stores 5-minute averages while the connected laptop simultaneously displays the parameters graphically. The system collects data from the sensors at 1-second intervals for all the sensors. An averaging function programmed into the datalogger then averages the data every 5 minutes. At the end of the each class visit, I downloaded the final averages to the laptop's hard disk along with data from the other transducers and assembled the data into a set of conditions representing each class visit, using only the data after the point of equilibrium.

The instrumentation kit also measured non-thermal variables. The following handheld instruments which were located next to the kit, included a carbon dioxide monitor connected to the Campbell data acquisition system and a particle counter that operated independently on its own data acquisition system.

Carbon dioxide. The Telaire 1050 carbon dioxide monitor functions by sampling air through a diffusion process where air is drawn in and passed through an infrared sensor. Before and after each season's field study, I calibrated the CO_2 monitor to insure the unit's accuracy and as a check against drift. CO_2 levels are digitally displayed and can be compared to the 1000 ppm guideline specified by *Standard 62*.[15] CO_2 levels are sometimes used as a proxy for ventilation effectiveness – higher concentrations of CO_2 indicating less effective ventilation, though there are no known biological consequences associated with high CO_2 levels. The instrument's digital display shows readings of 0-1,999 ppm of linear output. Higher readings, up to 5,000 ppm, can be recorded using the device's analog output feature.

Particles. The Biotest APC-1000 airborne particle counter samples and counts particles of 0.3, 0.5, 1.0 and 5.0 microns in diameter (within the range of "lung damaging dust") which are suspended in the classroom air, by pumping air into a chamber containing a laser diode and optical components, at a rate of 0.1 cubic feet of air per minute. The instrument used in this study received factory calibration prior to the start of each season's field study. Although there are no indoor air standards for particulates at this time against which to make comparison, I considering using particle counts to compare relative differences between the two buildings types. *Standard 62*'s table 1 does offer requirements for *outside air* maximum particle concentrations (National Ambient Air Quality Standard for Outdoor Air, NAAQS) set by the Environmental Protection Agency; and table 2 provides outdoor air requirements for ventilation. However, the standard reflects gravimetric (mass) data as a metric, and requires air monitoring for a minimum of three consecutive months.

4.6 Concurrent Outdoor Climatological Measurements

Monthly summaries (including 3-hour interval data) of local climatological data from Honolulu, Maui and Hilo airports, provided outdoor meteorological variables such as temperature, relative humidity, wind speed and direction, and other variables necessary to evaluate characterize ambient conditions. The summaries included minimum, maximum, and average temperatures for each day as well as observations at 3-hour intervals. Figure 4.3 and Figure 4.4 show the outdoor daily minimum and maximum temperature and relative humidity recorded during the two seasons of the field study.

Temperatures during the survey periods of the hot and cool seasons fell within ranges of 24-33°C and 20-29°C respectively. Relative humidity was higher during the cool season than in the hot season, occasionally reaching 90%. The thermal conditions of warm temperatures and high humidity, contribute in part to making Hawaii a suitable setting to carry out this study.

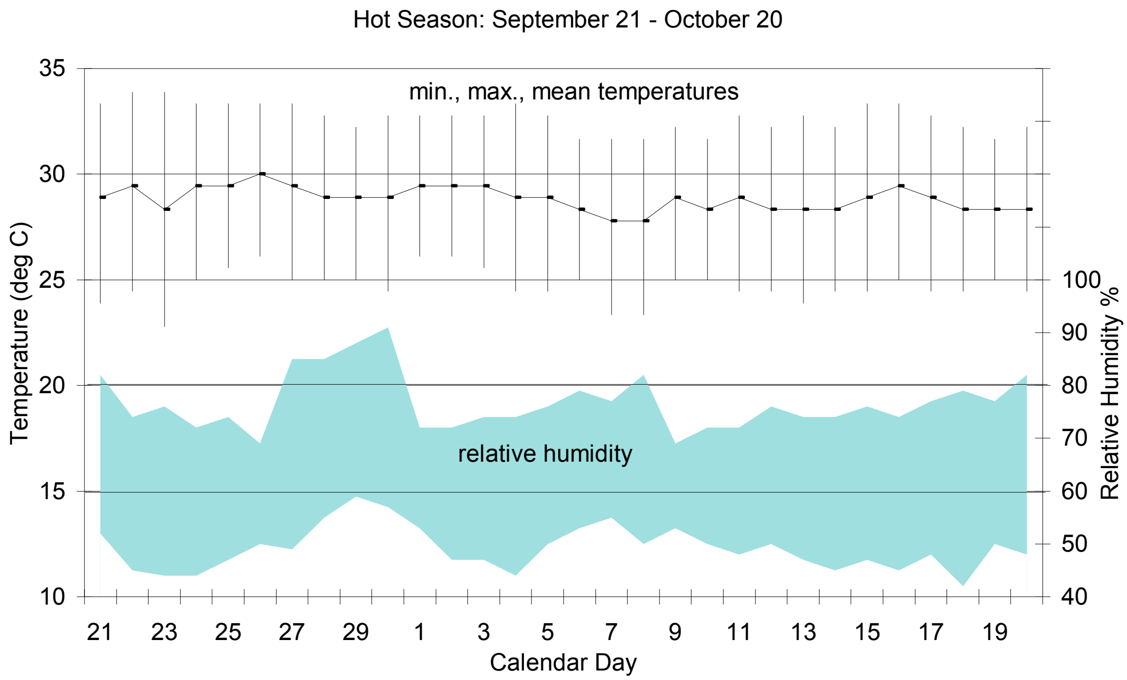

Figure 4.3 Hot season daily outdoor minimum and maximum temperatures and humidity

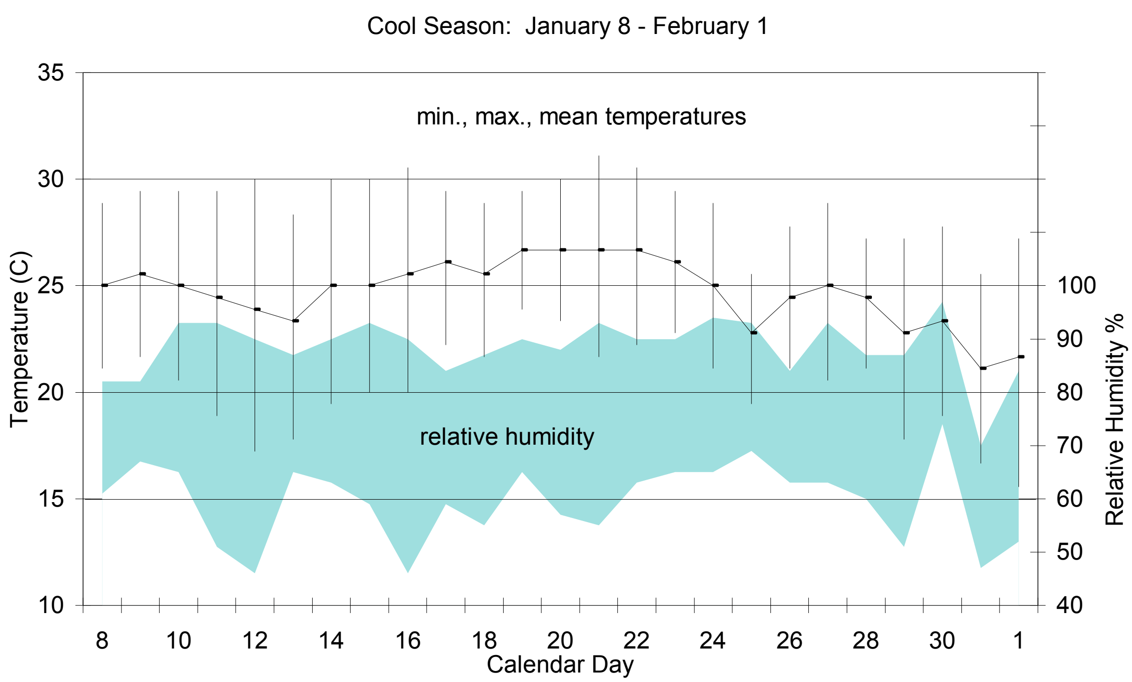

Figure 4.4 Cool season daily outdoor minimum and maximum temperatures and humidity

4.7 Standardized Questionnaire (Subjective Survey)

The six-page comfort survey (Appendix A) used in this study has questions in several categories. Some of the thermal comfort questions emulate classic thermal comfort field studies which asked subjects to assess their comfort on a variety of subjective scales (common scales described in Chapter 4), especially the ASHRAE 7-point thermal sensation scale. Most studies use this scale to determine neutral temperature, a temperature (ET* or T_{op}) at which the greatest percentage of people are expected to vote within the central "neutral" category of the sensation scale. In addition to personal thermal comfort questions, the questionnaire also included queries about indoor air quality, acoustics, and the influence of environmental factors on classwork. Combining the questions of past thermal comfort surveys and recasting them into the school context led to seven sections: personal comfort, environmental conditions, indoor air quality, acoustical conditions, clothing responses, general background information, and demographics. Thematically these sections fall into five sections of inquiry:

1) **Thermal Comfort**: The first section asks about the respondent's current status of thermal comfort using different scales: thermal sensation, preference, overall comfort, and acceptability. Responses to these conventional questions would allow comparisons to the comfort zone specifications and the 80% acceptability criteria of *Standard 55*. Responses would also enable comparisons to be made to the results of other office studies, and test the efficacy of using such a questionnaire in a school setting. Various comfort scales used in this section ask the respondent to make a subjective rating of their thermal condition while in their current and immediate classroom environment. The first question used the ASHRAE Thermal Sensation Scale, a continuous seven-point scale (cold = -3; cool = -2; slightly cool = -1; neutral = 0; slightly hot = +1; warm = +2; hot = +3). Respondents answer this question by marking an "X" along the graphic scale. This was followed by the McIntyre Preference Scale, "Right now I would prefer to be: cooler, no change, warmer." Third was general comfort scale question asking subjects to rate the overall

comfort of their classrooms, ranging from “very uncomfortable” to “very comfortable”. Although not considered a scale, but important for comparison to the satisfaction criteria found in *Standard 55* is the question of acceptability. Respondents were asked to rate their current thermal conditions as “acceptable” or “unacceptable” by checking a box. Questions on other variables such as humidity, air movement, air quality and acoustics subsequently used the format of the preference and acceptability scales.

2) **Classroom Environment**: The next section requested information about environmental conditions and their influence on school work. Responses between naturally-ventilated and air-conditioned classrooms might differ because of environmental conditions related to the design of the classroom. For example, we might presume that air velocities are higher in naturally-ventilated rooms. One of the questions in this section asks: When you have experienced too much air movement, how much does it interfere with your school work? Other questions asked whether air quality and acoustical conditions were problematic for students. In this study, I will make relative comparisons between these conditions in an attempt to verify anecdotal accounts of differences between naturally-ventilated and air-conditioned classrooms.
3) **Clothing**: This section asked about clothing worn by the subjects during the class visit. Thermal comfort researchers and Hawaii school administrators reviewed the survey for question construction, sensitivity, and semantic accuracy pertaining to the school context and Hawaii culture. *Standard 55* provided a starting point for clothing descriptions and insulation values. I adapted the clothing descriptions from the typical format used in office studies because of school dress codes, local tropical dress customs, and particular fashion patterns present among the student subjects. I added a number of clothing descriptions pertaining to teenage clothing items such as T-shirts, aloha shirts, shorts, jeans, athletic shoes, and sandals and did not separate clothing by gender. Respondents checked off the clothing items that most closely matched what they were wearing during the survey.
4) **Subject Demographics**: The final section gathered descriptions about age, gender, weight, height, and number of years spent in the tropics, but omitted ethnicity questions since the sample was drawn from a heterogeneous population of Chinese,

Japanese, Caucasian, Filipino, Korean, Portuguese, Hawaiian, and Native American extraction. It would have been impolitic to ask respondents to identify with a particular ethnic group. A series of questions also asked about the subjects' experiences with previous air-conditioned spaces to see if air-conditioning use might influence the comfort response.

5) **Open-ended Questions**: Several questions at the end of the questionnaire gave the respondents an opportunity to give general comments about the environmental conditions in their classroom and what might make them more comfortable.

The format and presentation of the questionnaire were important considerations in motivating participants to complete it. "White space" between the questions allowed each question to appear with maximum clarity. Since the order in which the questions are asked can affect responses as well as the overall data collection activity, the questionnaire began with the most interesting questions (perhaps the most valuable questions) in the first section, leaving the routine and open-ended questions to the last section. The intent here is that the respondent who glances casually over the first few questions should want to answer them. If it looks routine, there might not be the motivation to complete it[16] To facilitate data compilation and eliminate keypunch errors, the questionnaire was "pre-coded," by assigning small numerical codes next to the response set of each question.[17] Questionnaires were reproduced as double-sided copies because of the number of copies needed, funds available, and to conserve paper. Most of the schools require their teachers to reproduce their assignments as double-sided copies.

4.8 Indices and Scales

Researchers use several indices to predict and define comfort. The indices are classified as *environmental* if they pertain to parameters such as temperature, mean radiant temperature, humidity, or air velocity, or as *comfort* indices if they predict specific physiological responses. Indices are also classified depending on how they are developed, (e.g. rationally, empirically), or according to their application, (e.g. heat stress or cold stress).[18]

The following section presents a glossary of the environmental and comfort indices, referred to later in this dissertation:

Environmental Indices

ET* (New Effective Temperature) - ET* is the temperature of an environment where air and mean radiant temperature are equal to each other, relative humidity is 50%, and air velocity is 0.1 m/s, in which heat loss is the same as that which a sedentary person would experience in the actual, measured environment. Developed by Gagge, ET* forms the basis for *Standard 55*.[19]

SET* (Standard Effective Temperature) - SET* is the temperature of an isothermal environment (air and mean radiant temperature equal to each other, relative humidity of 50%, and air velocity of 0.1 m/s) in which a sedentary person with standard clothing would have the same heat loss (at the same skin temperature and skin wettedness) that the same person would have in an actual environment.[20]

Comfort Indices

PMV (Predicted Mean Vote) - The average, predicted vote on the 7-point thermal sensation scale by a hypothetical group of subjects when subjected to a particular set of environmental conditions. Based on Fanger's heat balance equation (1970), PMV forms the basis for the *ISO Standard 7730*.[21]

PPD (Predicted Percentage Dissatisfied) - The percentage of a hypothetical sample population who will be dissatisfied (uncomfortable) in a given environment. As PMV changes away from zero in either the positive or negative direction, PPD increases. It predicts the percentage of those dissatisfied on the thermal sensation scale, corresponding to the categories outside of the 3 central categories.[22]

DISC (Predicted Thermal Discomfort) - A predicted vote on a 5-point scale of thermal discomfort: intolerable, very uncomfortable, uncomfortable, slightly uncomfortable, comfortable.[23]

PD (Predicted percentage due to Draft) - The average percentage of a group of persons that will express thermal discomfort due to drafts. Calculated from air temperature, air velocity, and turbulence intensity.[24]

Comfort Scales. Rating scales, commonly used in assessing subjective comfort are shown in Table 4.2. The most widely used scale is the seven-point ASHRAE thermal sensation scale, where comfort is assumed to occur in the "neutral" region shown by the shading (-1 slightly cool, 1 neutral, +1 slightly warm). By inference, this is also the point of optimum temperature and maximum acceptability. Other scales depicted in Table 4.2 are the Bedford scale (not used in this study since it is found to be semantically similar to the thermal sensation scale), McIntyre's thermal preference scale (prefer cooler, warmer, no change), and thermal acceptability (acceptable, not acceptable).

Table 4.2 Common rating scales used in thermal comfort research

ASHRAE scale	-3 cold	-2 cool	-1 slightly cool	0 neutral	+1 slightly warm	+2 warm	+3 hot
Bedford	much too warm	too warm	comfortably warm	neither warm nor cool	comfortably cool	too cool	much too cool
Acceptability	unacceptable		acceptable			unacceptable	
Preference (McIntyre)	want warmer		no change			want cooler	

The questionnaire also included a six-point general comfort scale (very comfortable to very uncomfortable):

General Comfort	very	moderately	slightly	slightly	moderately	very
		uncomfortable			comfortable	

4.9 Measurement Protocol

Thermal comfort studies in office buildings often employ teams of two or three researchers to handle the various tasks of physical measurement and survey distribution. In this study, I carried out these tasks singly, though for a 3-day period during the hot season survey, six graduate students from the University of Hawaii gave assistance with survey administration and questionnaire coding. In a certain regard, conducting the field survey alone has the key advantage of maintaining control over the day-to-day data and questionnaire compilation. The protocol for the conduct of the survey followed these steps:

1) **Equipment**. Position the equipment tray in a central location within the classroom. Begin physical measurements after the start of the class period (classes typically meet for periods ranging from 45-90 minutes). During the first 5 minutes, check the display for proper functioning of the equipment and determine if the sensors have reached equilibrium;
2) **Introduction**. After approximately 25 minutes (the minimum time allowed for the students to reach a stable metabolic rate), present a brief description of the survey, explain its purpose and emphasize the importance of their responses;
3) **Survey distribution**. Upon receiving the questionnaire, students record the start time and room number (write the room number on the classroom chalkboard) in the space provided and ask questions if clarification is needed;
4) **Observations**. As subjects complete the survey, record additional observations and notes, the building room number, numerical codes, number of students, date, and time of day;
5) **Collect the surveys**. Allow subjects approximately 15 minutes to complete the survey, then collect them or allow subjects to bring them to the teacher's desk (a practice teachers often allow after students complete a test);
6) **Post-survey explanation**. Most classes requested that I give an explanation of the equipment and discuss the variables measured. This post-survey explanation occurs during the first survey period;
7) **Data retrieval**. When the class period ends, turn off the power to the sensors and retract the anemometer into its shield (for safety purposes), create a "stop section" in the data, to allow later matching of classroom environment data to each survey period. At the end of each survey day, import the data logger time- and date- stamped the data into a spreadsheet program on the laptop computer.
8) **Security**. After completing the data retrieval, place the equipment in a locked storage area, and take the laptop computer and surveys off-site for data analysis

4.10 Data Processing

Converting the raw data from the data acquisition system into a permanent spreadsheet for subsequent analysis required several of steps, with including operations and checkpoints prior to using the spreadsheet for statistical evaluation. The final Excel spreadsheet contained rows representing each subject, with their corresponding comfort responses, average indoor climate measured at the time of the class visit, corresponding calculated indices. The following diagram shows the sequence of steps to process the data:

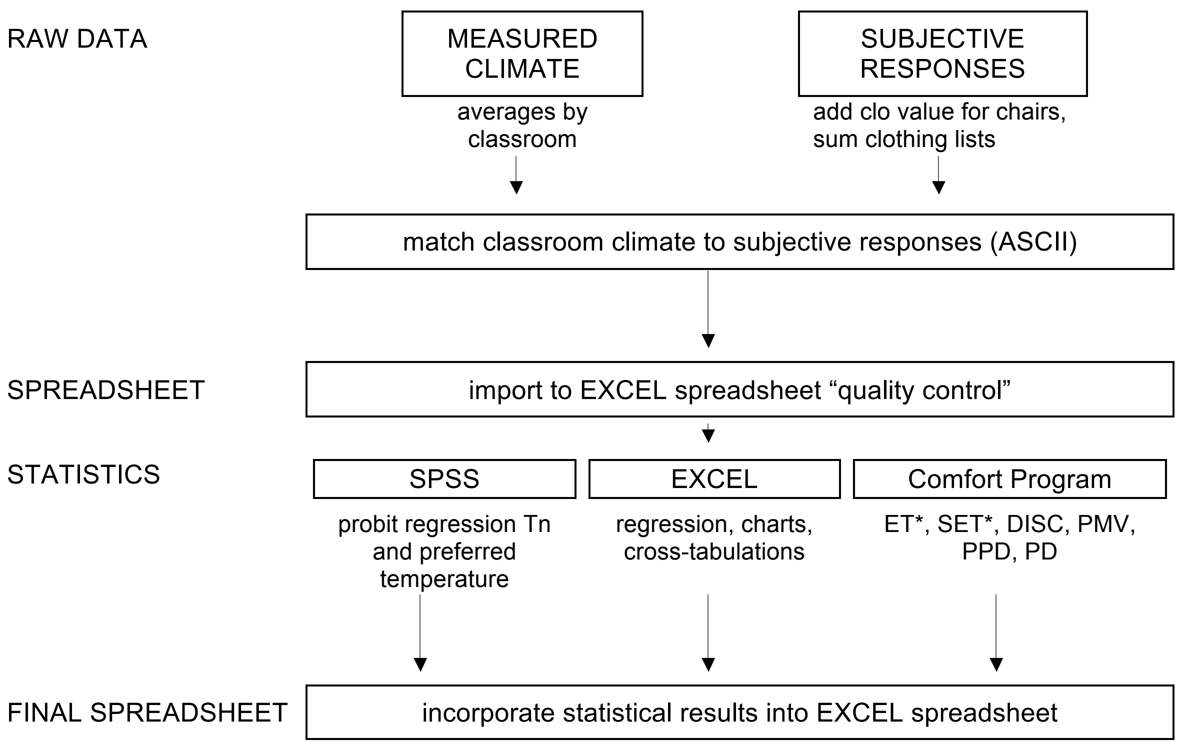

Figure 4.5 Data processing sequence

1) **Raw Data**

A. Climate data. At the end of each day, after downloading the indoor climate data contained in the Campbell Scientific to a microcomputer spreadsheet file, I created a set of average dry bulb temperature, mean radiant temperature (calculated), operative temperature (calculated), relative humidity, air velocity, carbon dioxide and particle data, for each class visit.

B. Questionnaires**.** Before keypunching the survey responses, each questionnaire received a code number for statistical purposes, and the totaled clothing insulation values:

> *Calculation of Clothing Insulation*. Insulation from clothing is typically expressed in terms of the clo unit, which represents the thermal resistance against heat loss provided by clothing covering the body. At the end of the day, I summed the reported clo values from the clothing checklists marked on the questionnaire (writing the total on a space provided on the questionnaire).
>
> *Effect of Chair Insulation*. Recent discussions about the effect of chairs on clo value indicate the incremental increase in clothing insulation value due to chairs should be included in the calculation of various comfort indices. Experiments on heat loss from an electronically-heated manikin in a variety of chairs established a value of 0.15 clo value as the clothing insulation increment for office chairs. [25] Since chairs used in schools are generally not of the cushioned type, I estimated the chair insulation value for a chair typically used in school classrooms (Figure 4.6) at 0.10 clo.[26] This number was added to the clo value in the final spreadsheet.

2) **Spreadsheet Structure**. The spreadsheet contained a row for each subject's survey responses and matched classroom climate data, thus 3,544 rows for this study. The columns of the spreadsheet are organized into four sections of information: a) subject responses to the questions of the survey, b) the averaged values for the indoor climate variables of the classroom measured by the data acquisition assembly, c) calculated comfort and environmental indices, d) outdoor meteorological (temperature) data matched to the date and time of each class visit.

Figure 4.6 Example of typical chairs used in Hawaii classrooms estimated to add an additional 0.10 insulative value

3) **Statistical Analysis**. Once the spreadsheet was organized, subsequent analysis and calculations using various software programs developed the results presented in Chapter 5. To calculate climate and comfort Indices, the ASHRAE Thermal Comfort Program[27] used data from the questionnaire responses matched to the averaged climate data collected in the classroom, to predict Effective Temperature ET*, SET* PMV, PPD, DISC, and PD. Analysis tools included with the spreadsheet software provided simple regression and cross-tabulation techniques to summarize, tabulate, and chart the data. Another software package (SPSS) contains probit regression analysis tools necessary for the calculation of neutral and preferred temperatures. *Probit analysis*,[28] an analysis method used to evaluate thermal comfort responses and temperature, and is originally drawn from studies of threshold pesticide levels and insect kill rates. Neutral temperature is determined by probit regression and has become the method of choice in determining neutral temperatures because it allows unequal increments of temperature between thermal sensation votes, as opposed to the equal increments with linear regression. Discussed by Ballantyne,[29] it also offers the advantage of being able to handle data that are shifted from a central tendency over the neutral category.

4.11 Summary

The methods, instrumentation, and measurement protocols used in this study come from those used in recent field investigations conducted in office buildings. The new approach taken here, applies these conventions to the school setting and using a sample comprise of the high school students and teachers in naturally-ventilated and air-conditioned classrooms in Hawaii.

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CHAPTER 5

RESULTS

5.1 Introduction

In this chapter, I examine the universal applicability of *Standard 55* to all building types. How do comfort standards, developed as air-conditioning standards in a temperate climate, function in a tropical climate and in buildings that are naturally-ventilated? I compare observed data with the prescriptions and acceptability criteria of *Thermal Environmental Conditions for Human Occupancy* (*Standard 55*). In most cases, my analyses compare responses and conditions in naturally-ventilated and air-conditioned classrooms, as well as other divisions of the entire sample to clarify or expand upon a point (e.g. hot season vs. cool season or hot season-AC vs. cool season-AC classrooms). A few sub-sections compare the field data to *Ventilation for Acceptable Indoor Air Quality* (*Standard 62*).

The applicability of comfort standards should be discussed in terms of both its temperature and humidity limits, the latter having continually changed over the last 20 years. For instance, the humidity-related limit of the comfort zone is of concern because indoor conditions of naturally-ventilated environments in tropical climates frequently lie beyond the limit, and therefore would not be considered to be "acceptable" if judged exclusively by the Standard.

The chapter is organized in four sections: section 5.2 provides demographic information about the sample such as size, gender, age, length of residence in the tropics, and use of air-conditioning; section 5.3 summarizes the thermal conditions in the classrooms and compares the results to the prescriptions of *Standard 55*; section 5.4 analyzes subjective, "observed" responses and compares them to the acceptability criterion of *Standard 55* and to predicted levels of acceptability; and section 5.5 summarizes the measurements of non-thermal variables in the classroom, such as carbon dioxide and particulate and discusses the influence of indoor air quality and acoustics on class work.

5.2 Descriptive Measures

5.2.1 Sample Size

Statistical summaries of the classroom occupants given in Table 5.1 describe the 3,544 respondents polled from classroom occupants at six schools during the hot (1,755) and cool (1,789) seasons. Most respondents took the survey twice, once in the hot season and once in the cool season, though no specific identification or "tracking" of subjects took place from season to season. Across both seasons, approximately two-thirds of the respondents (2,181) were from nineteen naturally-ventilated classrooms and the other third (1,363) were from nine air-conditioned classrooms. The sample included a total of 3,492 high school students and 52 teachers.

For some of the analyses, individual responses are expressed as group or classroom averages. For example, there were a total of 182 classroom visits to nineteen naturally-ventilated and nine air-conditioned classrooms (i.e. each class visit represents a different group of students. For example, a single classroom during the course of a day had up to 8 different groups or classes, therefore 8 class visits.). Each class typically contained approximately twenty students, however some groups were as small as seven students or as large as thirty-three. In most cases I discuss the data by classroom visit and use averaged data for classroom environmental conditions.

5.2.2 Gender and Age

The entire sample included 1,735 responses by men and 1,809 responses by women. Dividing the sample by students and teachers: 1,709 students were men and 1,783 students were women and of the teachers, 26 were men and 26 were women. Average age for the high school students was 16 years; and for teachers, 43 years. This study's sample represents roughly 2% of Hawaii's school-age children that are between the ages of 13 -19 years.[1]

Table 5.1 Statistical summary of building occupants

	ALL	SEASON		BLDG. TYPE		SUBJECTS	
		Hot	Cool	NV	AC	Students	Teachers
Sample size	3,544	1,755	1,789	2,181	1,363	3,492	52
Gender							
male	1,735	868	867	1,031	704	1,709	26
female	1,809	887	922	1,150	659	1,783	26
Age (years)							
mean	16.6	16.6	16.5	16.6	16.5	16.2	43.2
std dev	3.7	4.5	2.8	3.8	3.6	1.1	11.4
minimum	13.1	13.2	13.1	13.8	13.1	13.1	23.4
maximum	64.6	64.6	61.0	64.6	61.0	19.5	64.6
Height (cm)							
mean	166.3	166.1	166.5	166.2	166.5	166.2	170.4
std dev	9.4	9.4	9.4	9.6	9.1	9.4	11.2
minimum	127.0	127.0	137.2	129.5	127.0	127.0	152.4
maximum	208.3	208.3	195.6	208.3	198.1	208.3	193.0
Weight (kg)							
mean	59.1	59.2	59.2	58.9	59.5	59.0	71.8
std dev	13.0	13.3	12.7	12.9	13.1	12.8	17.4
minimum	31.8	31.8	34.1	31.8	34.1	31.8	45.5
maximum	149.6	136.4	149.6	149.5	135.5	149.5	122.7
Years in tropics							
mean	13.9	13.8	14.0	13.7	14.3	13.7	24.7
std dev	5.0	5.3	4.6	5.1	4.7	4.5	15.2
minimum	0.1	0.1	0.1	0.1	0.1	0.1	1.1
maximum	52.4	52.4	40.2	50.0	52.4	19.8	52.4
CLO							
mean	0.41	0.38	0.44	0.38	0.46	0.41	0.39
std dev	0.16	0.14	0.17	0.14	0.17	0.16	0.12
minimum	0.19	0.19	0.19	0.19	0.20	0.19	0.23
maximum	1.04	0.99	1.04	1.01	1.04	1.04	0.79

5.2.3 Length of Residence in Tropics

Figure 5.1 finds the majority of the sample residing in Hawaii for more than 15 years. Since the sample consists almost entirely of high school students, these results indicate that the subjects have had long-term experience with tropical climates (for most of their lives) and can be said to be acclimatized to the tropics. Hawaii residents are also accustomed to many air-conditioned environments, such as hotels, shopping malls, automobiles, restaurants and theaters, thus they have experience with and expectations associated with air-conditioned environments.

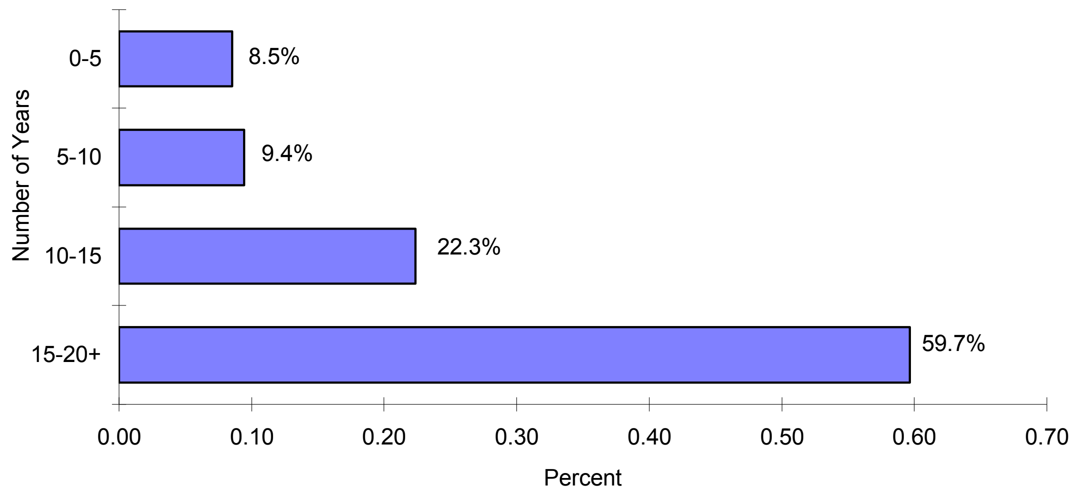


Figure 5.1 Length of residence in the tropics

5.2.4 Clothing and Metabolic Factors

Students and teachers wore clothing with an average insulation value of 0.38 clo during the hot season and 0.44 clo during the cool season. Table 5.1 shows the slight variability between seasons and ventilation type. Generally people wore more clothing (+0.06 clo) during the cool season than during the hot season and air-conditioned students wore more clothing (+0.08 clo) than in those in naturally-ventilated classrooms. This increase corresponds to a student wearing a long-sleeved rather than a short sleeved T-shirt, or long pants instead of shorts. Figure 5.3 divides the data by season, ventilation type and gender. The 0.04 clo difference between seasons for naturally-ventilated subjects can be considered a slight seasonal adjustment for cooler ambient conditions. However, the 0.10 clo difference from hot to cool season for the air-conditioned subjects might be caused by more than just a seasonal adjustment. – perhaps involving a psychological adjustment in the expectation that the air-conditioned rooms would feel cool or cold.

Clothing levels between gender were virtually the identical between seasons in both naturally-ventilated and air-conditioned classrooms. I observed students carrying sweatshirts or jackets and adjusting clothing levels as much as eight times a day, as they moved in and out of air-conditioned classes or the library.

Hot season attire

Cool season attire

Figure 5.2 Typical attire for students in Hawaii schools. The students in the left photo are wearing approximately 0.4 clo during the hot season. On the right, all three students are wearing an average of 0.6 clo during the cooler season (note the long sleeves).

Clothing fashion in schools differ greatly from office attire. Dress codes in schools allow students to wear shorts and T-shirts, though rules at one school indicated that boys must wear collared shirts. Typically, both male and female students wore similarly fashioned clothing such as cotton T-shirts, shorts, and athletic shoes. Footwear is required of all students, specifically covered footwear to be worn in science laboratories, where the surveys took place. Local fashion for some boys included wearing two pairs of shorts, “baggy” walking shorts worn over a set of swimming trunks. Several boys wore baseball caps, backwards for fashion reasons other than sun protection. I expected to see fashion trends dominating clothing preference. Instead, students appeared to dress comfortably, casually and appropriately for the climate.

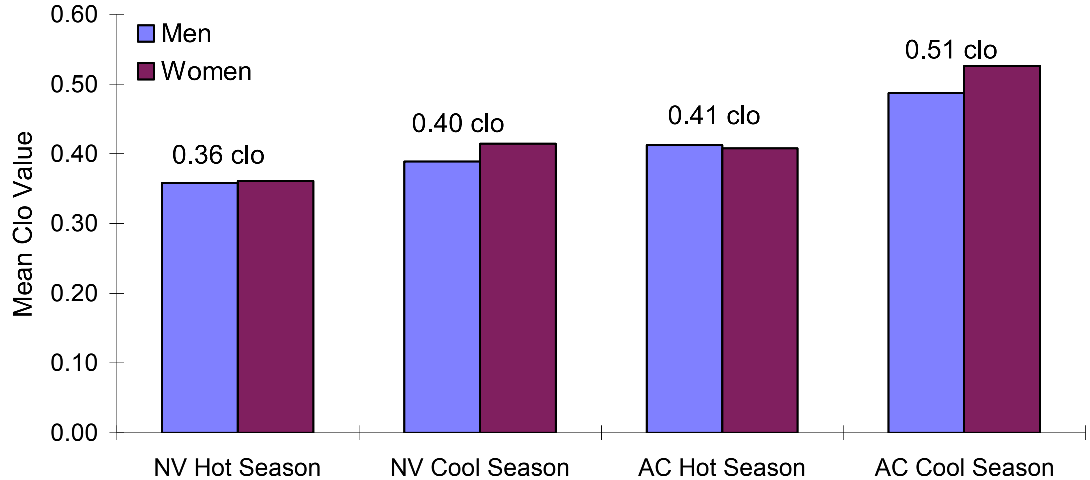


Figure 5.3 Mean clo values by gender

Metabolic rates were estimated to be 1.2 met (70 W/m^2) in both seasons for both genders, which corresponded to light office activity in *the ASHRAE Handbook of Fundamentals*.[2] Most students were seated and taking notes. Occasionally, classes were involved in laboratory activities such as standing and looking into a microscope, or seated while watching an experiment.

5.2.5 Use of Home/Car Air-Conditioning

Approximately 40% of the sample has air-conditioning installed in some of the rooms or their entire house (Table 5.2). Thirty-seven percent use the air-conditioning during the hot season and 28% claim to use it during the cool season. In contrast, three-quarters of the sample voted that they "occasionally" or "always" use the air-conditioners in their vehicles on their way to and from school. Car air-conditioning did not differ appreciably between seasons, though from the hot to cool season, fewer people "always" used their car air-conditioners, reflecting a seasonal adjustment.

Table 5.2 Seasonal use of air-conditioning at home or in car

	AC USE AT HOME (%)		AC USE IN THE CAR (%)	
	Hot Season	Cool Season	Hot Season	Cool Season
Not Available	56.7	57.9	8.9	9.6
Never	6.3	13.8	8.5	11.9
Occasionally	23.1	22.9	36.4	42.7
Always	13.9	5.5	46.2	35.8

5.3 Thermal - Physical

5.3.1 Measured Thermal Variables

Table 5.3 presents a statistical summary of the environmental data by season and building type. Appendix B provides statistical summaries of the physical data by total number of class visits during each season for each school. Described in the previous chapter, the sensors and a data acquisition system collected environmental conditions at a mid-classroom location, 1.1 m above floor level, while students completed the survey. (Spot measurements made at other heights, 0.1 and 0.6 m to check for vertical thermal asymmetry revealed negligible differences).

Dry bulb and globe temperatures averaged 27°C in naturally-ventilated classrooms and 23°C in air-conditioned classrooms for both seasons and relative humidity was about the same (around 60%) in both naturally-ventilated and air-conditioned buildings, though occasionally humidity reached 82% during the cool season. Average air velocities in naturally-ventilated buildings were 0.34 m/s and in air-conditioned classrooms, 0.14 m/s. Several naturally-ventilated classrooms used standing fans in the peripheral areas of the classroom, where velocities were measured (by spot measurements) as high than 2.0 m/s. The sensors and data acquisition system did not record fan velocities.

Table 5.3 Summary of indoor climate data

	Naturally-Ventilated		Air-Conditioned	
	Hot Season	Cool Season	Hot Season	Cool Season
Number of Classrooms	18	19	9	8
Number of Visits	48	54	40	40
Sample Size	1,052	1,129	703	660
Air Temperature (°C)				
mean	28.8	26.1	23.6	22.6
std dev	0.9	1.4	1.2	0.7
min	26.6	21.1	19.8	21.2
max	30.5	27.7	27.0	23.5
Mean Radiant Temp. (°C)				
mean	28.5	26.1	23.1	22.4
std dev	0.9	0.9	1.3	0.7
min	26.4	24.0	19.4	20.9
max	30.3	27.5	26.9	23.5
Relative Humidity (%)				
mean	59.8	66.2	57.0	64.0
std dev	5.0	7.1	7.2	6.5
min	51.3	47.5	43.1	51.8
max	75.5	81.5	74.9	72.6
Air Velocity (m/s)				
mean	0.36	0.33	0.15	0.15
std dev	0.10	0.14	0.07	0.05
min	0.20	0.10	0.07	0.07
max	0.72	0.66	0.33	0.24

5.3.2 Indoor Climate Indices

Table 5.4 summarizes the distribution of operative temperature, ET*, and SET*, categorized by season and classroom type. ET* is important when comparing the survey results to *Standard 55*, since the cool and warm edges of the comfort zone are prescribed in terms of ET*.

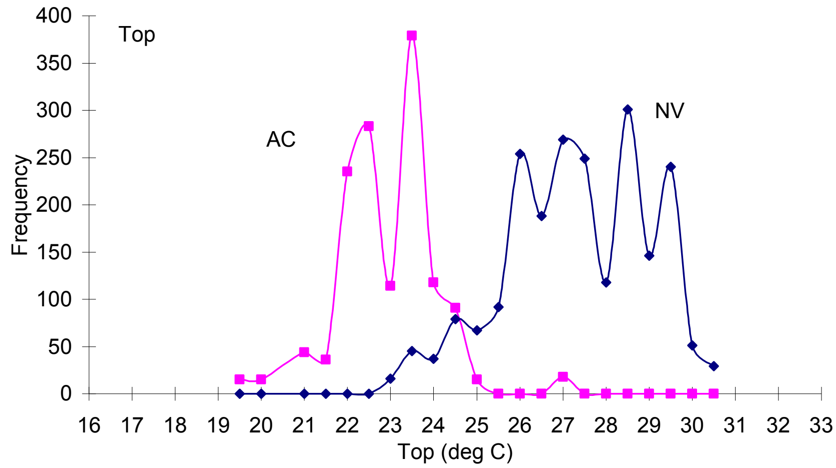
Frequency distributions of all three indices - T_{op}, ET*, and SET* - by ventilation mode and across both seasons (Figure 5.4), show a distinct bi-modal separation between the conditions in naturally-ventilated and air-conditioned classrooms. Although we might expect a normal distribution across the comfort zone, the most frequent temperatures for both the naturally-ventilated and air-conditioned occurred at the cool and warm boundaries (23 and 26°C) of the comfort zone.

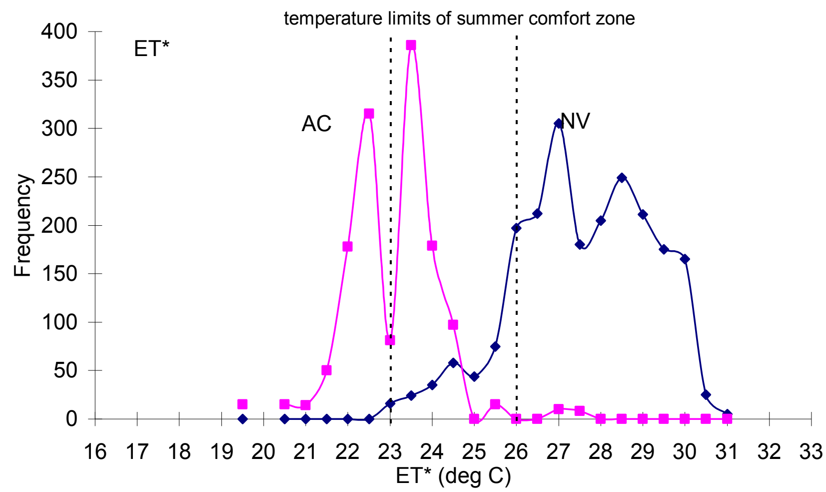
Table 5.4 Summary of calculated indoor climate indices

	NATURALLY-VENTILATED		AIR-CONDITIONED	
	Hot Season	Cool Season	Hot Season	Cool Season
Number of Visits	48	54	40	40
Sample Size	1052	1129	703	660
Operative Temperature (°C)				
mean	28.6	26.1	23.3	22.5
std dev	0.9	1.1	1.2	0.7
min	26.5	23.1	19.6	21.0
max	30.4	27.6	26.9	23.5
ET* (°C)				
mean	28.9	26.3	23.4	22.7
std dev	0.9	1.1	1.3	0.7
min	26.8	23.1	19.7	21.2
max	30.9	28.2	27.7	23.8
SET* (°C)				
mean	26.2	24.2	21.9	22.0
std dev	1.5	1.6	2.0	1.6
min	22.7	19.6	15.4	18.3
max	32.2	29.0	30.6	26.4
SET* (°C) (+0.10 chair insulation)				
mean	27.1	25.1	22.8	22.9
std dev	1.4	1.6	1.9	1.6
min	23.7	20.6	16.6	19.3
max	32.8	29.8	31.3	27.3

5.3.3 Comparisons to the Comfort Zone

Averaged temperature and humidity data for each class visit are plotted on a psychrometric chart and compared to the criteria specified by the *Standard 55* for summer conditions (Figure 5.5). More than 75% of the total number of classroom visits (139 of 182) fell outside the standard's comfort zone requirements. 92% of the naturally-ventilated classrooms (94 of 102 visits) had conditions well outside of the *Standard 55* prescriptions that were warm and humid, exceeding the Standard's upper humidity limit (20°C wet bulb). Less than half (44%) of the air-conditioned class visits had conditions within the boundaries of the comfort zone, most falling beyond the cool boundary (<23°C ET*)., reflecting over-cooled conditions by the air-conditioning systems. Both a temperature and humidity shift is clearly evident between naturally-ventilated and air-conditioned classrooms. Although seasonal differences are graphically less distinct, Table 5.4 indicates more than a 2.5°C temperature difference between the hot and cool seasons in the naturally-ventilated classrooms.





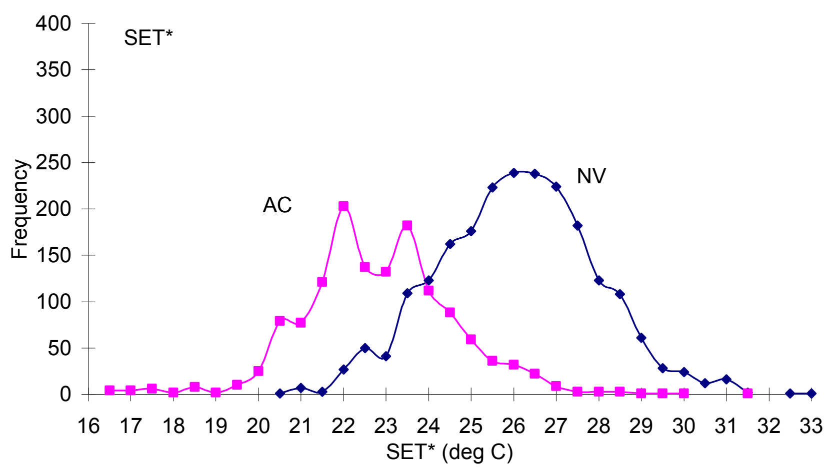
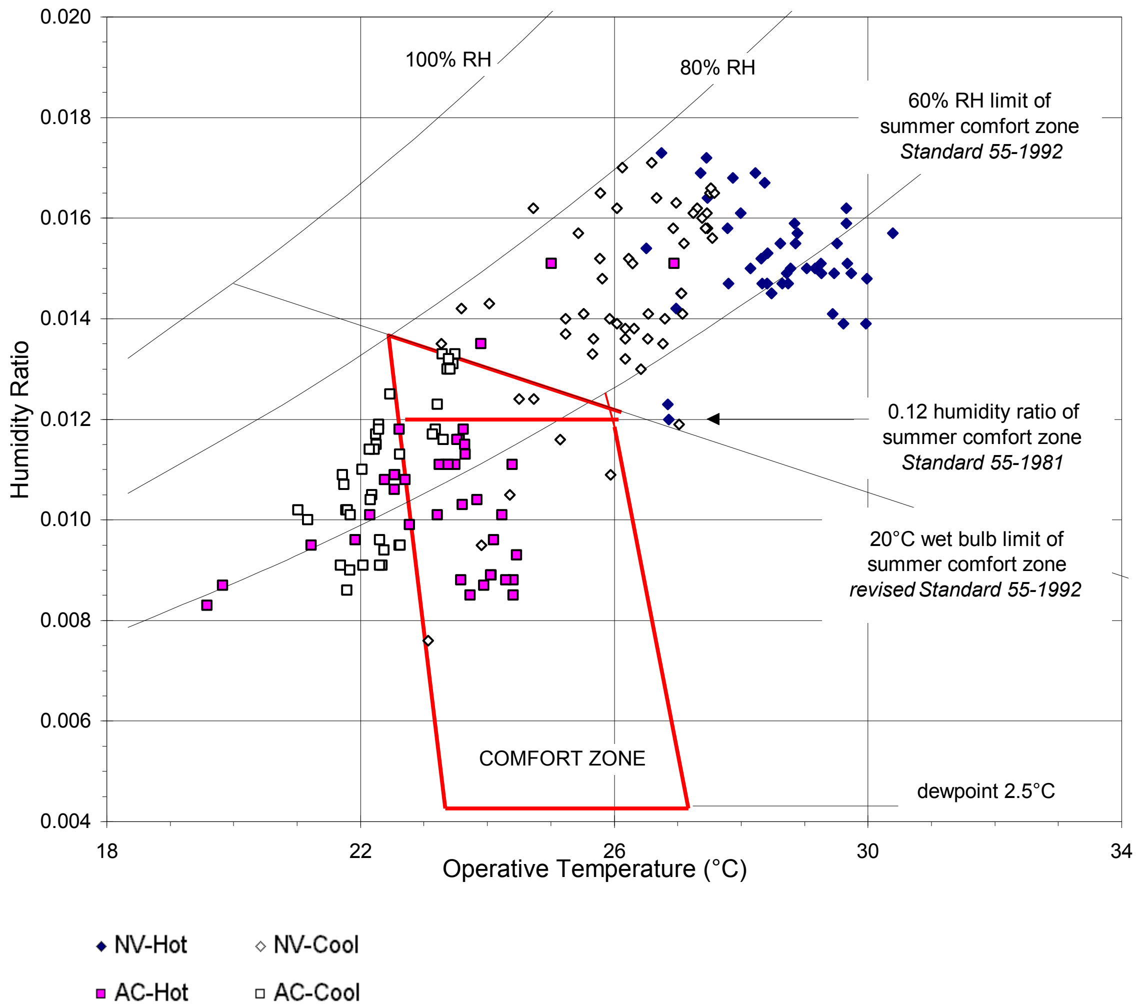


Figure 5.4 Frequency distributions of T_{op}, ET*, and SET* across both seasons (SET* includes +0.10 chair insulation)



Within comfort zone	NV Hot	NV Cool	AC Hot	AC Cool	Row Totals	
Classrooms within comfort zone/total visits (plotted)	0/48	8/54	24/40	11/40	43/182	(24%)
Occupants (not plotted)	0/1052	164/1129	441/703	215/660	820/3544	(23%)

Figure 5.5 Indoor climate conditions on *Standard 55* revised summer comfort chart (each symbol represents averaged climate values for a class visit)

5.4 Thermal - Subjective

Questions of comfort and satisfaction with the indoor environment can best be answered by using a combination of subjective scales. The ASHRAE thermal sensation scale is the traditional scale used in both laboratory and field studies, and will be the most valuable for comparing these results to other studies. Although it provides clear feedback about one's overall thermal state, it does not by itself tell us anything about the subject's level of satisfaction with that state. Instead in most thermal comfort research and in the standards themselves, this association is indirectly *assumed*. The traditional assumptions have been: 1) that "neutral" thermal sensation represents optimal conditions, and 2) the three central categories of the thermal sensation scale (slightly cool, neutral, and slightly warm) represents comfort, or acceptability. A corollary to this assumption is that the thermal sensations outside of these central 3 categories are unacceptable, or indicative of discomfort.

Another scale - the McIntyre Preference scale - is a more direct assessment of ideal conditions, since the occupant is asked to indicate how they would ideally like to feel (warmer, no change, cooler). This scale serves two important purposes: 1) to assess optimum comfort conditions defined in terms of preferred temperature, and 2) to compare simultaneous votes of thermal sensation and preference to determine whether "neutrality" actually represents the optimal thermal response for the group of subjects.

The direct acceptability question is important because the comfort zone is defined in terms of thermal environments that are "acceptable to at least 80% of the occupants."[3] Currently, *Standard 55* defines its comfort zone boundaries of acceptability *indirectly*, using the temperatures associated with the central 3 thermal sensation categories in which 80% or more of the occupants will vote. A direct acceptability question, however, allows: 1) occupants to make their own judgments about whether the physical conditions, and associated thermal sensations, are acceptable, and 2) comparisons of simultaneous votes of thermal sensation and acceptability to determine whether the central 3 categories of the thermal sensation scales is the appropriate place to draw the acceptability line for a give group of subjects.

After comparing subjective measures to each other, and to the physical measurements,, I will also compare them to predicted indices such as PMV/PPD and DISC. This analysis will help evaluate the extent to which laboratory-based models can be used to predict thermal response in naturally-ventilated schools in the tropics.

5.4.1 Observed Measurements and Calculations

Statistical summaries of thermal sensation votes, thermal preference, and general comfort are shown in Figure 5.5.

5.4.1.1 Thermal Sensation

The mean thermal sensation vote for the air-conditioned subjects centered around -0.9 (slightly cool), while naturally-ventilated subjects responses averaged 0.2 (neutral). Seasonal differences varied between the two building types. Comparing cool season responses to the hot season in naturally-ventilated buildings, respondents voted nearly a full unit lower on the thermal sensation scale (0.8), which is what one would expect given that the mean ET* was also considerably lower (2.6°C) while mean clothing varied very little between seasons (Figure 5.3 shows a 0.04 clo increase). A different pattern emerged in the air-conditioned buildings. Although mean indoor ET* dropped very little in the cool season (0.7°C), there was a relatively higher increase in mean clo values in the air-conditioned buildings (0.10 clo), resulting in a slight increase in mean thermal sensation (0.2 units) in spite of the decrease in temperatures.

Table 5.6 provides a cross-tabulation of responses on the thermal sensation scale as a function of ET* for both building types. It reveals a bi-modal distribution of responses from subjects in naturally-ventilated and air-conditioned classrooms. Conditions ranged from 22.5 to 31.0°C ET* for the naturally-ventilated classrooms and 19.5 to 27.5°C ET* for the air-conditioned classrooms.

In the frequency distribution of thermal sensation votes for both seasons and building type in Figure 5.6, the curve of air-conditioned responses is centered over the category of slightly cool (-1), consistent with the data shown in Figure 5.5, where a large number of the air-conditioned classroom visits had conditions on the cool side of the comfort zone.

Although we expect that a significant majority of people *within* the comfort zone would vote within the central 3 categories of the 7-point thermal sensations scale, the data revealed a different pattern. Table 5.7 shows that only a slight majority of naturally-ventilated (57%) and air-conditioned occupants (60%) voted within these central categories when the physical conditions comfort zone conditions, while a significant number (38% in each building type) found those same comfort zone conditions to be in the categories of “too cool” and “cold.” The shift in central tendency of the air-conditioned votes begins to raise several questions that I will be able to address in further analysis: 1) does the clustering of votes around thermal sensation = -1 suggest that a significant number of people are uncomfortable cool, or do the prefer a sensation of “slightly cool” instead of “neutral”?; and 2) how does the asymmetric distribution of thermal sensation votes affect the way in which one calculates neutral temperature?

Table 5.5 Summary of subjective responses to classroom comfort

	NATURALLY-VENTILATED		AIR-CONDITIONED	
	Hot Season	Cool Season	Hot Season	Cool Season
Number of Visits	48	54	40	40
Sample Size	1052	1129	703	660
Thermal Sensation (-3 = cold to +3 = hot)				
mean	0.6	-0.2	-1.0	-0.8
std dev	1.2	1.3	1.1	1.2
min	-3.0	-3.0	-3.0	-3.0
max	3.0	3.0	2.5	2.5
Thermal Preference (-1=want cooler; 0=no change; +1=want warmer)				
mean	-0.7	-0.4	-0.1	0.1
std dev	0.5	0.6	0.7	0.7
min	-1.0	-1.0	-1.0	-1.0
max	1.0	1.0	1.0	1.0
General Comfort (1=very uncomfortable; 6=very comfortable)				
mean	4.1	4.4	4.6	4.4
std dev	1.1	1.0	1.0	1.0
min	1.0	1.0	1.0	1.0
max	6.0	6.0	6.0	6.0
Air Movement Preference (1=less air; 2=no change; 3=more air)				
mean	2.6	2.4	2.2	2.3
std dev	0.5	0.6	0.5	0.6
min	1.0	1.0	1.0	1.0
max	3.0	3.0	3.0	3.0
Humidity Preference (1=want drier air; 2=no change; 3=more moisture)				
mean	1.6	1.8	2.0	2.0
std dev	0.6	0.5	0.5	0.5
min	1.0	1.0	1.0	1.0
max	3.0	3.0	3.0	4.0

Table 5.6 Cross-tabulation of ET* and thermal sensation by building type

	Naturally-Ventilated Thermal Sensation Scale								**Air-Conditioned** Thermal Sensation Scale							
ET*	-3	-2	-1	0	1	2	3	Total	-3	-2	-1	0	1	2	3	Total
19.5	0	0	0	0	0	0	0	0	0	5	6	4	0	0	0	15
20	0	0	0	0	0	0	0	0	0	7	6	1	1	0	0	15
20.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	1	7	4	1	1	0	14
21.5	0	0	0	0	0	0	0	0	4	19	17	8	2	0	0	50
22	0	0	0	0	0	0	0	0	9	59	54	42	11	3	0	178
22.5	0	0	0	0	0	0	0	0	16	80	102	73	37	7	0	315
23	4	6	4	2	0	0	0	16	2	29	30	16	4	0	0	81
23.5	0	3	6	8	4	3	0	24	17	99	126	94	40	8	2	386
24	2	10	15	6	1	1	0	35	4	47	59	37	24	8	0	179
24.5	5	17	10	18	6	2	0	58	7	30	27	23	7	3	0	97
25	1	10	14	11	6	2	0	44	0	0	0	0	0	0	0	0
25.5	1	15	28	13	10	7	1	75	0	0	2	5	7	1	0	15
26	0	22	43	54	61	16	1	197	0	0	0	0	0	0	0	0
26.5	1	33	67	59	35	16	1	212	0	0	0	0	0	0	0	0
27	1	25	85	103	63	23	5	305	0	0	2	5	3	0	0	10
27.5	0	6	32	48	54	36	4	180	0	0	0	2	4	2	0	8
28	0	7	29	64	55	36	14	205	0	0	0	0	0	0	0	0
28.5	0	4	37	85	70	41	12	249	0	0	0	0	0	0	0	0
29	0	5	19	64	83	30	10	211	0	0	0	0	0	0	0	0
29.5	0	4	25	54	55	25	12	175	0	0	0	0	0	0	0	0
30	0	5	9	32	48	49	22	165	0	0	0	0	0	0	0	0
30.5	0	1	2	5	4	10	3	25	0	0	0	0	0	0	0	0
31.0	0	0	0	2	3	0	0	5	0	0	0	0	0	0	0	0
Column Totals	15 (1%)	173 (8%)	425 (19%)	628 (29%)	558 (26%)	297 (14%)	85 (4%)	2181	59 (4%)	376 (28%)	438 (32%)	314 (23%)	141 (10%)	33 (2%)	2 (0%)	1363

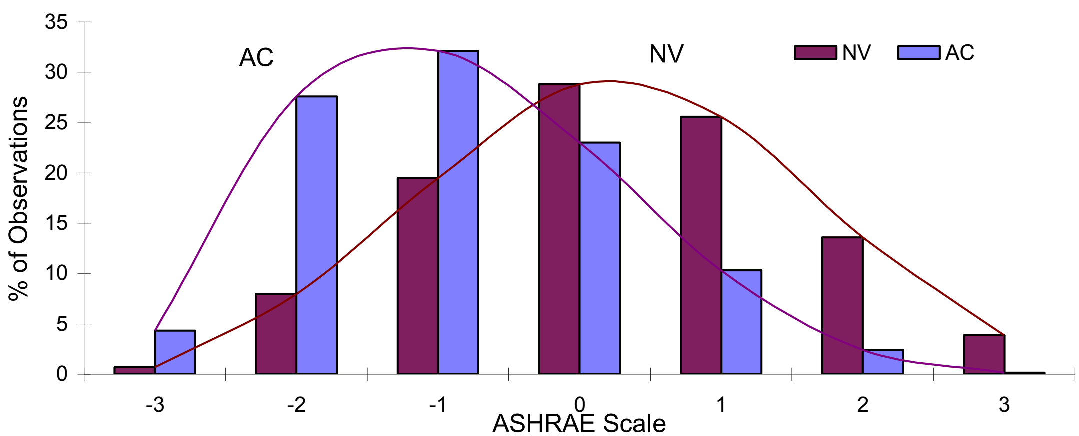


Figure 5.6 Relative frequency of ASHRAE votes

Table 5.7 Cross-tabulation of thermal sensation and ET* for subjects *within* the comfort zone

	Naturally-ventilated Classrooms								Air-conditioned Classrooms							
	ASHRAE Scale								ASHRAE Scale							
ET*	-3	-2	-1	0	1	2	3	Total	-3	-2	-1	0	1	2	3	Total
23.0	5	6	5	0	0	0	0	16	3	7	12	3	0	0	0	25
23.5	0	3	7	11	0	3	0	24	43	103	122	84	29	5	0	386
24.0	2	5	6	1	0	0	0	14	8	48	48	26	14	4	0	148
24.5	8	9	8	8	1	1	0	35	7	32	29	20	8	1	0	97
25.0	1	7	10	5	1	2	0	26	0	0	0	0	0	0	0	0
25.5	4	8	8	4	3	0	0	27	0	0	0	0	0	0	0	0
26.0	2	3	7	6	3	1	0	22	0	0	0	0	0	0	0	0
Column	22	41	51	35	8	7	0	164	61	190	211	133	51	10	0	656
Totals	13%	25%	31%	21%	5%	4%	0%		9%	29%	32%	20%	8%	2%	0%	

5.4.1.2 Thermal Preference

Subjects were asked to indicate whether they would prefer “warmer”, “cooler”, or “no change” to their environmental conditions. The preference responses are cross-tabulated with ET* (0.5°C bins) in Table 5.8, and show a marked contrast between the naturally-ventilated and air-conditioned classrooms. There were seasonal differences in preferences as well as differences between ventilation type shown in the disaggregated sets of data in Table 5.9. Significantly more naturally-ventilated occupants experiencing near neutral thermal sensations, wanted cooler conditions during the hot season (69%) than during the cool season (43%). This reflects the response to higher mean temperatures (2.6°C ET*). The majority of air-conditioned occupants experiencing “slightly cool” thermal sensations, preferred “no change” between seasons, which is what one would expect since temperatures varied by less than 1°C. These results suggest that neutral thermal sensations are not necessarily people’s preferred or ideal thermal state.

Table 5.8 Cross-tabulation of ET* and McIntyre Scale

QUESTION: Right now, I would prefer to be:

ET*	Naturally-Ventilated: Want Cooler	Naturally-Ventilated: No Change	Naturally-Ventilated: Want Warmer	Naturally-Ventilated: Row Totals	Air-Conditioned: Want Cooler	Air-Conditioned: No Change	Air-Conditioned: Want Warmer	Air-Conditioned: Row Totals
19.5	0	0	0	0	1	10	4	15
20	0	0	0	0	3	9	3	15
20.5	0	0	0	0	0	0	0	0
21	0	0	0	0	2	7	5	14
21.5	0	0	0	0	1	29	20	50
22	0	0	0	0	28	93	57	178
22.5	0	0	0	0	71	168	76	315
23	0	8	8	16	11	57	13	81
23.5	3	15	6	24	89	200	97	386
24	4	18	13	35	64	86	29	179
24.5	20	19	19	58	27	60	10	97
25	12	27	5	44	0	0	0	0
25.5	33	36	6	75	12	3	0	15
26	80	109	8	197	0	0	0	0
26.5	69	127	16	212	0	0	0	0
27	147	148	10	305	6	3	1	10
27.5	102	74	4	180	7	1	0	8
28	139	62	4	205	0	0	0	0
28.5	168	75	6	249	0	0	0	0
29	152	58	1	211	0	0	0	0
29.5	116	58	1	175	0	0	0	0
30	141	20	4	165	0	0	0	0
30.5	22	3	0	25	0	0	0	0
31	3	2	0	5	0	0	0	0
Column Totals	1211 (55.5%)	859 (39.4%)	111 (5.1%)	2181	322 (23.6%)	726 (53.3%)	315 (23.1%)	1363

Table 5.9 Summary of thermal preference

	"Want Cooler" (%)	"No Change" (%)	"Want Warmer" (%)	Mean ET* (°C)
NV classrooms	55.5	39.4	5.1	27.6
Hot season NV	68.6	29.8	1.5	28.9
Cool season NV	43.3	48.3	8.4	26.3
AC classrooms	23.6	53.3	23.1	23.1
Hot season AC	24.2	57.9	17.9	23.4
Cool season AC	23.0	48.3	28.6	22.7

These results are better understood by comparing simultaneous votes on both the thermal sensation and preference scales, as shown in Table 5.10. Overall, the results suggest that neutral thermal sensations are not always the ideal, or preferred, thermal state for people. This was most apparent in the naturally-ventilated buildings, and particularly in the hot season where 62% of the people voting within the three central categories of thermal sensation still wanted to feel cooler. This pattern was reduced but still significant during the cool season in these same buildings. Only half (52%) of people experiencing the central sensations found those to be ideal, while 43% still wanted to feel cooler.

Another way of looking at the data is to test the assumption that people will feel dissatisfied at the more extreme thermal sensations. For the naturally-ventilated buildings, 68% (hot season) and 58% (cool) season of people feeling cool or cold (-2, -3) preferred “no change.” These results demonstrate that many people in the tropics *want* to feel much cooler than neutrality, and standards based on a goal of neutrality may be inappropriate.

Table 5.10 Cross-tabulation of thermal sensation and thermal preference scales by season and building type

HOT	**Naturally-Ventilated** Thermal Preference Scale *Right now I would prefer to be*:				**Air-Conditioned** Thermal Preference Scale *Right now I would prefer to be:*			
TS Scale	Cooler	No Change	Warmer	Totals	Cooler	No Change	Warmer	Totals
+3, +2	96% (233)	4% (9)	0% (2)	(244)	69% (9)	31% (4)	0% (0)	(13)
+1, 0, -1	62% (483)	37% (286)	1% (11)	(780)	32% (140)	62% (272)	6% (29)	(441)
-3, -2	21% (6)	68% (19)	11% (3)	(28)	8% (21)	53% (131)	39% (97)	(249)
Totals	69% (722)	30% (314)	1% (16)	(1052)	24% (170)	58% (407)	18% (126)	(703)
COOL	Cooler	No Change	Warmer	Totals	Cooler	No Change	Warmer	Totals
+3, +2	86% (118)	14% (20)	0% (0)	(138)	77% (17)	23% (5)	0% (0)	(22)
+1, 0, -1	43% (357)	52% (432)	5% (42)	(831)	28% (128)	55% (246)	17% (78)	(452)
-3, -2	9% (14)	58% (93)	33% (53)	(160)	4% (7)	36% (68)	60% (111)	(186)
Totals	43%	48%	9%		23%	48%	29%	

(489)	(545)	(95)	(1129)	(152)	(319)	(189)	(660)

5.4.1.3 General Comfort

Beyond the typical measures used in field research, the general comfort question attempts to get a broader look at the thermal state of the occupant by using a six-point scale comfort scale to distinguish thermal sensation from overall comfort, in that the two questions ask the subjects to interpret their comfort in different ways. The mean general comfort votes in Table 5.11 do not show significant differences between ventilation type or season. During the cool season, both naturally-ventilated and air-conditioned occupants voted on average the same, at 4.4 (between slightly comfortable and moderately comfortable).

Table 5.11 General Comfort Responses

	Naturally-Ventilated (%)			Air-Conditioned (%)		
	Both	Hot Season	Cool Season	Both	Hot Season	Cool Season
6 Very Comfortable	7.8	5.8	9.8	11.1	13.6	8.5
5 Moderately Comfortable	38.9	35.3	42.3	47.5	52.2	42.6
4 Slightly Comfortable	28.9	30.0	27.9	24.1	19.1	29.6
3 Slightly Uncomfortable	17.5	19.8	15.3	13.4	12.4	14.4
2 Moderately Uncomfortable	5.0	6.9	3.4	3.2	2.0	4.4
1 Very Uncomfortable	1.7	2.2	1.3	0.6	0.7	0.5

5.4.1.4 Thermal Acceptability

A variety of scales and measures can be used to determine acceptability of the thermal environment. The traditional and most commonly used method is an indirect measure which equates satisfaction (or acceptability) with the central three categories of the 7-point thermal sensation scale. This is indicated by the shaded portions in Table 5.6. By this measure, 74% of naturally-ventilated and 65% of air-conditioned occupants are assumed to be satisfied with their thermal conditions.

By the direct measure of asking, “Do you find this environment thermally acceptable,” both naturally-ventilated and air-conditioned occupants found conditions acceptable (Table 5.12), exceeding the 80% acceptability criterion specified by *Standard 55*. A high degree of acceptability to conditions *within* the comfort zone is expected, and both naturally-ventilated and air-conditioned subjects indeed voted conditions acceptable (Table 5.13), however these results incorporate less than a quarter of the total sample (820 of 3544). The majority of the sample experienced temperature and humidity conditions beyond Standard 55's comfort zone limits and also found those conditions acceptable (Table 5.14).

Table 5.12 Cross-tabulation of ET* and direct acceptability

QUESTION: Are the conditions (thermal) in this classroom acceptable to you *right now*?

ET*	**Naturally-Ventilated**				**Air-conditioned**			
(°C)	Accept	Not Accept	Row Totals		Accept	Not Accept	Row Totals	
19.5	0	0	0	(0%)	15	0	15	(1.1%)
20	0	0	0	(0%)	15	0	15	(1.1%)
20.5	0	0	0	(0%)	0	0	0	(0.0%)
21	0	0	0	(0%)	13	1	14	(1.0%)
21.5	0	0	0	(0%)	41	9	50	(3.7%)
22	0	0	0	(0%)	161	17	178	(13.1%)
22.5	0	0	0	(0%)	290	25	315	(23.1%)
23	14	2	16	(0.7%)	75	6	81	(5.9%)
23.5	24	0	24	(1.1%)	357	29	386	(28.3%)
24	30	5	35	(1.6%)	169	10	179	(13.1%)
24.5	51	7	58	(2.7%)	94	3	97	(7.1%)
25	42	2	44	(2.0%)	0	0	0	(0.0%)
25.5	67	8	75	(3.4%)	10	5	15	(1%)
26	185	12	197	(9.0%)	0	0	0	(0%)
26.5	204	8	212	(9.7%)	0	0	0	(0%)
27	275	30	305	(14.0%)	9	1	10	(1%)
27.5	154	26	180	(8%)	4	4	8	(1%)
28	168	37	205	(9%)	0	0	0	(0%)
28.5	206	43	249	(11%)	0	0	0	(0%)
29	180	31	211	(10%)	0	0	0	(0%)
29.5	141	34	175	(8%)	0	0	0	(0%)
30	111	54	165	(8%)	0	0	0	(0%)
30.5	21	4	25	(1%)	0	0	0	(0%)
31	4	1	5	(0.2%)	0	0	0	(0.0%)
Column Totals	1877 (86.1%)	304 (13.9%)	2181 (100%)	(100%)	1253 (91.9%)	110 (8.1%)	1363 (100%)	(100%)

Total number of votes in each ET* bin; numbers in parentheses are row/column percentages.

Table 5.13 Cross-tabulation of acceptability for subjects *within* the comfort zone (ET* and humidity limits)

ET* (°C)	NV (164/2181 individuals) Accept	Not Accept	Row Totals		AC (656/1363 individuals) Accept	Not Accept	Row Totals	
23	14	2	16	(9.8%)	22	3	25	(3.8%)
23.5	24	0	24	(14.6%)	357	29	386	(58.8%)
24	13	1	14	(8.5%)	141	7	148	(22.6%)
24.5	31	4	35	(21.3%)	94	3	97	(14.8%)
25	24	2	26	(15.9%)	0	0	0	(0%)
25.5	24	3	27	(16%)	0	0	0	(0%)
26	22	0	22	(13.4%)	0	0	0	(0%)
Column Totals	152 (92.7%)	12 (7.3%)	164 (100%)	(100%)	614 (93.6%)	42 (6.4%)	656 (100%)	(100%)

Total number of votes within each ET* bin: number in parentheses are row/column percentages.

Table 5.14 Cross-tabulation of acceptability for subjects *outside* of the comfort zone (ET* and humidity limits)

ET* (°C)	NV (1725/2181 individuals) Accept	Not Accept	Row Totals		AC (639/1363 individuals) Accept	Not Accept	Row Totals	
19.5	0	0	0	(0%)	15	0	15	(2.1%)
20	0	0	0	(0%)	15	0	15	(2.1%)
20.5	0	0	0	(0%)	0	0	0	(0.0%)
21	0	0	0	(0%)	13	1	14	(2.0%)
21.5	0	0	0	(0%)	41	9	50	(7.1%)
22	0	0	0	(0%)	161	17	178	(25.2%)
22.5	0	0	0	(0%)	290	25	315	(44.6%)
23	0	0	0	(0%)	53	3	56	(7.9%)
23.5	0	0	0	(0%)	0	0	0	(0%)
24	17	4	21	(1.0%)	28	3	31	(4.4%)
24.5	20	3	23	(1.1%)	0	0	0	(0%)
25	18	0	18	(0.9%)	0	0	0	(0%)
25.5	43	5	48	(2.4%)	10	5	15	(2.1%)
26	163	12	175	(8.7%)	0	0	0	(0%)
26.5	204	8	212	(10.5%)	0	0	0	(0%)
27	275	30	305	(15.1%)	9	1	10	(1.4%)
27.5	154	26	180	(8.9%)	4	4	8	(1.1%)
28	168	37	205	(10.2%)	0	0	0	(0%)
28.5	206	43	249	(12.3%)	0	0	0	(0%)
29	180	31	211	(10.5%)	0	0	0	(0%)
29.5	141	34	175	(8.7%)	0	0	0	(0%)
30	111	54	165	(8.2%)	0	0	0	(0%)
30.5	21	4	25	(1.2%)	0	0	0	(0%)
31	4	1	5	(0%)	0	0	0	(0%)
Column Totals	1725 (85.5%)	292 (14.5%)	2017 (100%)	(100%)	639 (90.4%)	68 (9.6%)	707 (100%)	(100%)

Total number of votes within each ET* bin: number in parentheses are row/column percentages.
Note: data reported for points between 23 - 26*C exceeded humidity (wet bulb) limits for comfort zone.

Of people experience physical conditions *within* the comfort zone, and at the same time expressing thermal sensations in the central 3 categories, only 58 - 63% still voted “acceptable” in response to a direct question (Table 5.15). The combination of acceptability methods in this figure shows how the direct method allows for a wider range of acceptability than assessment by thermal sensation. For example, even subjects experiencing thermal sensations outside of the 3 central categories (cold, cool, warm, hot) found conditions acceptable.

Table 5.15 Cross-tabulation of direct acceptability and central three categories of the thermal sensation scale for subjects within the comfort zone

	NV Classrooms in Comfort Zone ASHRAE Scale								**AC Classrooms in Comfort Zone** ASHRAE Scale							
	-3.0	-2.0	-1.0	0	1.0	2.0	3.0	Totals	-3.0	-2.0	-1.0	0	1.0	2.0	3.0	Totals
Acceptable	8	41	46	36	13	8	0	152	16	169	205	150	57	15	2	614
Not Accept	3	4	4	0	1	0	0	12	12	9	11	3	4	3	0	42
				(58%)				164				(63%)				656

As discussed earlier, *Standard 55* defines an acceptable thermal environment as one that satisfies at least 80% of the occupants. Under this prescription, Brager *et al*. outlines several methods to determine compliance to the 80% satisfaction criteria of *Standard 55*:

1. Ask *directly* through surveying the occupants, “do you find this environment thermally acceptable?” Determine whether a minimum of 80% answered “yes”;
2. Use thermal sensation scale responses to determine if a minimum 80% of the votes are within the central three categories of thermal sensation scale (“slightly cool,” “neutral,” “slightly warm”);
3. Compare the extent to which the interior environment meets physical specifications of the *Standard 55* comfort zone. A base assumption is that for those occupants within the comfort zone, at least 80% will find the conditions acceptable;
4. Use other scales as indirect measures (e.g. preference, general comfort), determine whether a minimum of 80% of the votes fall into their respective definitions of acceptability.[4]

This section uses the Hawaii data to compare each of these methods to the acceptability criterion of *Standard 55*. Although many studies have not asked a direct acceptability question, I used this question (immediately following the thermal sensation question) with a present time condition: "Are the conditions in this classroom acceptable to you, right now?" The second option (indirect method) is by far the most common approach in the literature and is based on the traditional assumption that responses in the middle three categories are votes of acceptability. The third method uses the analysis from a previous section (Figure 5.5), comparing the physical conditions of the classroom and the environmental prescriptions of *Standard 55*. In the fourth method, I use votes of "no change" on the preference scale as an assumption of acceptability.[5] Also considered is the general comfort question where the assumption of acceptability includes a response of "slightly comfortable" or better on the general comfort scale. For each of these methods, responses are compared by building type: naturally-ventilated and air conditioned.

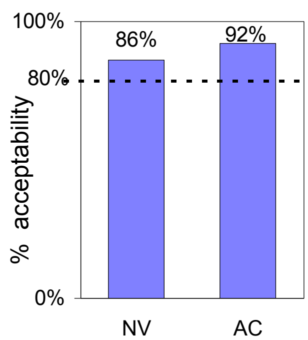


Figure 5.7 Direct acceptability of thermal conditions

1. Direct Acceptability. This approach asks "are these conditions acceptable?" My implementation of this question asks about thermal acceptability specifically at that point in time, "Are the conditions (thermal) in this classroom acceptable to you *right now*?" The cross-tabulation in Table 5.12 shows 86% of the naturally-ventilated occupants and 92% of the air-conditioned occupants found acceptable thermal conditions.

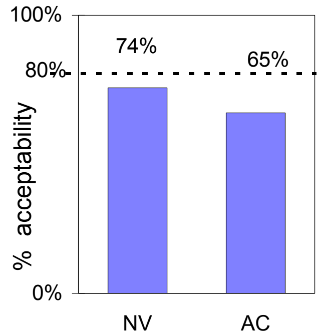


Figure 5.8 Acceptability using central 3 categories of thermal sensation scale

2. Thermal Sensation. The second option assumes the central three categories of the thermal sensation scale indicate acceptability (Table 5.6). In each building type, fewer than 80% of the survey sample experienced these sensations. Naturally-ventilated occupants voted with slightly higher acceptability than the air-conditioned occupants under this method., This may in part be because the naturally-ventilated responses were centrally distributed around the neutral thermal sensation and therefore encompassed more of the population.

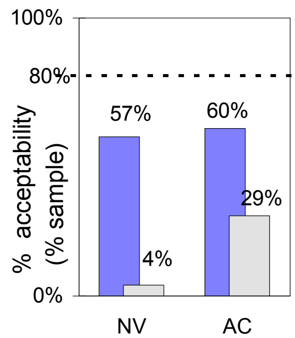


Figure 5.9 Thermal sensation acceptability of occupants within comfort zone

Using this same indirect method to analyze the responses of those classrooms *within* the *Standard 55* comfort zone conditions, acceptability levels (Table 5.7) were further below the 80% acceptability target: 57% of the naturally-ventilated occupants and 60% of the air-conditioned occupants voted acceptable thermal sensations (Figure 5.9). Subjects experiencing these comfort zone conditions, however, represented only small portion of the total sample surveyed (4% of naturally-ventilated and 29% of air-conditioned occupants).

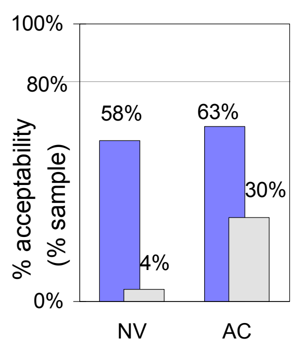


Figure 5.10 Direct acceptability of occupants within comfort zone, voting in the central 3 categories

Further analysis of the thermal sensation method shows, by cross-tabulation of people *within* the comfort zone (Table 5.15), and experiencing thermal sensations within the 3 central categories, only 58% of the naturally-ventilated and 63% of the air-conditioned occupants found conditions acceptable. These results only represent a small portion the sample. In part, the low indirect acceptability results in Figure 5.9 and Figure 5.10 might be because this method uses data representing those subjects experiencing thermal sensations within the central three categories. Responses from the warmer side of the scale (naturally-ventilated) and the cooler side of the scale (air-conditioned), might report conditions acceptable.

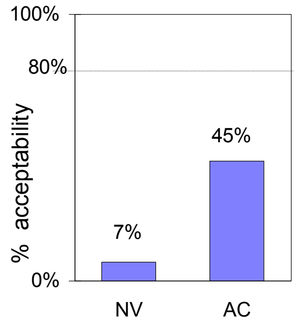


Figure 5.11 Physical conditions within comfort zone

3. Physical Environment. This method assumes that those within the comfort zone prescriptions of *Standard 55* will find conditions acceptable. The data from Figure 5.5 showed a relatively low proportion of the total sample had conditions within the comfort zone. 7% of the naturally-ventilated and 45% of the air-conditioned occupants, representing less than a quarter of the entire sample (820 of 3544 subjects), had environments complying with *Standard 55* specifications. Further examination of the standard's 80% acceptability criterion of those comfort zone occupants will be discussed in a later section.

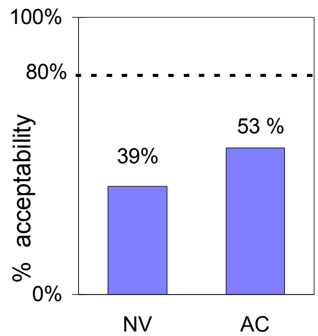


Figure 5.12 Acceptability using thermal preference vote of "no change"

4a. Thermal Preference. The percentages responding in the "no change" category of the thermal preference scale are far below the standard's 80% satisfaction criterion. Though it should be noted that these values may appear this way because the question forces the response into a particular category and demonstrates the difference between a more stringent measure of ideal (preferred) conditions vs. wider acceptable range. For example, the majority of naturally-ventilated occupants *preferred* to feel cooler (Table 5.8), but still found surrounding warm conditions acceptable (Table 5.12).

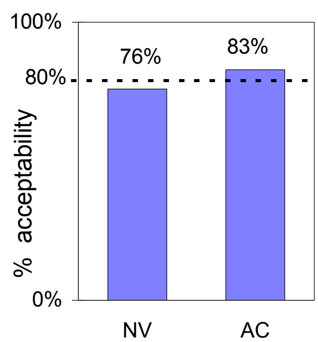


Figure 5.13 Acceptability using votes of "comfortable" or better

4b. General Comfort. This indirect measure assigns votes to the acceptable categories ("slightly comfortable," "moderately comfortable," or "very comfortable") in Table 5.11. Both naturally-ventilated and air-conditioned subjects found similar acceptability levels, close to the standard's 80% criterion. Brager et al[6] suggest an "expanded thermal comfort" approach by expanding the "acceptability criterion" to include the "slightly uncomfortable" votes. This would then satisfy a greater number of people, 93% of the naturally-ventilated sample and 96% of the air-conditioned sample.

How acceptable is acceptable? The preceding methods of measuring acceptability produced widely differing results. Using the direct method, we saw the Standard's 80% criterion exceeded in both naturally-ventilated and air-conditioned classrooms. For a better understanding of acceptability in the context of the physical conditions of the classroom, the responses are plotted onto the various coordinates of the psychrometric chart, similar to Figure 5.5.

Figure 5.14 shows the same representation of physical conditions as in Figure 5.5, but with symbols representing if a class reached *Standard 55's* 80% acceptability criterion. As expected, in all but 2 of the 43 class visits *within* the comfort zone, regardless of being naturally-ventilated or air-conditioned, at least 80% of the occupants found conditions acceptable. For the 139 visits *outside* of the comfort zone, the majority of classroom occupants also exceeded the 80% acceptability criterion.

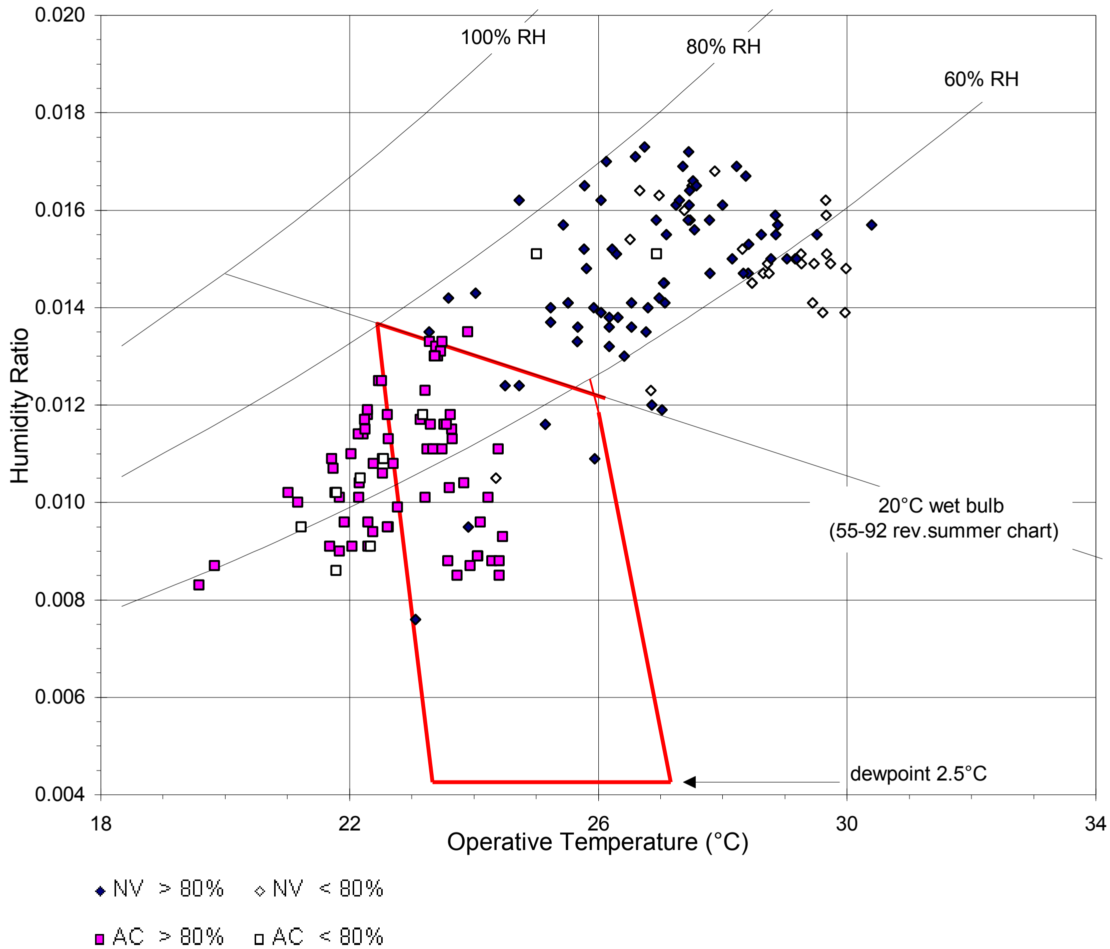
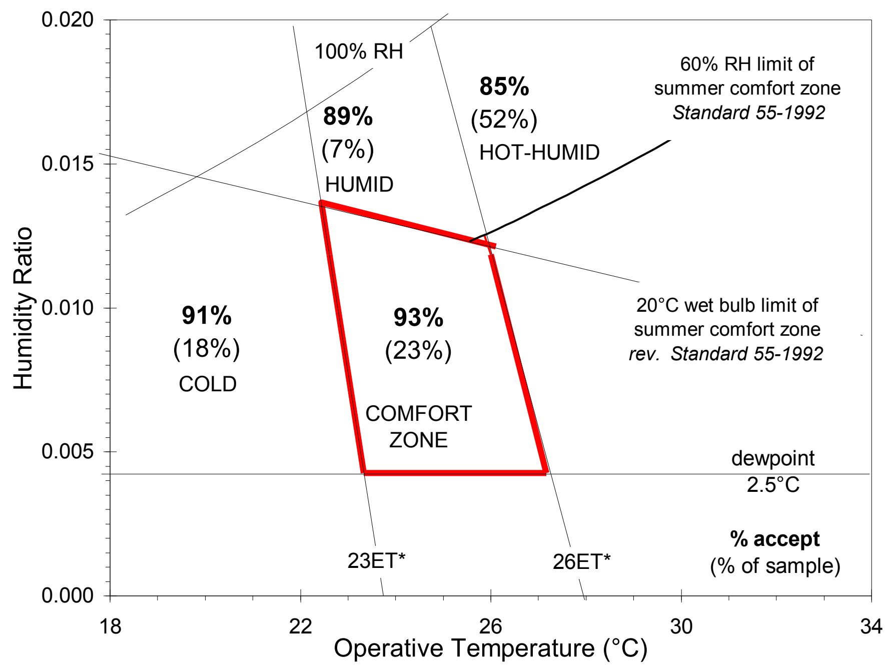


Figure 5.14 Direct acceptability by classroom visit superimposed on *Standard 55* revised summer comfort chart

The previous analysis used acceptability calculated as an average of those voting by classroom. An examination of acceptability on an individual basis (measured against average conditions for each specific classroom), might reveal a lower acceptability response. However, Figure 5.15 shows a high level of acceptability by direct assessment in all quadrants of the psychrometric chart. The direct method is useful in that it provides an additional measure by which to differentiate between the various zones surrounding the comfort zone.



ZONE	Conditions Acceptable? YES	NO	% in area
Too Cold	91% (588)	9% (52)	18% (643)
Comfort Zone	93% (748)	7% (52)	23% (800)
Hot and Humid	85% (1565)	15% (280)	52% (1845)
Too Humid	89% (229)	11% (27)	7% (256)
Totals (individuals)	88% (3130)	12% (414)	(3544)

Figure 5.15 Distribution of direct acceptability falling within areas on the *Standard 55* summer comfort zone

5.4.1.5 Air movement

Subjects assessed air movement in the classroom in terms of *preference* and *acceptability*. The air movement preference question gave three options to subjects: "want more air movement," "no change," and "want less air movement". Table 5.16 shows air movement preference over a range of operative temperatures and Table 5.17 shows percentages of responses in each of the three categories, by season and ventilation mode. Although a majority (63%) of all air-conditioned subjects preferred "no change" to the ambient air movement conditions (0.15 m/s) they experienced in their classrooms, almost a third wanted more air movement. Why would these air-conditioned occupants who experience "slightly cool" thermal sensations (-0.9) prefer *more* air movement while they are in conditions beyond the cool margin of the comfort zone? Again, we need to turn back to the summary of thermal preferences in Table 5.9 to find that almost half of the air-conditioned subjects preferred to be cooler or warmer. An analysis of those dissatisfied occupants (Table 5.18) gives rise to several interpretations about why occupants wanted more air movement: 1) subjects felt cold and interpreted the question as wanting warm *outside* air moving through the space, 2) subjects wanted to feel even cooler, i.e. "slightly cool" thermal sensations felt warm to them, 3) subjects desired air movement in and of itself, independent of its general cooling effect, or 4) subjects considered air to be "stuffy" and desired air movement to improve air quality conditions.

As one might expect, naturally-ventilated occupants preferred more air movement during the hot season, when temperatures were higher, than during the cool season. Thermally dissatisfied occupants in naturally-ventilated classrooms (Table 5.12) not only preferred cooler conditions, but the majority (98%) wanted more air movement (Table 5.18). Since most of the classroom physical conditions were located beyond the upper boundary of the comfort zone, as measured in terms of ET*, it is not surprising that occupants preferred more air movement for thermal comfort.

Table 5.16 Cross-tabulation of air movement preference and operative temperature

	Naturally-Ventilated Air Movement Preference					Air-Conditioned Air Movement Preference				
T_{op}	Want Less	No Change	Want More	Row Totals	Mean Air Velocity (m/s)	Want Less	No Change	Want More	Row Totals	Mean Air Velocity (m/s)
19.5	0	0	0	0	----	0	12	3	15	0.33
20	0	0	0	0	----	1	9	5	15	0.32
20.5	0	0	0	0	----	0	0	0	0	----
21	0	0	0	0	----	0	36	8	44	0.14
21.5	0	0	0	0	----	1	26	9	36	0.11
22	0	0	0	0	----	13	138	84	235	0.13
22.5	0	0	0	0	----	9	188	86	283	0.13
23	1	15	0	16	0.23	10	76	28	115	0.18
23.5	2	35	8	45	0.17	26	209	144	379	0.17
24	2	24	11	37	0.22	5	88	25	118	0.15
24.5	3	51	25	79	0.36	1	64	26	91	0.13
25	3	36	28	67	0.28	1	3	11	15	0.09
25.5	3	46	43	92	0.30	0	0	0	0	----
26	18	142	94	254	0.30	0	0	0	0	----
26.5	16	95	77	188	0.37	0	0	0	0	----
27	8	126	135	269	0.33	0	9	9	18	0.15
27.5	5	110	134	249	0.35	0	0	0	0	----
28	3	55	60	118	0.36	0	0	0	0	----
28.5	5	89	207	301	0.36	0	0	0	0	----
29	6	68	72	146	0.37	0	0	0	0	----
29.5	7	65	168	240	0.35	0	0	0	0	----
30	2	8	41	51	0.62	0	0	0	0	----
30.5	1	7	21	29	0.32	0	0	0	0	----
Column Totals	85 (3.9%)	972 (44.6%)	1124 (51.5%)	2181	0.34	67 (4.9%)	858 (63.0%)	438 (32.1%)	1363	0.15

Table 5.17 Summary of air movement preference

Classrooms	"Want LESS Air Movement" (%)	"No Change" (%)	"Want MORE Air Movement" (%)	Mean Air Velocity* (m/s)
NV classrooms	3.9	44.6	51.5	0.34
Hot season NV	2.8	36.3	60.9	0.36
Cool season NV	5.0	52.3	42.7	0.33
AC classrooms	4.9	63.0	32.1	0.15
Hot season AC	4.6	70.2	25.2	0.15
Cool season AC	5.3	55.1	39.6	0.15

*mean calculated from measured air velocities of classroom visits

Table 5.18 Cross-tabulation of air movement and thermal preference for *dissatisfied* occupants

	Naturally-Ventilated Thermal Preference Scale *Right now I would prefer to be:*				**Air-Conditioned** Thermal Preference Scale *Right now I would prefer to be:*			
Air Movement Preference	Cooler	No Change	Warmer	Row Totals	Cooler	No Change	Warmer	Row Totals
Less air movement	63% (5)	0% (0)	38% (3)	(8)	6% (1)	0% (0)	94% (17)	(18)
No change	53% (23)	12% (5)	35% (15)	(43)	6% (3)	0% (0)	94% (47)	(50)
More air movement	98% (248)	0% (1)	2% (4)	(253)	76% (32)	0% (0)	24% (10)	(42)
Column Totals	91% (276)	2% (6)	7% (22)	100% (304)	33% (36)	0% (0)	67% (74)	100% (110)

Standard 55 sets an upper limit of around 0.2 m/s (assuming typical turbulence around 40%), for air velocities within the basic comfort zone to reduce the risk of discomfort from drafts. Higher air speeds are acceptable in an extended zone up to 0.8 m/s “if the person has individual control of the local air speed” and “to increase temperatures to 3°C above the comfort zone.”[7]

80% of all naturally-ventilated subjects found air movement acceptable, as did 89% of the air-conditioned subjects. Figure 5.16 shows direct thermal acceptability for all subjects superimposed on a chart of temperature versus airspeeds. The base and extended comfort zones are also shown and the 80% acceptability criterion for thermal comfort is used. Figure 5.17 shows the same distribution of class visits, but with the symbols representing how the class voted to the 85% acceptability criterion used for *Standard 55's* draft limit. Approximately half of the naturally-ventilated classrooms did not meet this criterion (voting “acceptable” less than 85%). For the 63 classroom visits where the temperature was above the base and extended comfort zone boundaries, the majority (56%) of those polled expressed dissatisfaction with the air movement. Most of these 63 visits are below the airspeed boundary needed to be in the comfort zone.

During several class visits, observations were made of a few individuals who had control of standing fans located in peripheral areas of the classrooms. After directing the fan on themselves, these students were able to sustain high air velocities of approximately 2.0 m/s for the duration of the class period. However, in the majority of classrooms, students have virtually no individual control of windows or ceiling fans. Strictly speaking, the *Standard 55* comfort zone does not apply in these schools because there is no individual control. However, roughly half of these thermally comfortable, naturally-ventilated occupants wanted more air movement even as they experienced air velocities beyond the 0.2 m/s draft limit of *Standard 55*. Figure 5.17 suggests that the Standard's draft criterion should be reexamined in the context of naturally-ventilated buildings. The draft limit is based on draft risk in air-conditioned spaces and may not be appropriate in naturally-ventilated environments.

Table 5.19 Cross-tabulation of acceptability to air movement

	Naturally-Ventilated			Air-Conditioned		
Velocity (m/s)	Accept	Not Accept	Row Totals	Accept	Not Accept	Row Totals
≤ 0.10	0	0	0	283	36	319
0.10-0.20	127	21	148	701	101	802
0.20-0.30	649	174	823	199	13	212
0.30-0.40	464	101	565	29	1	30
0.40-0.50	257	80	337	0	0	0
0.50-0.60	170	43	213	0	0	0
0.60-0.70	67	3	70	0	0	0
0.70-0.80	19	6	25	0	0	0
Column Totals	1753 (80.4%)	428 (19.6%)	2181	1212 (88.9%)	151 (11.1%)	1363

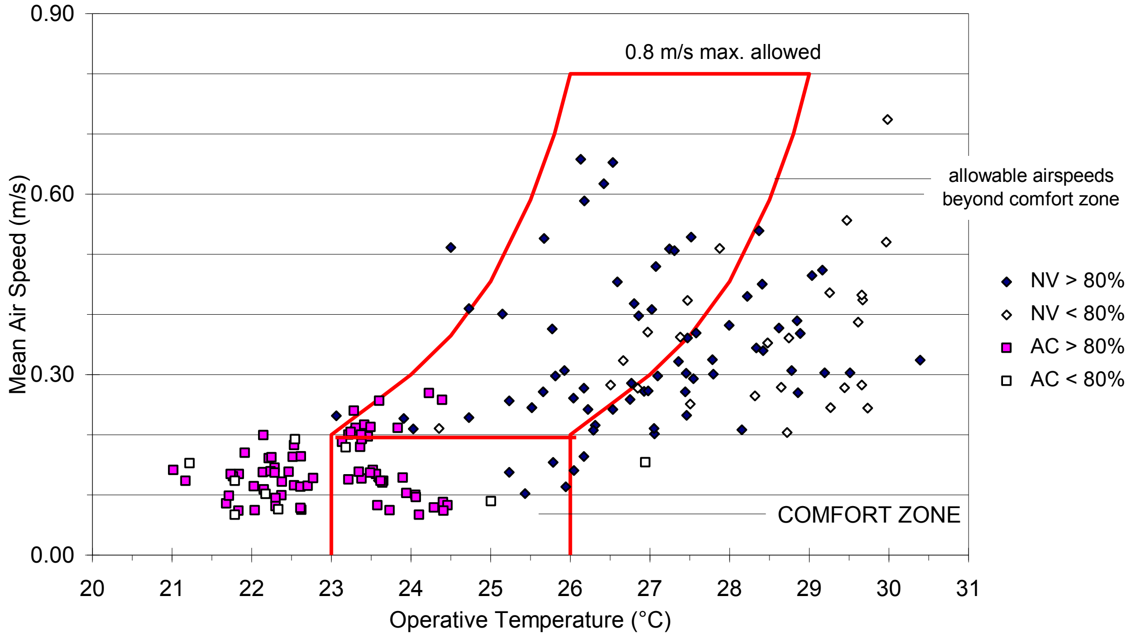


Figure 5.16 Direct thermal acceptability compared to air movement criteria of *Standard 55* summer comfort zone
(each symbol represents an average of acceptable votes for a classroom visit)

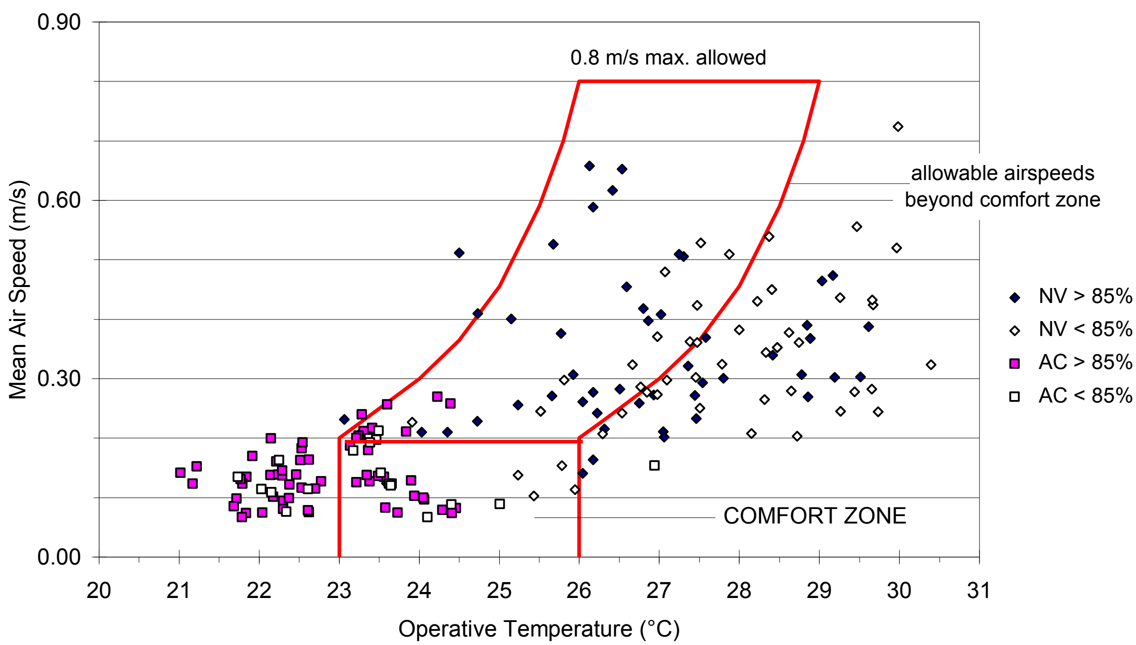


Figure 5.17 Air movement acceptability compared to air movement criteria of *Standard 55* summer comfort zone
(each symbol represents an average of acceptable votes for a classroom visit)

5.4.1.6 Humidity

Preference and acceptability of humidity are used to distinguish between responses of naturally-ventilated and air-conditioned environments, using a question format similar as for the thermal questions. The humidity preference question gave three options to subjects: “want more moisture,” “no change,” and “want drier air.” Table 5.20 shows percentages of responses in each of the three categories, by season and ventilation mode. 78% of all air-conditioned subjects preferred “no change” to classroom humidity – a figure that did not change seasonally. However, significantly more naturally-ventilated occupants preferred “no change” to humidity conditions (66% rh) during the cool season than in the hot season when temperatures were higher (2.6°C ET*), but in fact humidity was lower (60% rh). The seasonal results suggests that humidity preference might be associated with temperature.

Table 5.20 Summary of humidity preference

Classrooms	"Want DRIER Air" (%)	"No Change" (%)	"Want MORE Moisture" (%)	Mean Relative Humidity* (%)
NV classrooms	35.5	56.9	7.6	63.1
Hot season NV	44.6	46.3	9.1	59.8
Cool season NV	27.1	66.7	6.2	66.2
AC classrooms	11.9	78.3	9.8	60.4
Hot season AC	11.7	78.1	10.2	57.0
Cool season AC	12.0	78.5	9.5	64.0

* mean calculated from humidity measurements of classroom visits

Occupants were asked an acceptability question about humidity in order to compare acceptability or satisfaction with the upper humidity limit specified by the standard. In the previous *Standard 55,* this limit had a boundary of 60%. Relative humidity in the revised *Standard 55* follows a 20°C wet bulb line (Figure 5.5). 80% of the naturally-ventilated subjects responded that humidity was acceptable, as did 95% of the air-conditioned subjects (Table 5.21). Even at humidity levels above 70%, the majority (85%) of the naturally-ventilated subjects responded that these conditions were acceptable.

Table 5.21 Cross-tabulation of acceptability of responses and relative humidity

Relative Humidity (%)	Naturally-Ventilated Accept	Not Accept	Row Totals	Air-Conditioned Accept	Not Accept	Row Totals
40-45	0	0	0	48	2	50
45-50	16	0	16	104	4	108
50-55	156	49	205	201	10	211
55-60	435	167	602	163	8	171
60-65	512	67	579	396	15	411
65-70	363	119	482	215	13	228
70-75	97	23	120	169	15	184
75-80	133	23	156	0	0	0
80-85	19	2	21	0	0	0
Column Totals	1731 (79.4%)	450 (20.6%)	2181	1296 (95.1%)	67 (4.9%)	1363

5.4.2 Optimum Temperatures

5.4.2.1 Thermal Neutrality (T_n)

Neutral temperature is the temperature, either in ET* or operative temperature, in which the greatest percentage of the people are expected to vote within the middle ("neutral") category of the thermal sensation scale.[8] Comfort research defines the center of a comfort zone by assuming that comfort is associated with specified thermal sensations, and "neutrality" is assumed to be ideal. This assumption disregards the notion that neutral temperature might not necessarily be the temperature that populations prefer (i.e. people might prefer a sensation slightly warmer or cooler than neutral, depending on a variety of contextual factors).

Probit regression analysis determined thermal neutralities using thermal sensation data from 0.5°C temperature bins (Table 5.6), which were then divided into two groups: "warmer than neutral" and "cooler than neutral" (neutral category divided equally). As was previously shown in Figure 5.6, the air-conditioned classrooms had a skewed distribution centered on "slightly cool" rather than around neutral. Ballantyne[9] suggests dividing the skewed set equally about its central tendency, in this case at the "slightly cool" (-1) category, rather than the neutral category.

The curves Figure 5.18 show that the point where the maximum number of people voted "neutral" occurred at 26.8°C in naturally-ventilated classrooms, and at 22.6°C in air-conditioned classrooms. Ballantyne calls this a "transition temperature," or neutral temperature at which there are equal probabilities of a particular vote being cast warmer or cooler than the central tendency. The data symbols on the probit curves do not represent actual data (e.g. air-conditioned occupants did not actually experience classroom temperatures below 18°C), but are the "value of the standard normal curve (transformed through the probit model) below which the observed proportion of the area is found." Each of the points on the curve are associated with 95% confidence intervals – however, these were not established for the air-conditioned sample.

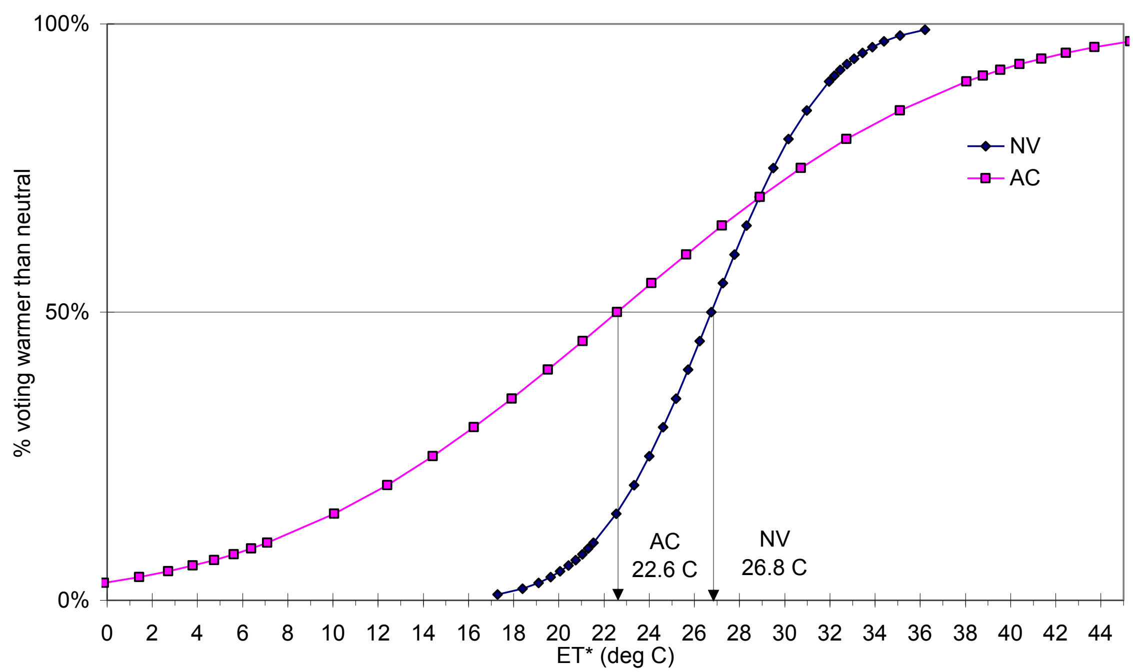


Figure 5.18 Probit regression models using thermal sensation votes to calculate thermal neutrality in naturally-ventilated classrooms

5.4.2.2 Preferred Temperature

From the cross-tabulations of thermal preference responses and operative temperature (in 0.5°C bins from Table 5.8), probit analysis was used to estimate preferred temperature from the groups of "want warmer" and "want cooler" responses. The intersection point of the two probit curves represents the preferred temperature (Figure 5.19), which occurred about 24.3°C (ET*) for naturally-ventilated classrooms and about 23.2°C (ET*) for air-conditioned classrooms.

Table 5.22 provides a basis for comparing these temperatures and gives rise to the question, "What scale best represents thermal comfort for tropical populations?" It appears that naturally-ventilated occupants a preferred temperature approximately 2.5°C (ET*) cooler than that which produced thermal neutrality. In contrast, the air-conditioned occupants preferred a temperature approximately 0.6°C (ET*) warmer than the neutrality temperature. These results in part support McIntyre's hypothesis[10] that there is a climate-based semantic bias in people's responses. Subjects surveyed in a cold climate might respond that their preferred neutral state is "slightly warm," and people in warm climates such as Hawaii's might vote that their preferred neutral state is "slightly cool."

Table 5.22 Summary of various optimum temperatures based on thermal sensation and preference

	ET* (°C)		SET* (°C)		T_{op} (°C)	
	NV	AC	NV	AC	NV	AC
Neutral Temperature[a]	26.8	22.6*	24.1	20.5	26.5	21.4*
Preferred Temperature [b]	24.3	23.2	21.0	23.0	24.0	23.0

*confidence limits not established
[a] probit regression of -1 to 3 votes on thermal sensation scale (50% effective dose) for AC, 0 to 3 for NV
[b] probit regression of McIntyre preference scale, want warmer and want cooler votes

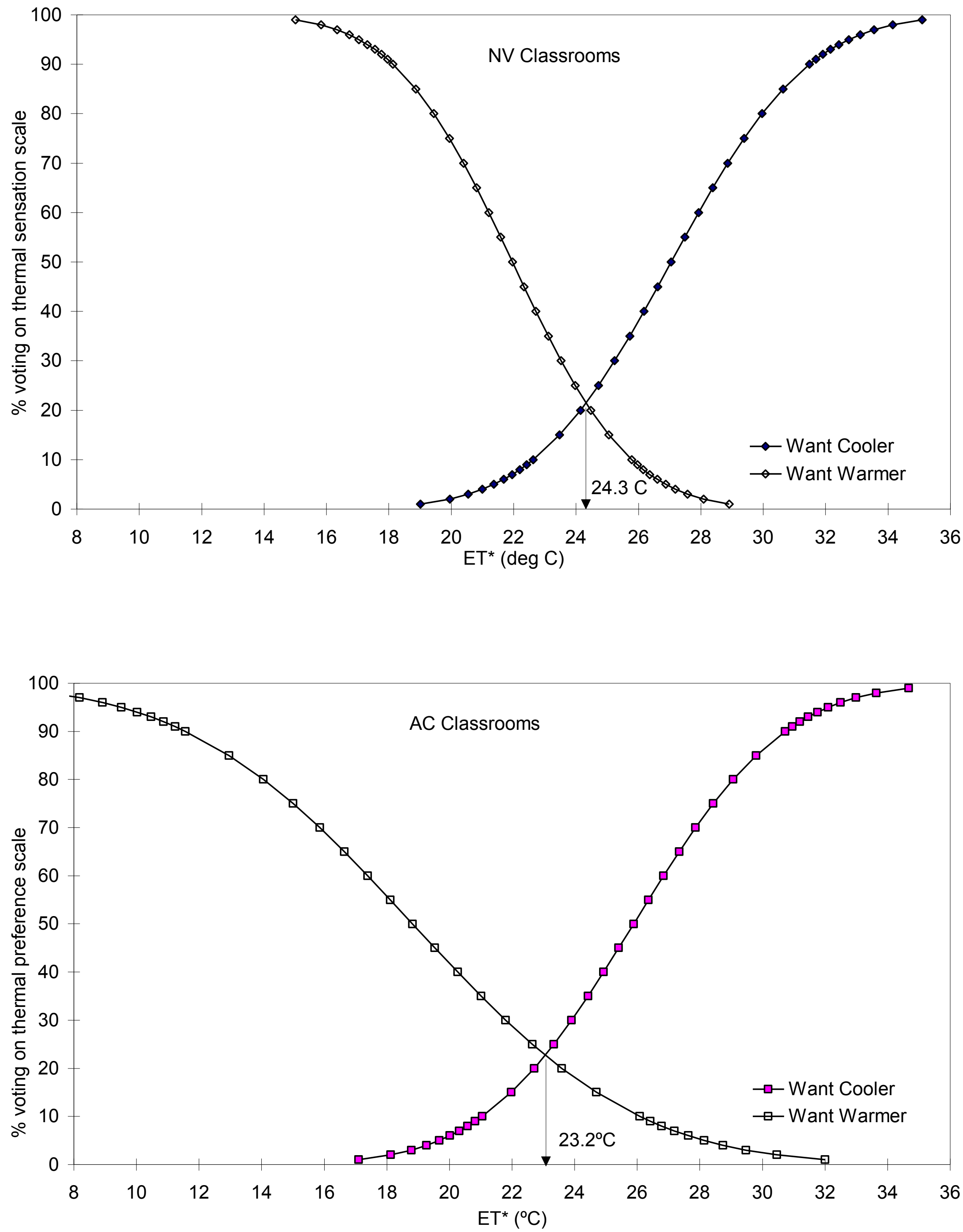


Figure 5.19 Preferred effective temperature in naturally-ventilated and air-conditioned classrooms

5.4.3 Comparison to Predictive Models

To assess the response to thermal environments, we may draw upon measurements and calculations from subjective surveys (presented in the previous section) and also from models that predict the comfort response in the absence of subjective data. This section compares the contrasting approaches of the PMV heat-balance model and the adaptive model in assessing comfort and determining optimum temperatures. The comparison provides a format to address several questions: 1) How does the match between observed and predicted comfort responses compare between naturally-ventilated and air-conditioned classrooms? 2) Are ideal conditions best determined observed subjective measures or predictive models of comfort?

5.4.3.1 Heat Balance Based Models

Section 5.3.1 examined T_{op}, ET* and SET* as single-number aggregates of environmental variables, that do not incorporate the human subjective response. There are, however, indices which do. Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), Predicted percent dissatisfied due to Draft (PD), and Predicted Thermal Discomfort (DISC) are empirical predictive models of comfort or discomfort, based on heat-balance equations.

Table 5.23 presents a statistical summary of calculated comfort indices, PMV, PPD, PD, and DISC, organized by ventilation type and season. The PMV calculations indicated conditions slightly cooler than neutral in both naturally-ventilated and air-conditioned classrooms during the cool season. The table also contains comfort indices which take into account the insulative effect of chairs that students used in the classroom as they took the survey. The incremental +0.10 clo from the chair increased PMV by 0.3 units for both naturally-ventilated and air-conditioned classrooms.

PMV predicted warmer thermal sensations than observed by more than 0.3 thermal sensation units. PMV without the chair closely predicted observed thermal sensations. These results differ from office studies where the addition of the incremental clo value for an office chair improved PMV predictions.[11]

When discussing PMV and thermal sensations, we need to return to the purpose of *Standard 55* and the specifications for acceptable thermal environments. Within the 80% acceptability criterion, the 20% dissatisfied include 10% due to general discomfort and 10% due to local discomfort. Although the PMV/PPD index predicts the mean value along the 7-point thermal sensation scale, it also recommends that PPD be lower than 10%. Because PMV/PPD was developed in the laboratory, local asymmetries that might have caused local discomfort, were controlled, minimized or eliminated. So, PMV and the PMV/PPD relationship represents *only* overall thermal response. When people are asked to vote on the thermal sensation scale in the field, the thermal sensation they are experiencing is a combination of all conditions they are exposed to: general and local effects, and their votes are not likely to distinguish between the two. Therefore, my interpretation is that observed thermal sensation votes combine both general and local discomfort, whereas PMV predictions, using ambient measurements as inputs, will only be predicting general thermal response.

When considering the match between observed thermal sensation and PMV, this distinction becomes important in any field setting where local asymmetries might be occurring and may in fact be one of the reasons for PMV's overestimation of thermal sensations. Other factors such as clothing may have contributed to the difference. Students wearing shorts are more susceptible to asymmetric radiation and air movement (drafts on legs), and consequently their thermal response would change.

Transient effects might have enhanced feelings of coolness. After being outside and most likely sweaty, students might feel even cooler in their air-conditioned surroundings. PMV would then estimate warmer thermal sensations values.

As one of the inputs into the PMV model, the assumed met rate of 1.2 could have also contributed to the overestimation. However, I would venture to say that a 1.2 met rate could have been a conservative estimate in schools, where students are typically much more active and "on the go" between classes than office workers.

Since the uncertainties were virtually the same in both building types, it is possible that the additional chair clo was not appropriate for a school setting where classroom occupants are not seated for long periods of time as are office workers. Several classrooms were science laboratories where the students sat on stools at lab desks, rather than in the typical desk/chair (Figure 4.6). Consequently, the subjects would have had less contact between the chair and their seat back and the chair insulation used would have over estimated the actual insulating value.

Table 5.23 Statistical summary of predicted responses to classroom comfort

		NATURALLY-VENTILATED		AIR-CONDITIONED	
		Hot Season	Cool Season	Hot Season	Cool Season
Number of Classroom Visits		48	54	40	40
Sample Size		1052	1129	703	660
PMV					
	mean	0.7	-0.1	-0.8	-0.8
	std dev	0.4	0.5	0.7	0.5
	min	-0.5	-2.1	-3.4	-1.9
	max	1.9	1.0	1.2	0.3
PMV (+0.10 chair insulation)					
	mean	0.9	0.2	-0.5	-0.5
	std dev	0.4	0.5	0.6	0.4
	min	-0.2	-1.7	-2.8	-1.6
	max	2.0	1.2	1.3	0.4
PPD (%)					
	mean	19.9	10.7	24.6	24.6
	std dev	12.8	8.9	21.8	21.8
	min	5.0	5.0	5.0	5.0
	max	73.0	82.0	100.0	100.0
PPD (%) (+0.10 chair insulation)					
	mean	25.6	9.8	17.2	13.7
	std dev	13.8	6.1	17.6	9.3
	min	5.0	5.0	5.0	5.0
	max	76.0	60.0	98.0	54.0
DISC (from 2-node)					
	mean	0.4	0.1	-0.2	-0.2
	std dev	0.4	0.2	0.2	0.1
	min	-0.1	-0.4	-0.8	-0.4
	max	2.3	1.2	1.6	0.3
DISC (from 2-node) (+0.10 chair insulation)					
	mean	0.6	0.2	-0.1	-0.1
	std dev	0.4	0.3	0.2	0.1
	min	-0.1	-0.3	-0.6	-0.4
	max	2.6	1.4	1.9	0.6
PD (%)					
	mean	15.9	22.0	18.6	18.6
	std dev	4.7	10.1	10.0	4.6
	min	8.0	8.0	10.0	12.0
	max	27.0	48.0	57.0	29.0

Neutrality predicted by PMV was calculated by solving the linear regression equation: $y = b_0 + b_n * t$ (temperature), where y (mean thermal sensation) = 0. A summary of PMV-based neutral temperatures in Table 5.24 shows the predicted neutralities were approximately a 1°C warmer in naturally-ventilated classrooms compared to air-conditioned classrooms.

Predicted neutralities were 1°C cooler than the observed neutralities in naturally-ventilated classrooms and 2.2°C warmer than observed neutralities in air-conditioned classrooms. The discrepancy between the predicted and observed air-conditioned neutralities is most likely explained by a combination of reasons described earlier: the additional chair insulation and transient effects from moving outdoors to indoors.

Table 5.24 Summary of PMV-based neutrality by weighted linear regression of binned PMV on ET* and T_{op}

Effective Temperature (ET*)	**Naturally-Ventilated**	**Air-conditioned**
b_0 = mean model constant	-7.71	-6.95
b_n = regression coefficient (slope)	0.30	0.28
R^2	0.97	0.81
PMV-based neutrality	25.7°C	24.8°C
Observed neutrality (based on probit)	26.8°C	22.6°C

Operative Temperature (T_{op})	**Naturally-Ventilated**	**Air-conditioned**
b_0 = mean model constant	-7.40	-6.85
b_n = regression coefficient (slope)	0.29	0.28
R^2	0.97	0.79
PMV-based neutrality	25.5°C	24.5°C
Observed neutrality (based on probit)	26.5°C	21.4°C

95% statistical significance

As extension of PMV, the PPD index predicts the percentage of thermally dissatisfied people that will vote: cold (-3), cool (-2), warm (+2) or hot (+3) on the 7-point thermal sensation scale. It is assumed that these votes represent thermal dissatisfaction. From Table 5.23, PPD (with the chair insulation) predicted an average of

18% dissatisfaction for occupants in the naturally-ventilated classrooms and 16% for air-conditioned rooms. Comparing these predicted dissatisfied percentages to the corresponding groups tallied from the dissatisfied thermal sensation votes (-3, -2, +2, +3) in Table 5.6, shows that PPD underestimated dissatisfaction by approximately 9% for the naturally-ventilated occupants and 18% for the air-conditioned occupants.

Figure 5.20 and Figure 5.21 illustrate simple (unweighted) regressions for mean thermal sensations, PMV and DISC indices on operative temperatures. (A regression line is not shown for the observed air-conditioned classrooms since the probit analysis, summarized in Table 5.22, proved more reliable). PMV predicted to within 0.5 thermal sensation units of the observed for the naturally-ventilated occupants and also estimated neutrality approximately 1°C cooler than observed thermal neutrality for the naturally-ventilated occupants (Figure 5.20). For the air-conditioned occupants, PMV predicted neutrality 2°C warmer than observed (compare neutralities in Table 5.24).

The slope of the regression line can be an indicator of sensitivity to temperature changes. The PMV results for both naturally-ventilated and air-conditioned classrooms are similar (Table 5.24), indicating that occupants would change their vote one unit on the thermal sensation scale (e.g. from 0 to +1) for an approximate 3.5°C change in operative temperature. The DISC model performed less satisfactorily, being fairly removed from both sets of observed data.

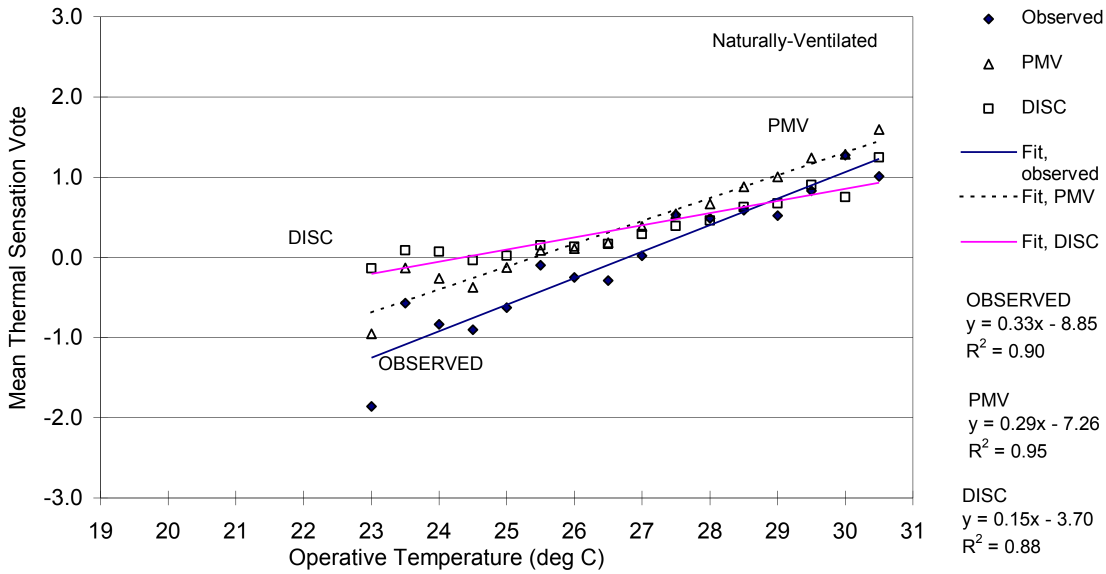


Figure 5.20 Mean thermal sensation, PMV, and DISC for operative temperatures in *naturally-ventilated* classrooms (includes +0.10 chair insulation)

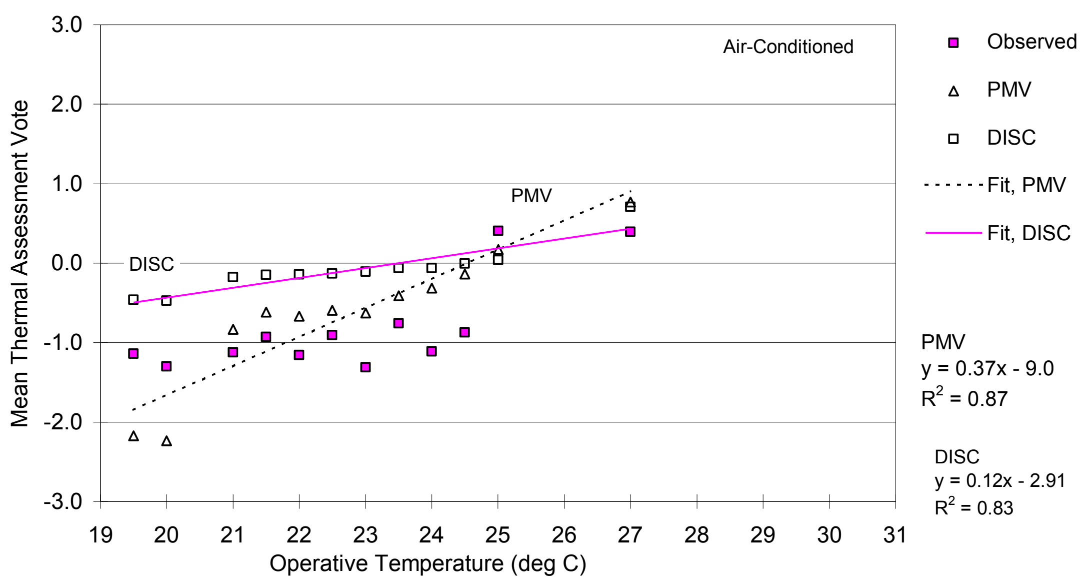


Figure 5.21 Mean thermal sensation, PMV, and DISC for operative temperatures in *air-conditioned* classrooms (includes +0.10 chair insulation)

5.4.3.2 Adaptive Models

In the proceedings to a conference titled, *Thermal comfort: past, present and future*, de Dear[12] writes, "The fundamental distinction between the heat balance and adaptive models is their underlying basis or cause for a shift in comfort temperatures. The former permits only adjustments to heat balance variables such as clothing or air velocity, where as the adaptive model is premised on changing the expectations of building occupants." The underlying hypothesis of the adaptive model is that one's satisfaction with the thermal environment is guided by adaptive adjustments (behavioral, physiological, and psychological) to not only the prevailing environmental conditions (outdoor climate), but to what we *expect* our indoor conditions to be. In a review of earlier comfort studies, de Dear[13] describes the development of several adaptive models of comfort that are strongly associated with indoor and outdoor climate, several of which are selected for this study for comparison to this study's data set. This section examines the reliability of predictive models as a means of assessing comfort for tropical populations. From the previously cited proceedings, de Dear gives a comprehensive review of the basis of the equations used in the adaptive model and writes:

Humphreys[14] equation, based on data from naturally-ventilated buildings found thermal neutrality (t_ψ) strongly associated with outdoor (t_o) climate:

Humphreys $$t_{\psi,o} = 0.534\ t_o + 11.9 \qquad (1)$$

After revising Humphreys' data set, removing outliers and adding new studies from various climate zones, Auliciems[15] developed an equation by combining naturally-ventilated and air-conditioned data sets and running a linear regression. Current discussions on the adaptive model use this equation:

Auliciems $$t_{\psi,o,i} = 0.48\ t_i + 0.14\ t_o + 9.22 \qquad (2)$$

Thermal neutralities calculated by probit analysis (using mean monthly outdoor temperatures obtained from 3-hour, local climatological data[16] and keyed to each class visit) for both adaptive models are shown in Table 5.25. For naturally-ventilated classrooms, both Auliciems' Equation 2 ($t_{\psi,o,i}$) and Humphreys ($t_{\psi,o}$) predicted the observed neutrality to within 0.4°C. Predictions for air-conditioned neutralities were less congruent. The naturally-ventilated results indicate a certain degree of support for the adaptive model. This was not the case for air-conditioned results classrooms in the Hawaii study.

Table 5.25 Comparison of neutral temperatures (°C)

	indoor	mean outdoor	observed by probit regress.	predicted Fanger PMV		Humphreys (1)		Auliciems (2)	
	Ti	To	T_ψ (ET*)	T_ψ (ET*)		T_ψ (o)		T_ψ (i,o)	
NV	27.5	28.6	26.8	25.7	-(1.1)	27.2	-(0.4)	26.4	(0.3)
AC	23.1	27.3	22.6*	25.5	-(2.9)	26.5	-(3.9)	24.1	-(1.5)

() numbers in parentheses are the calculated difference between observed and predicted Tψ, for each predictive model
*confidence limits not established

5.4.4 Comparisons to Other Studies

5.4.4.1 Physical Data

The psychrometric format, (first shown in Figure 5.5) provides both a quantitative and qualitative display of how data from other tropical studies compares to the comfort zone limits. Data sets from other studies are available from a public domain website (http://atmos.es.mq.edu.au/~rdedear/ashrae_rp884_appendc.html), developed by Macquarie University's ASHRAE RP-884 Adaptive Model project.[17] Led by de Dear, RP-884 has collected a database of 160 buildings and about 21,000 sets of thermal comfort data from around the world. Figure 5.22 and Figure 5.23 present downloaded data from two previous tropical thermal comfort studies (Bangkok and Singapore). The data are presented as comparative context for the Hawaii data, and to further examine the performance of the comfort standard in hot and humid conditions. The specifications of *Standard 55-1981* (0.12 humidity ratio limit) applied at the time during which the Bangkok and Singapore field studies took place - therefore the figures present the data on the *Standard 55-1981* summer comfort zone.

Qualitatively, the character of the building operation is quite clear - naturally-ventilated conditions are clustered in the hot and humid region of the chart while air-conditioned building data generally fall along the cool side of the comfort zone. The Bangkok office study included 392 subjects in naturally-ventilated buildings (0% in the comfort zone) and 769 subjects from air-conditioned buildings (63% within the comfort zone). The Singapore field study polled 583 subjects in naturally-ventilated residential buildings (0% in the comfort zone) and 232 subjects air-conditioned office buildings (60% in the comfort zone). For the Hawaii data set shown in Figure 5.5, only 15% of the naturally-ventilated classrooms and 44% of the air-conditioned classrooms had conditions within the comfort zone.

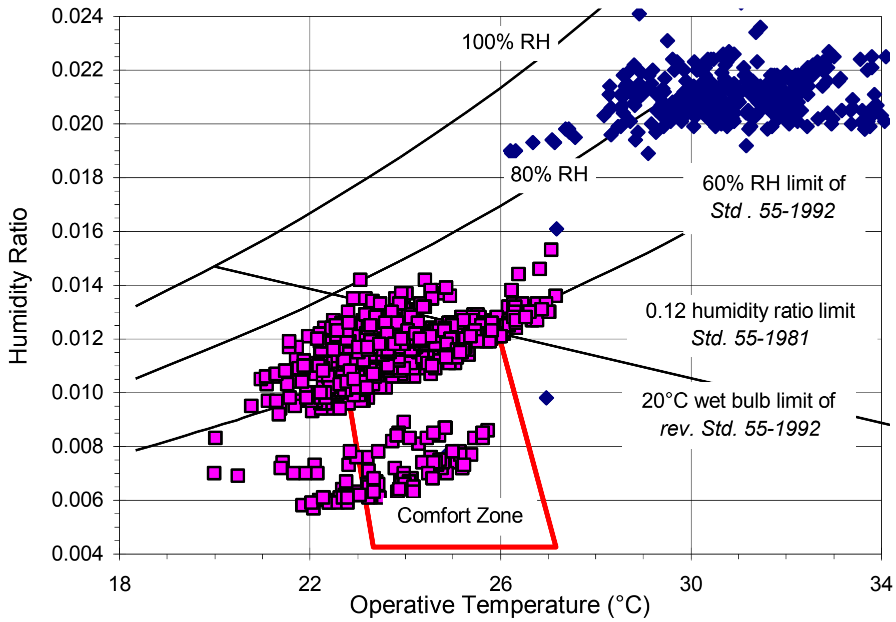


Figure 5.22 Bangkok indoor climate conditions on *ASHRAE Standard 55-1981* summer comfort chart[18]

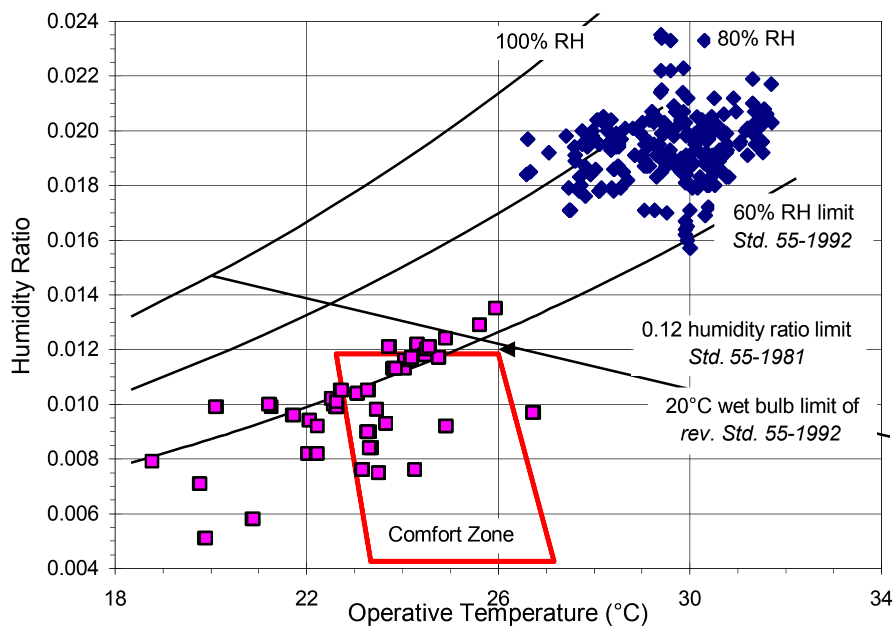


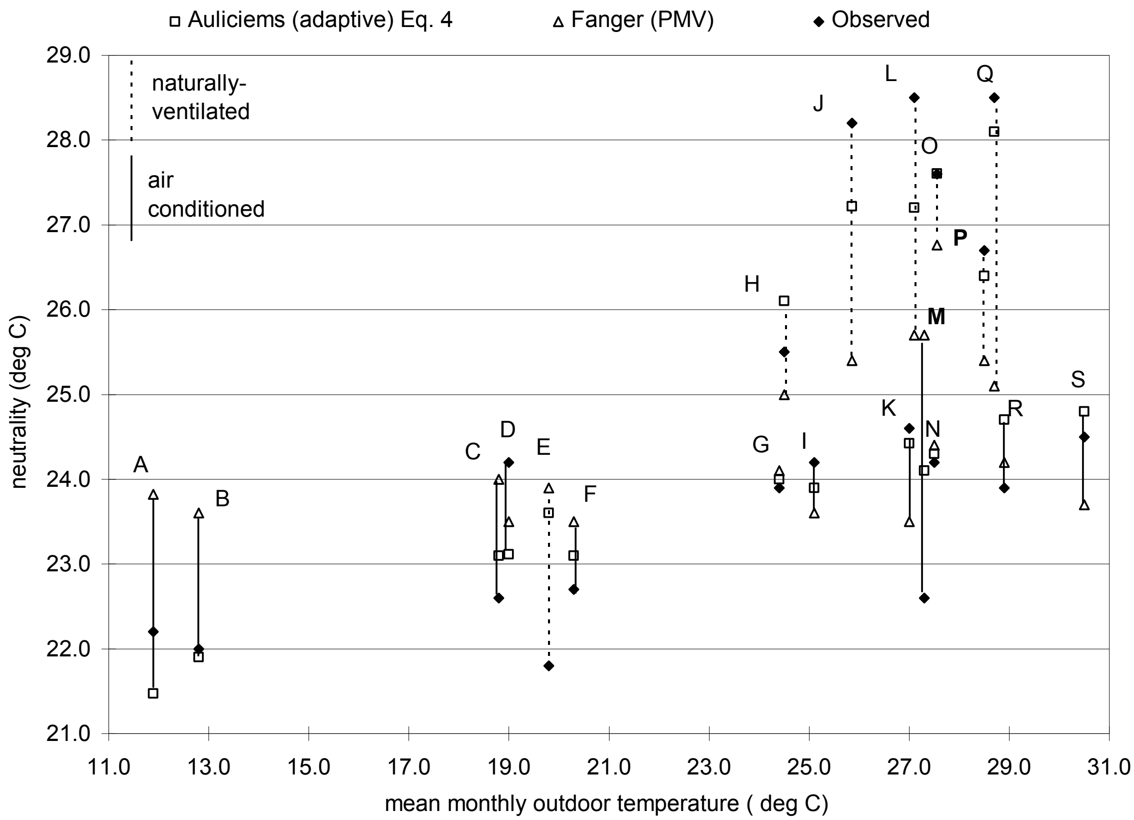
Figure 5.23 Singapore indoor climate conditions on *ASHRAE Standard 55-1981* summer comfort chart[19]

5.4.4.2 Comparison of Neutralities

Figure 5.24 presents an overview comparing observed neutralities with those predicted by Fanger's PMV heat balance and Auliciems' adaptation model (equation 4), developed by de Dear in the paper proceedings, *Thermal comfort: past, present and future*.[20] I use it here to compare the Hawaii data to other warm climate office studies (with the exception of San Francisco's Mediterranean climate). Most of the other field studies (labeled as D, E, F, G, H, K, and R) use the probit method to calculate neutralities.

Both predicted and observed thermal neutralities, show a steady, upward trend as outdoor temperatures increase. This trend is more remarkable in naturally-ventilated buildings. It appears that at mean monthly outdoor temperatures below 24°C, Fanger's PMV model overestimates observed neutralities (A, B, C, E, and F denoted in Figure 5.24). Above a mean monthly outdoor temperature of 24°C, the reverse is observed; here the PMV model underestimated all of the naturally-ventilated neutralities and most of the air-conditioned neutralities. Overall, Auliciems' adaptive model consistently estimated naturally-ventilated neutralities within an average of 0.8°C and in air-conditioned buildings to within an average of 0.5°C of the observed neutralities. The PMV model either overestimated or underestimated the observed neutralities by an average of 2.0°C in naturally-ventilated buildings and 1.0°C in air-conditioned buildings.

The Hawaii naturally-ventilated neutrality (labeled P) of 26.8°C ET* is in relatively close agreement with the other naturally-ventilated building studies: Bangkok (28.5°C), Singapore (28.5°C), Jakarta (27.6°C), Athens (28.2°C) and Brisbane (25.6°C). The air-conditioned neutrality (labeled M) of 22.6 is also in close agreement with temperate climate studies such as San Francisco (22.0, 22.6°C), Auburn (22.0°C) and Melbourne (22.7°C). It is however, lower than other tropical field studies, Townsville, (24.2, 24.5°C), Bangkok (24.5°C), and Singapore (24.2°C). Consistent with the adaptive theory, indoor neutralities will track prevailing outdoor climates. Hawaii's climate is not as warm as Bangkok and Singapore and the adaptive model would therefore predict that Hawaii neutralities would be lower as well, which they were.



Code	Location & Season	Vent. Type	Author
E	Melbourne-summer	NV	de Dear and Auliciems (1985)
F	Melbourne-summer	AC	de Dear and Auliciems (1985)
G	Brisbane-summer	AC	de Dear and Auliciems (1985)
H	Brisbane-summer	NV	de Dear and Auliciems (1985)
I	Darwin-Dry	AC	de Dear and Auliciems (1985)
B	San Francisco-winter	AC	Schiler et al. (1988)
C	San Francisco-summer	AC	Schiller et al. (1988)
Q	Bangkok	NV	Busch (1990)
S	Bangkok	AC	Busch (1990)
L	Singapore	NV	de Dear et al. (1991)
N	Singapore	AC	de Dear et al. (1991)
R	Darwin-Wet	AC	de Dear and Auliciems (1985)
A	Auburn*	AC	Benton and Brager (1993)
D	Townsville-dry*	AC	de Dear et al. (1993)
K	Townsville*	AC	de Dear et al. (1993)
J	Athens*	NV	Baker and Standeven (1994)
O	Jakarta*	NV	Karyono (1996)
M	Hawaii	AC	this study, Kwok (1997)
P	Hawaii	NV	this study, Kwok (1997)

Figure originally compiled by Richard deDear in de Dear, R.J. 1994. Outdoor climatic influences on indoor thermal comfort requirements. In: Thermal comfort: past, present and future, p. 115.
* indicates studies that I added to the original figure

Figure 5.24 Observed and predicted neutralities of thermal comfort field studies

5.4.4.3 Comparison of Sensitivity

While the linear regression intercept is used to determine the neutral temperature, the gradient coefficient (slope) of the regression line for mean thermal sensation can be used to judge the sensitivity of the occupants to indoor temperature. For naturally-ventilated classrooms, the regression equation from Figure 5.20:

$$\text{NV Thermal Sensation} = -8.85 + 0.33 * T_{op}$$

These subjects had a gradient coefficient of 0.33 thermal sensation units per °C. Therefore, they will experience a 1 unit change in their thermal state for every 3°C change in operative temperature.

Regressions of thermal sensation responses in naturally-ventilated buildings have also been presented by Busch[21] for Bangkok, and by de Dear and Brager[22] for a cumulative global database. The gradients in their regressions were 0.24 and 0.27, respectively (although it should be noted that Busch's analysis was done in terms of ET*). The Hawaii students were slightly more sensitive to changes in temperature, which would be expected since their average clothing level was somewhat smaller than the average in both the Busch and de Dear databases.

5.4.4.4 Comparison of Preference vs. Thermal Sensation

The data in the Hawaii classrooms showed a significant number of people experiencing neutral thermal sensations still preferred to feel cooler – between 1/3 - 1/2 of all subjects in the naturally-ventilated buildings in both seasons, and over 1/3 of the air-conditioned subjects in the hot season. Similar results were found in Busch's study[23] in Bangkok, where 2/3 of the neutral naturally-ventilated subjects and over 1/3 of the air-conditioned subjects still preferred to feel cooler. These findings strongly suggest that "neutral" is not ideal in all contexts, and that people's preferred thermal state may be influenced by culture and climate.

Naturally-ventilated occupants preferred temperatures 2.5°C cooler than the observed neutrality corroborating a similar difference (2.1°C cooler) between preferred and neutral temperatures of Brisbane[24] office occupants. The air-conditioned Hawaii classroom occupants however, preferred temperatures 1.6°C T_{op} (0.6°C ET* difference) warmer than their observed neutrality which was not consistent with studies in Darwin[25] (0.7°C, 0.1°C cooler), Melbourne[26] (1.3°C cooler), Townsville[27] (0.9°C cooler), or Bangkok[28] (2.2°C cooler).

5.4.5 Creating New Temperature Range for Naturally-Ventilated Classrooms

Standard 55 forms the comfort zone using an 80% acceptability criterion for environments that are defined by thermal conditions ranging from 23 - 26°C ET* for summer conditions. Past comfort studies typically assume acceptability by using the responses in the middle 3 categories of the thermal sensation scale. A few studies, including this one, have asked the acceptability question directly: are the conditions in this classroom "acceptable" or "not acceptable." We can also use predictive models, such as PMV, to determine acceptability. This section describes the application of two methods to create a new zone of acceptable temperatures for naturally-ventilated classrooms. One method uses traditional methods, based on the premise that "neutral" is ideal, and the 3 central thermal sensation categories are "acceptable." The other method is based on the direct acceptability.

Indirect method. This method uses an approach developed by de Dear and Brager (1997) in their proposal for an adaptive comfort standard. The method combines Fanger's predictive models, PMV/PPD, and the observed thermal sensation data from a global database of field studies. The assumptions of the PMV/PPD model (Figure 5.25) are that thermal sensations correspond to $-0.85<PMV<+0.85$, with a PPD of 20% (matching ±2, ±3 on the thermal sensation scale).

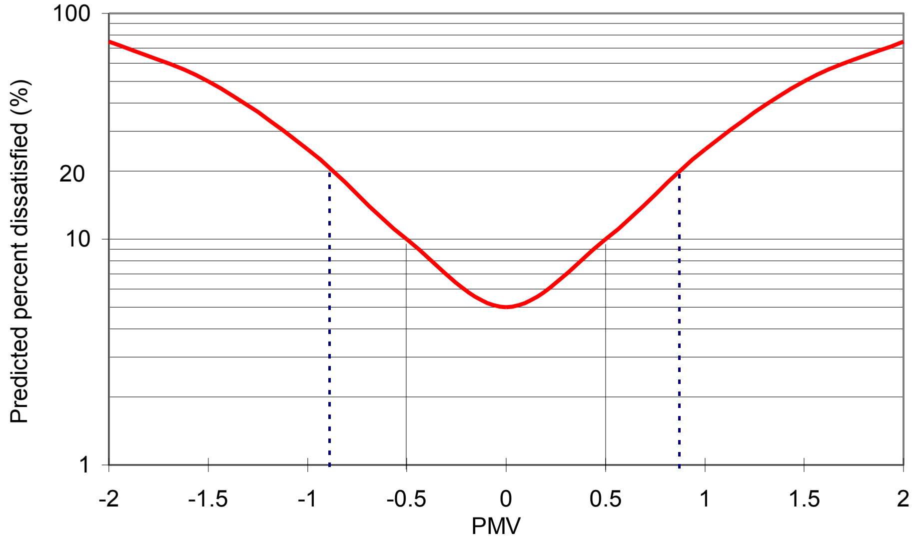


Figure 5.25 Predicted percentage of dissatisfied (PPD)
as a function of predicted mean vote (PMV)

The 90% acceptability criterion of PMV (10% PPD) restricts the corresponding thermal sensations with limits of -0.5<PMV<+0.5. Using the linear regression equation for operative temperature (Figure 5.20), thermal sensation = -8.85 + 0.33 * T_{op} and solving it with the 80% acceptability criteria (±0.85), the new range of acceptable opertive temperatures = 24.2 - 29.5°C. At the 90% acceptability criteria (±0.5) the range = 25.3 - 28.3°C.

Direct method. Compared to votes of direct acceptability (or direct dissatisfaction), PPD is a closer match than with the dissatisfied thermal sensation votes. Figure 5.26 illustrates the similarity in the percentage dissatisfied between the observed curve and the polynomial fit to the PPD data and is also useful for determining ranges of acceptable operative temperatures, summarized in Table 5.26.

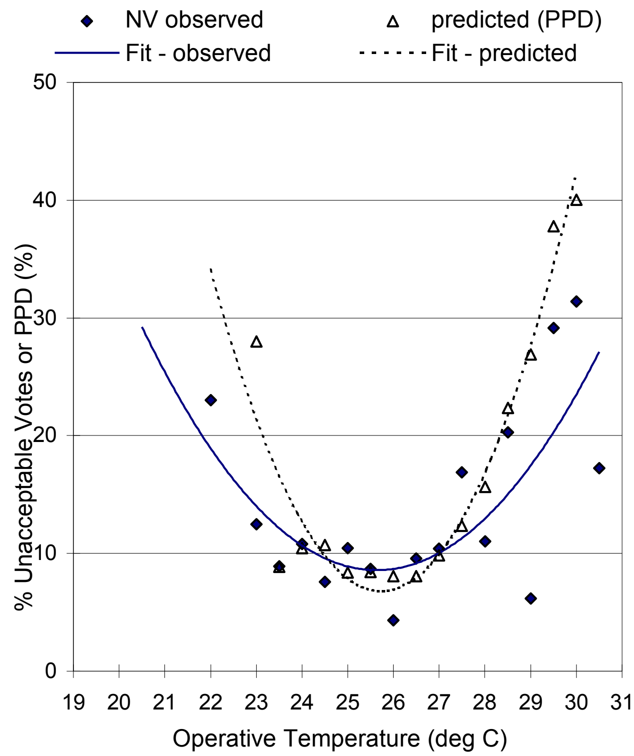


Figure 5.26 Comparison of observed and predicted thermal acceptability to operative temperature

The new range of operative temperatures taken at the 20% PPD line (80% acceptable), shows the naturally-ventilated subjects were tolerant of a wider range of operative temperatures than was predicted. Both the indirect method and the direct methods are comparable in that they extend the warm boundary of the Standard 55 summer comfort zone by 3.5°C. The direct method estimated the lower limit about 2°C cooler than with the indirect approach, though given the typical warm conditions in naturally-ventilated classrooms, people's preferences for cooler temperatures and any clothing adjustments taken by classroom occupants, a lower boundary might not be of great concern.

Table 5.26 Temperature ranges for 80% and 90% acceptability in naturally-ventilated classrooms

	Operative Temperature Range for Acceptability Criteria (°C)	
Method used to define "acceptability"	80% (20% dissatisfied)	90% (10% dissatisfied)
Direct acceptability question	22.0-29.5	23.5-26.5
Predicted Percent Dissatisfied (PPD)	23.0-28.5	24.5-27.0

5.5 Non-Thermal Environment

The nature of a field study like this naturally touches upon areas not directly related to the study of thermal comfort, but nevertheless vitally connected to the environmental experience of the classroom and to the operational strategies of controlling windows and air-conditioning. Some of these variables, such as air quality, acoustics and dust, are factors that might change depending on whether a space is air-conditioned. My objective in this portion of the questionnaire is to examine problems commonly associated with naturally-ventilated and air-conditioned rooms, such as air quality, dust, and acoustics. Subsequent questions ask students about these environmental conditions relative to their class work, e.g. "If you have experienced too little air movement in this classroom, how much does this interfere with your work?"

5.5.1 Non-Thermal - Physical

Carbon dioxide and particle counts measured in classrooms are summarized by building type and season in Table 5.27, showing seasonal differences that will be discussed in further detail in the following sections.

Table 5.27 Summary of non-thermal measurements in Hawaii classrooms

		Naturally-Ventilated		Air-Conditioned	
		Hot Season	Cool Season	Hot Season	Cool Season
Number of Classrooms		18	19	9	8
Number of Visits		48	54	40	40
Sample Size		1,052	1,129	703	660
Carbon Dioxide (ppm)					
	mean	497	444	1,482	1,688
	std dev	25	55	513	851
	min	452	338	651	612
	max	562	657	2,436	3,117
Particulate ($\#/ft^3$)					
	mean	21,500	71,700	29,500	58,400
	std dev	14,600	26,900	14,000	19,300
	min	3,200	26,200	6,800	18,900
	max	93,800	118,900	59,500	92,700

Carbon Dioxide. Figure 5.27 shows that indoor concentrations of carbon dioxide (CO_2), a non-thermal variable, varied dramatically between ventilation modes. Naturally-ventilated classrooms, almost without exception, had low concentrations of CO_2, around outdoor levels of 425 ppm. Air-conditioned classrooms varied in a way not related to temperature. At times CO_2 levels were significantly higher than the *Standard 62* CO_2 guideline, suggesting that the rate of ventilation in air-conditioned rooms was not high enough to remove CO_2 from the classroom. Carbon dioxide levels were highest in air-conditioned rooms using packaged air-conditioning systems. The paradox here is that explicitly engineered, sealed school buildings designed to provide comfort and proper ventilation to its occupants, have the highest CO_2 measurements with majority of these classrooms exceeding the *Standard 62* guideline of 1000 ppm.

The ventilation patterns are evident in Figure 5.28 showing CO_2 levels during a typical day in both naturally-ventilated and air-conditioned classrooms. In air-conditioned classrooms, CO_2 levels steadily increased, fluctuating with a few regularly spaced dips. These do not indicate major changes, but show when the doors open for a five-minute class change period. During the lunch period when the classroom was empty, CO_2 levels dropped but not to levels of outside air. Anecdotal and observational evidence suggested that students seemed drowsy, particularly in classes after lunch. The cause of this was difficult to confirm because of many potential influencing factors. For example, I took an informal poll from several classes, asking students how many hours of sleep they had the night before. Most slept an average of 6 hours, many as few as 3 or 4 hours. Regrettably, this was not investigated in a systematic fashion, though further investigation might look at drowsiness and increased levels of CO_2.

Particulate. I expected to find higher levels of particulate in naturally-ventilated classrooms than in air-conditioned classrooms, based upon the assumptions that 1) dust and dirt would come in through open windows of naturally-ventilated classrooms and 2) air-conditioning filters would remove particulate matter from incoming air to air-conditioned classrooms.

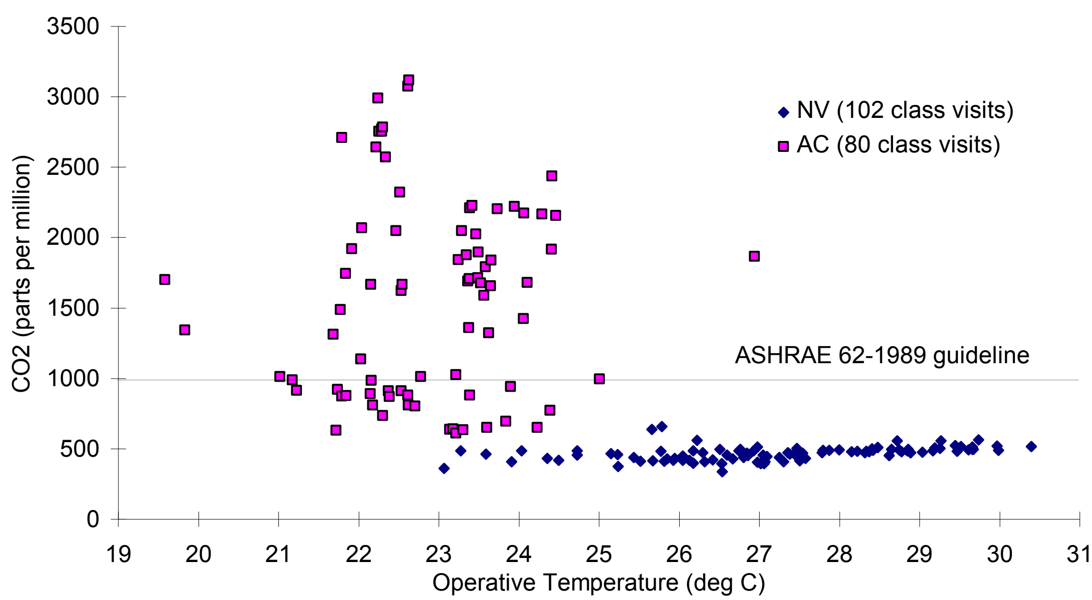


Figure 5.27 Carbon dioxide vs. operative temperature

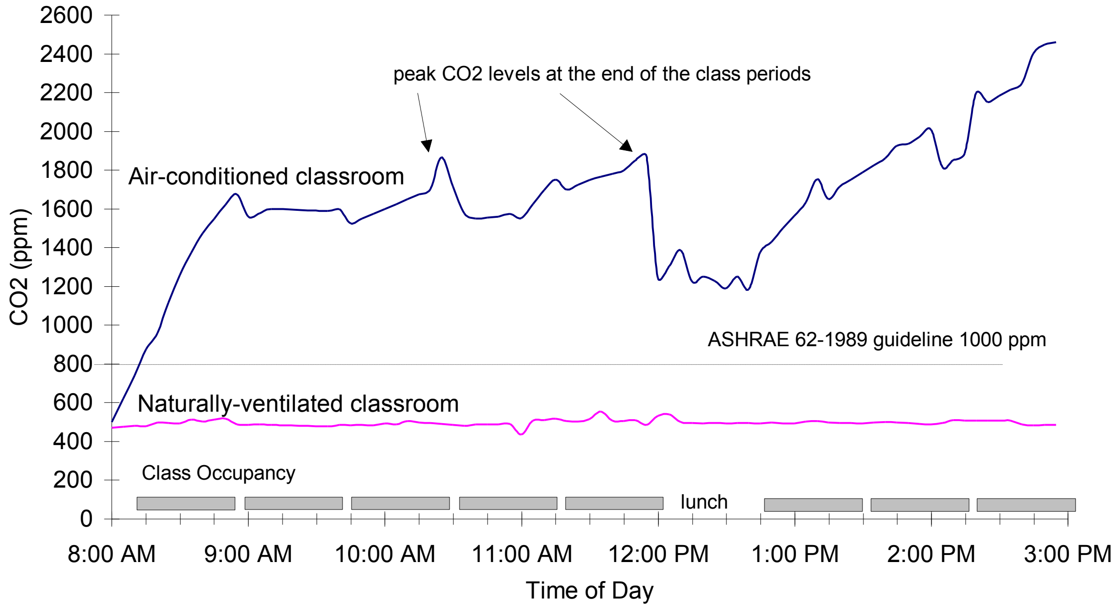


Figure 5.28 Daily CO_2 levels in a typical NV and AC classroom

Particle counts in naturally-ventilated and air-conditioned classrooms were relatively similar, during the hot season (though particle counts measured in carpeted, air-conditioned classrooms were higher than in classrooms without carpets). During the cool season, particle counts were much higher than in the hot season (Figure 5.29) for both naturally-ventilated and air-conditioned classrooms, which indicated a possible strong outdoor source. This may be attributable to the presence of “vog,” or the volcanic smog sometimes occurring in Hawaii. For several days during the cool season survey period, the predominant northeasterly trade winds shifted direction, carried the vog from the erupting volcano on the Big Island over the island chain. Particle counts were higher in the naturally-ventilated classrooms during the cool season, leading to the possibility that the air-conditioning systems filtered ambient particulate – although only naturally-ventilated classrooms were surveyed during “voggy” days. Other factors might also might account for elevated particle counts in classrooms, such as high occupant density, entrainment of particles from carpeted floors, and low ventilation rates.

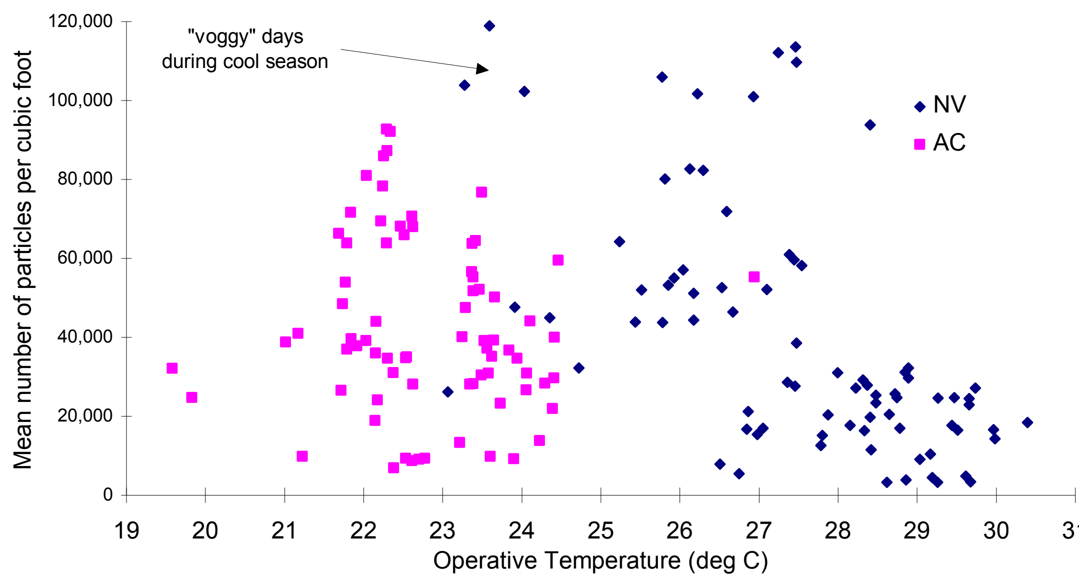


Figure 5.29 Particulate measurements vs. operative temperature

5.5.2 Non-Thermal - Subjective

5.5.2.1 Air Quality Conditions

The questionnaire asked subjects to rate the freshness of the classroom air using a 7-point scale ranging from “very fresh” (1) to “very stale” (7), and “neutral” (4) in the middle of the scale. Between seasons, naturally-ventilated and air-conditioned respondents rated the air quality almost identically. However, when comparing ventilation modes, air-conditioned respondents ranked classroom air quality on the stale side of neutral (4.2 units), while those in the naturally-ventilated classrooms ranked air quality slightly fresher (3.7 units). Students were keenly aware of odors in the classroom, and complained of “damp, mildew odors” in several of the carpeted air-conditioned classrooms.

Acceptability of air quality was slightly higher in air-conditioned classrooms than in naturally-ventilated classrooms. After further dividing the sample by season, Table 5.28 shows the highest acceptability of air quality occurred in naturally-ventilated classrooms during the cool season (92%). Air quality acceptability in naturally-ventilated classrooms during the hot season was also high (85%). Air-conditioned occupants voted with similarly high acceptability percentages, although during the cool season acceptability (89%) was not as high as during the hot season (91%). These results suggest cool temperatures did not necessarily influence acceptable perceptions of air quality in these classrooms.

Students were asked to rate air quality conditions such as dust, stuffiness of air, and the presence of unpleasant odors, using a scale of “little problem, “moderate problem,” “big problem,” or “not a problem at all.” The majority of the sample generally had little or no problem with these issues. The only noticeable difference evident in Table 5.29, is that 23% of air-conditioned respondents had a “moderate” to “big” problem with unpleasant odors, compared to 14% of the naturally-ventilated respondents, perhaps attributable to poor ventilation (discussed in a previous section). Responses were virtually identical on the stuffiness of air between air-conditioned and naturally-ventilated classrooms. Dust was thought to be a “moderate” to “big” problem for 25% of the naturally-ventilated respondents, compared to 17% of the air-conditioned. This might be related to dust coming through open windows of a cross-ventilated classroom, and possibly related to the higher particle counts measured in those rooms.

Table 5.28 Cross-tabulation of operative temperature and air quality acceptability

	Naturally-Ventilated				Air-Conditoned			
Top	Hot Season		Cool Season		Hot Season		Cool Season	
(°C)	Accept	Not Accept	Accept	Not Accept	Accept	Not Accept	Accept	Not Accept
19.5	0	0	0	0	14	1	0	0
20	0	0	0	0	14	1	0	0
20.5	0	0	0	0	0	0	0	0
21	0	0	0	0	14	1	29	0
21.5	0	0	0	0	0	0	35	1
22	0	0	0	0	53	3	168	11
22.5	0	0	0	0	91	5	170	17
23	0	0	16	0	45	5	56	8
23.5	0	0	43	2	186	28	127	38
24	0	0	34	3	112	6	0	0
24.5	0	0	74	5	85	6	0	0
25	0	0	59	8	11	4	0	0
25.5	0	0	80	12	0	0	0	0
26	0	0	240	14	0	0	0	0
26.5	28	2	147	11	0	0	0	0
27	68	9	173	19	16	2	0	0
27.5	58	2	168	21	0	0	0	0
28	108	10	0	0	0	0	0	0
28.5	239	62	0	0	0	0	0	0
29	139	7	0	0	0	0	0	0
29.5	201	39	0	0	0	0	0	0
30	39	12	0	0	0	0	0	0
30.5	23	6	0	0	0	0	0	0
Column Totals	903 (86%)	149 (14%)	1034 (92%)	95 (8%)	641 (91%)	62 (9%)	585 (89%)	75 (11%)

Table 5.29 Responses to air quality conditions

	Odors		Stuffy Air		Dust	
Problem?	NV	AC	NV	AC	NV	AC
Not Applicable	11%	9%	4%	6%	6%	9%
Not at all	43%	33%	26%	30%	32%	45%
A little	31%	35%	44%	39%	36%	28%
Moderate	9%	14%	18%	18%	15%	10%
Big	5%	9%	8%	7%	10%	7%

5.5.2.2 Acoustical Conditions

Acoustical complaints are a common issue associated with naturally-ventilated classrooms. The intent of this series of questions was to compare acoustical issues between the two modes of ventilation. Table 5.30 shows that acoustical issues associated with classrooms, buzzing (ballasts) lights, noise from the air-conditioning system, outside traffic, and outside noise from surrounding activities (construction, playground noises, conversations and laughter, airplanes overhead), did not bother the majority of students in either naturally -ventilated or air-conditioned classrooms. Some of the science classrooms had noisy pumps connected to large fish tanks, which students found annoying. Traffic and school activity noises were problematic for a higher percentage of naturally-ventilated students, and noises from the air-conditioning system were more problematic for the air-conditioned students.

Table 5.30 Responses to acoustical conditions

	Lights Buzzing		AC Noise		Traffic Noise		Outside Noise	
Problem?	NV	AC	NV	AC	NV	AC	NV	AC
Not applicable	15%	15%	60%	2%	6%	23%	4%	6%
Not at all	65%	69%	21%	22%	34%	54%	32%	31%
A little	14%	12%	12%	48%	41%	17%	42%	48%
Moderate	4%	3%	5%	24%	15%	4%	17%	13%
Big	1%	1%	1%	4%	4%	1%	4%	2%

5.5.2.3 Physical Conditions and Work Interference

This section describes the perceptions that students have about their class work performance in the context of the thermal environment. Among the teachers that I interviewed, it was commonly thought that teaching and learning performance declined at high temperatures. Several teachers observed their students “come to life” and “score better on tests” in the coolth of air-conditioning. Determining school performance under different ventilation regimes would be a complex task, involving an examination of potentially confounding factors. The intent of this set of questions was to determine whether classroom environmental conditions in naturally-ventilated and air-conditioned classrooms might influence student perception of class work impedance. Table 5.31 shows the majority of students in naturally-ventilated classrooms responded that when they experience conditions that are too hot, have too little or too much air movement, or hear outside noises, they are bothered to the extent that it interferes with their work. However, the responses from the air-conditioned students were not altogether different, except for the "too cold" percentages. When the air-conditioning is too cold, students find that it interferes with their work much more than if conditions are too cold in naturally ventilated classrooms. This might explain the pattern of thermal preferences and sensations discussed in a previous section.

Table 5.31 Comparison of environmental conditions between ventilation modes on class work

Interfere with	Too Hot		Too Cold		Too Little Air Movement		Too Much Air Movement		Outside Noises	
class work?	NV	AC	NV	AC	NV	AC	NV	AC	NV	AC
Not at all	11%	18%	50%	24%	23%	45%	45%	58%	17%	20%
Somewhat	45%	41%	35%	48%	46%	39%	40%	29%	47%	47%
Moderately	29%	27%	12%	23%	23%	13%	12%	9%	27%	23%
Very Much	14%	14%	4%	5%	8%	4%	3%	3%	9%	10%

5.6 Summary

The physical conditions measured in the majority of naturally-ventilated and air-conditioned classrooms surveyed were well outside the allowable limits set by *Standard 55*. While occupants experienced physical conditions outside the comfort zone, they still found that these conditions were acceptable (based on answers to the direct acceptability question). Other methods of assessment revealed a different story. Although responses on the thermal sensation scale indicated neutrality or comfort, the thermal preference question indicated that occupants desired different temperatures. Predictive models such as the adaptive model, estimated neutrality closely, while the PMV model predictions did not closely match observations in both naturally-ventilated and air-conditioned classrooms. Additionally, there were negligible differences in responses to ambient conditions and their effect on school work between naturally-ventilated and air-conditioned classrooms. The three most notable results are: 1) in the tropical contest the two building types create two distinct sets of indoor conditions, 2) *Standard 55* may be less applicable in the tropical climate, and 3) comfort assessments vary dramatically depending on the method of acceptability being applied.

References and Notes

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2. ASHRAE. 1993. *1993 ASHRAE Handbook of fundamentals*. Atlanta, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
3. ASHRAE. 1992. *ANSI/ASHRAE Standard 55-1992, Thermal environmental conditions for human occupancy*. Atlanta, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
4. Brager, G. S., M. E. Fountain, et al. 1994. *A comparison of methods for assessing thermal Sensation and acceptability in the field*. Thermal Comfort: Past, Present and Future, Garston, Building Research Establishment.

5. Conversation with Gail Brager: a 3-point scale would always expect a lower percentage than found with the central 3 categories of thermal sensation. Preference is a better tool for determining ideal conditions and is not generally used as a measure of acceptability. I use it here to show this point.

6. Brager, G. S., M. E. Fountain, et al. *op. cit*.

7 ASHRAE, 1992. *op. cit.*

8. It seems that for something so central to defining the parameters of the comfort zone, that a definition for neutrality would be easy to find - perhaps even in the standard itself. Nicol describes neutral temperature as comfort temperature. The broadest definition comes from McIntyre, D. A. 1980. *Indoor Climate*. London, Applied Science Publishers Ltd..

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17. de Dear, R., G. Brager, et al. 1997. Developing an adaptive model of thermal comfort and preference. Sydney, Macquarie University.

18. *Ibid.* The project's website provided a database from which I downloaded the Bangkok data. The process of assimilation and data standardization of the RP-884 database is credited to Richard de Dear of Macquarie University. I put the data set through the WinComf Thermal Comfort Program to establish humidity ratios which then could be plotted onto the psychrometric chart.

19. *Ibid.* The project's website provided a database from which I downloaded the Singapore data. The process of assimilation and data standardization of the RP-884 database is credited to Richard de Dear of Macquarie University. I put the data set through the WinComf Thermal Comfort Program to establish humidity

ratios which then could be plotted onto the psychrometric chart. There were 333 air-conditioned subjects indicated in this data set, of which 101 were selected out because of anomalous data that showed data in the hot and humid region (papers published on this study showed that there were 235 ac subjects). In April 14, 1997 correspondence with de Dear, he thought there might have been a problem with the data entry into the data base.

20. de Dear, R. J. 1994. *op. cit*.

21. Busch, J. F., Jr. 1990. From Comfort to Kilowatts: An Integrated Assessment of Electricity Conservation in Thailand's Commercial Sector, University of California, Berkeley.

22. de Dear, R., G. Brager, et al. 1997. Developing an adaptive model of thermal comfort and preference. Sydney, Macquarie University).

23. Busch, J. F., Jr. 1990. *op. cit.*

24. de Dear, R. J. and A. Aulidiems. 1985. "Validation of the predicted mean vote model of thermal comfort in six Australian field studies," *ASHRAE Transactions* 91(2): 451-468.

25. *Ibid*.

26. *Ibid*.

27. de Dear, R., M. Fountain, et al. 1993. A field study of occupant comfort and office thermal environments in a hot-humid climate. Atlanta, ASHRAE.

28. Busch, 1990. *op. cit.* I calculated the preferred temperature in the Bangkok study using data downloaded from the ASHRAE RP-884 website (de Dear, R., G. Brager, et al. 1997. Developing an adaptive model of thermal comfort and preference. Sydney, Macquarie University). Probit regression analysis determined the preferred temperatures. However, there was not a statistically significant result for the naturally-ventilated data.

CHAPTER 6

DISCUSSION

The objectives of this study were to: a) characterize the physical environment of classrooms selected to represent two typical conditioning regimes, natural ventilation and air-conditioned classrooms, b) compare measured physical conditions to the comfort zone specifications of the *Standard 55* for each classroom, c) compare thermal comfort responses by the classroom occupants (subjective response) to criteria specified by *Standard 55*, using a variety of comfort scales and environmental indices, d) compare observed and predicted responses calculated by various comfort prediction models, e) compare the results with findings from other thermal comfort studies. This discussion not only questions the applicability of the thermal comfort standard, *Standard 55*, in tropical climates, but challenges the notion that the standard is interpreted as being universally applicable to building types that are not mechanically-controlled (e.g. naturally-ventilated buildings).

6.1 What ranges of thermal environmental conditions are found in tropical classrooms and do they comply with *Standard 55*?

Standard 55 specifies physical conditions for indoor climates that will provide thermal comfort to building occupants. I anticipated that indoor conditions for the naturally-ventilated classrooms would exceed limits specified by the standard and the air-conditioned classrooms would fall within comfort zone conditions.

The range of thermal environmental conditions found in Hawaii classrooms is a bi-modal distribution of Top, ET*, and SET* frequencies (**Error! Reference source not found.**), associated with the two building types: naturally-ventilated and air-conditioned classrooms. The distribution indicates two distinct sets of physical conditions that serve as context for the collected the subjective responses.

Standard 55 uses 23 and 26°C ET* lines to delineate the temperature boundaries of the comfort zone on the psychrometric chart. Looking at the sample in its entirety, as the standard is currently interpreted, finds poor compliance to the standard's criteria for the physical environment. More than 75% of the classroom visits had physical conditions that did not fall within the comfort zone (**Error! Reference source not found.**), with many classrooms exceeding the warmer margin of the comfort zone by 4°C. Dividing the sample by ventilation strategy, 92% of the naturally-ventilated classrooms had conditions well beyond the humidity boundary of the *Standard 55* comfort zone. Air-conditioned classrooms, the group hypothesized to fall within the standard's prescriptions, only had 44% within the comfort zone, with many classrooms running 4°C lower than the cooler margin of the comfort zone. Results of other tropical studies (**Error! Reference source not found.** and **Error! Reference source not found.**) such as Bangkok (63% of visits within comfort zone) and Singapore (60% within comfort zone) and Townsville (55% within comfort zone) also showed the distinct character between the two regimes. *Standard 55*'*s* criteria appear too restrictive to apply universally to *all* building types (not to mention that even if the applied solely to air-conditioned environments, the data suggest that air-conditioning systems do not operate within the Standard's prescriptions). However, the real test for this are the subjective responses to those conditions, discussed in the next section.

6.2 Do classroom occupants responses match the 80% acceptability criteria from *Standard 55*?

As a basis for determining the physical limits of the comfort zone, *Standard 55* explicitly states that a satisfactory environment is one that 80% of the occupants find thermally acceptable. To determine compliance to the acceptability criteria of the *Standard 55,* a variety of methods measure perceptions of thermal comfort in this study: the thermal sensation scale, thermal preference scales, direct acceptability, and through predictive models and indices.

Indirect, Direct and Preference. These methods of measuring acceptability showed differing results. The direct method yielded high acceptability levels from both naturally-ventilated (86%) and air-conditioned subjects (92%), exceeding the Standard's 80% criterion (**Error! Reference source not found.**). In fact, when dividing the sample across the coordinates of the comfort zone prescriptions (**Error! Reference source not found.**), those *within* the comfort zone (although representing a small portion of the sample, **Error! Reference source not found.**) and those *outside* of the comfort zone, found conditions acceptable above the Standard's criteria.

In contrast, using the traditional indirect measure of acceptability using the 3 central categories of the thermal sensation scale, both naturally-ventilated occupants (74%) and the air-conditioned occupants (65%) acceptability did not meet the 80% acceptability criterion of *Standard 55* (**Error! Reference source not found.** and **Error! Reference source not found.**). Because of the assumption that neutral sensations indicate acceptability, this method does not take into account the fact that people experiencing non-neutral thermal sensation might consider conditions acceptable, which the Hawaii sample expressed through the direct acceptability question (**Error! Reference source not found.**).

Direct thermal acceptability data of the Hawaii air-conditioned occupants corroborated the results of the data in Townsville,[1] which also met the Standard's 80% acceptability goal (though it should be noted that close agreement was found between indirect and direct assessment in that study).

The assumptions associated with the indirect method become more apparent when examining thermal preferences. A significant number of people (62% during the hot season and 43% during the cool season) in naturally-ventilated classrooms preferred to feel cooler while experiencing neutral thermal sensations. This corroborates the results of Busch's Bangkok study where 64% of naturally-ventilated office workers preferred cooler conditions while experiencing neutral sensations. These findings strongly suggest that "neutral" thermal sensations do not correlate to people's ideal or preferred thermal state.

Neutralities. HVAC engineering by the standard practices strive to maintain stable, optimum temperatures in air-conditioned spaces. By definition, optimum temperature or thermal neutrality, is located in the center of the comfort zone. Neutrality calculated through probit from thermal sensations for naturally-ventilated was 26.8°C ET*, similar to the neutralities of tropical studies in Singapore, Bangkok and Jakarta. Yet, the Hawaii naturally-ventilated occupants preferred temperatures 2.5°C cooler than the observed neutrality. Neutrality for air-conditioned classrooms was 22.6°C ET*, but occupants preferred temperatures 0.6°C warmer (1.6°C warmer than the observed 21.4°C neutrality for T_{op}). This finding was not consistent with the preferences in most air-conditioned studies for cooler conditions, and could not be explained at this time.

The contrasting results between the indirect and direct methods has shown that the validity of the assumptions that associate neutral sensations with acceptability are questionable for two reasons: 1) a significant number of people experiencing non-neutral thermal sensations voted the conditions as acceptable, and 2) thermal neutralities calculated by thermal sensation did not match those calculated using preference. Results also suggest that neutrality is not necessarily ideal and that measures of direct acceptability and thermal preference are perhaps better tools for determining ideal conditions (single, optimum temperatures) instead of neutral temperatures. One approach might ask subjects to mark on the thermal sensation scale their preferred thermal condition (rather than the three choices, "want warmer," "no change," or "want cooler"). In turn, the results might be easier to compare to the thermal sensation scale itself.

What caused discomfort and dissatisfaction? Thermal environments cannot possibly please everyone,[2] hence the Standard's criterion of 80% acceptable (20% dissatisfied), half of those dissatisfied (10% of the sample) are dissatisfied because of general, overall thermal balance, while the other half (10% of the sample) are dissatisfied due to local asymmetries. This leads us into a discussion about the factors causing thermal discomfort and dissatisfaction.

For example, non-uniformity of the thermal environment, such as vertical temperature differences, radiant temperature asymmetry, warm or cold floors, and draft might have caused local discomfort. However by measurements shown in **Error! Reference source not found.**, vertical air temperatures, measured at different heights (spot measurements at 0.1 m and 0.6 m) did not exceed the 3°C variation allowed by standard. Spot measurements verified that radiant temperatures from warm or cool surfaces in the classrooms, did not exceed the standard's specifications of 5°C in the vertical direction or 10°C in horizontal direction. And floor temperatures, also measured by spot measurement, were within the temperature range of 18°-29°C specified by the standard.

Local discomfort can also be caused by drafts such as excessive air movement, turbulence, or a combination of both. *Standard 55* not only specifies an air movement limit (for draft) of 0.2 m/s and a "draft dissatisfaction" criterion not to exceed 15%. Calculations of the predicted percent dissatisfied due to draft (PD) of both naturally-ventilated and air-conditioned occupants was 19%, exceeding the standard's 15% dissatisfied criteria by a small margin. Since the majority of *air-conditioned* classrooms had locations either outside and along the cooler region of the comfort zone, one might suspect that draft caused discomfort to those occupants (that is, too much air movement from the ventilation systems and therefore too cold). However, of the 110 thermally dissatisfied air-conditioned occupants (**Error! Reference source not found.**), only 16% preferred less air less air movement (**Error! Reference source not found.**). In contrast 38% wanted *more* air movement. Although subjects were not asked their reasons for wanting more or less air movement, such indications might have come about from the subjects' interpretation of the question: 1) subjects felt cold and interpreted the question as wanting warm *outside* air moving through the space, 2) subjects perhaps wanted to feel even cooler, i.e. their "slightly cool" thermal sensations felt warm to them, 3) subjects desired air movement in and of itself, independent of its general cooling effect, or 4subjects considered air to be "stuffy" and desired air movement to improve air quality conditions.

Naturally-ventilated classrooms by design require high levels of air movement for cooling comfort and in fact, 92% of these classrooms had conditions exceeding the 2.0 m/s air movement limit of *Standard 55's* basic comfort zone. Even with the Standard's higher allowable air speeds (up to 0.8 m/s if the individual has control of the local air movement), the majority of these classrooms were still beyond the extended comfort zone.

The majority (98%) of thermally dissatisfied, naturally-ventilated occupants (**Error! Reference source not found.**) who preferred cooler conditions, also preferred more air movement. When asked *directly* about air-movement acceptability, for comparison to the Standard's 85% acceptable criterion, the majority (65%) of classroom occupants voted the conditions unacceptable. Arens et al.[3] reported air movement preference and acceptability of air velocities as high as 1.4 m/s for cooling by occupants (at 1.2 met) with individual control of air movement. These air-speeds clearly exceed even the allowable limit. Although the Hawaii data did not show air velocities above the0.8 m/s limit, it did indicate that occupants desired higher levels of air movement, *regardless* of the draft limit restriction. This is particularly important in schools where student occupants have virtually no personal control in a classroom is versus the potential for control for control in an individual office space. Naturally-ventilated subjects also were more discerning of humidity than their air-conditioned counterparts (**Error! Reference source not found.**), an important factor particularly in the hot and humid tropics where higher air speeds are necessary for convective cooling. Since air movement in naturally-ventilated spaces is typically dynamic and fluctuating, it is possible, though conjecture at this point, that expectations of air movement in naturally-ventilated spaces might indeed be for such irregular patterns, and that draft may be less of a concern.

6.3 How well do the prediction models of comfort match the observed subjective responses?

Fanger's PMV prediction model (without the chair insulation value) matched the average thermal sensation votes of the naturally-ventilated and air-conditioned subjects to within 0.1 PMV unit. Adding the chair insulation (+0.10 clo) to the PMV calculations (**Error! Reference source not found.** and **Error! Reference source not found.**), weakened the agreement by predicting warmer thermal sensations than observed for *both* naturally-ventilated and air-conditioned occupants by approximately 0.4 units. Since this over-prediction occurred in similar magnitude for both regimes, it suggests there might have been a systematic uncertainty introduced, such as clothing insulation, met, or simply the assumptions of the PMV model itself.

Discrepancies between Predictions and Observed Data. Inputs for clothing values came from the actual surveys. It is possible, but unlikely that clothing estimates were too high, since the mean clo values for the sample of 0.38 and 0.46 respectively for naturally-ventilated and air-conditioned occupants, were well below intrinsic clothing values in other tropical field studies: Townsville, 0.69 and 0.59 in air-conditioned offices; Bangkok, 0.50 clo in naturally-ventilated offices, 0.56 in air-conditioned offices). Met values estimated at 1.2 were thought to be representative of general student activity while seated, such as note-taking. An overestimation of met is also considered unlikely given the general state of activity engaged in by high school students.

In previous office studies, the addition of the insulation value provided by office chairs reduced or eliminated the discrepancies between PMV and thermal sensations.[4] Chairs used in schools are generally not of the cushioned type and I estimated the chair insulation value for a chair typically used in school classrooms (**Error! Reference source not found.**) at 0.10 clo based on a review of the literature.[5] Since students are typically seated for such a brief time, as opposed to office workers, the additional 0.10 clo might have been unnecessary and contributed to the overestimation by PMV.

Assumptions inherent to the PMV model are that the PMV/PPD relationship represents only *overall* thermal response. Because the model was developed in the laboratory, local asymmetries that might have caused local discomfort, were controlled, minimized or eliminated. However, in Standard 55's 80% acceptability criterion, the 20% dissatisfied includes 10% due to general, overall discomfort and 10% due to local discomfort. So, when people are asked to vote on the thermal sensation scale in the field, the thermal sensation they are experiencing is a combination of all conditions they are exposed to: general and local effects, and their votes are not likely to distinguish between the two. Therefore, my interpretation is that observed thermal sensation votes combine both general and local discomfort, whereas PMV predictions, using ambient measurements as inputs, will only predict general thermal response. If we were able to remove local asymmetries from the thermal sensation data, PMV might have come closer to thermal sensation.

Estimating Neutralities. The PMV model estimated neutrality approximately 1°C cooler than the observed neutrality in naturally-ventilated neutrality classrooms and more than 2°C warmer than the air-conditioned neutrality. Auliciems' adaptive model, based on indoor temperatures and mean monthly outdoor temperatures, predicted observed neutralities to within 0.2°C in naturally-ventilated classrooms and approximately 1.5°C warmer than air-conditioned neutralities.

Hawaii's naturally-ventilated neutrality, 26.8°C ET*, was consistent with other tropical field studies in naturally-ventilated buildings such as, 28.5°C in Bangkok by Busch,[6] 26.1°C and 26.7°C in Singapore by Ellis,[7] and 28.5°C also in Singapore by de Dear et al.[8] Although the air-conditioned neutrality of 22.6°C ET* was approximately 2.0°C cooler than other tropical field studies, it was consistent with field studies done in temperature climates (**Error! Reference source not found.**).

The predictions of both the PMV and adaptive models to the observed Hawaii neutralities were similar to the approximation of the models to other field studies, shown in **Error! Reference source not found.**. The adaptive model predicted neutralities more closely than the PMV model. This distinction was greatest in naturally-ventilated buildings where PMV neutralities were 3°C cooler than the observed in warm regimes. Since the model is based upon research carried out in controlled climate chambers, for the purpose of recommending guidelines for mechanically-controlled environments, its application to naturally-ventilated environments that are inherently dynamic, should not be expected to show close agreement. These findings are consistent with the adaptive theory which says that indoor optimum comfort will track the prevailing outdoor climate.

6.4 Do perceptions of other non-thermal conditions have an influence on class work?

This study took a brief look at a few non-thermal factors that might have influence on student perception of class work. The intent was to quantify a range of factors, such as air quality, acoustical, and thermal conditions between building types. Air quality in terms of measured carbon dioxide levels, distinguished the two building types clearly. Naturally-ventilated classrooms without exception maintained levels of CO_2 similar to outside air. Levels in air-conditioned classrooms varied depending on the type of air-conditioning systems used. The highest levels, those above the *Standard 62* guideline of 1000 ppm, occurred in classrooms that used packaged window units and central systems. The lowest levels found were in 2 classrooms that had packaged units sized for cooling a library, rather than a classroom.

No clear distinctions could be made about ventilation between in naturally-ventilated and air-conditioned classrooms using particle measurements because of the incident volcanic smog during various days during the cool season survey period. Measurements did record higher particle counts in carpeted air-conditioned classrooms than in uncarpeted air-conditioned classrooms.

Perceptions about work interference from air quality, acoustical, and thermal conditions were virtually identical between building types and not problematic. Distracting outdoor noises was problematic for class work, regardless of building type. In naturally-ventilated classrooms, outdoor noise was easily discernible as noise from traffic or school activity. However, in air-conditioned classrooms, outdoor noise came from the air-conditioning system.

6.5 Can the naturally-ventilated and air-conditioned data from Hawaii classrooms inform future revisions of the comfort standards?

Schools in the tropics have several key "opportunities" that might contribute information to change the comfort standard. Schools might take advantage of the *transient effects* of comfort (sensations experienced when moving from one thermal environment into another). Throughout this study, references are made to the assumptions of acceptability and neutrality when using the central three categories of the thermal sensation scale. Students move in and out of classes during the course of the typical school day, sometimes eight to ten times a day. Their movement from the hot outdoor environment into cool classrooms, may enhance cool feelings. Consequently, students probably responded with cool thermal sensations, as seen in the Hawaii air-conditioned data where thermal sensations occurred toward the cold side of the thermal sensation scale. Combined with a significant number of occupants preferring warmer temperatures, the opportunity lies in the fact that air-conditioned classrooms need not aim to cool to the degree that was practiced in Hawaii classrooms.

A second opportunity relates to clothing. Compared to offices, schools have relaxed fashion norms where students are often free to wear what they please. Measured clo values were in some cases more than 1.0 clo lower than other tropical field studies. Even in schools which had dress codes (e.g. collared shirts, covered shoes), observations showed students dressing sensibly for the tropical climate. Students brought extra clothing with them for use their air-conditioned classes. “Slightly cool” thermal sensations and preferences for warmer conditions by air-conditioned students indicate in part that *clothing level adjustments* were not enough to offset heat loss. Even though students wore a jacket or sweatshirt over their T-shirts, their legs were exposed because they wore shorts, contributing to local discomfort. Cool sensations would be enhanced, particularly if they arrived from outdoors, where they were likely perspiring. The adaptive opportunity means that students will adjust their clothing levels accordingly, and rooms need not be overcooled.

The third opportunity is specific to the design of naturally-ventilated environments. The “jurisdiction” or universal applicability of the *Standard 55* to all building types is a questionable premise because of: 1) the distinct character of the physical conditions between naturally-ventilated and air-conditioned classroom environments and, 2) the differences in occupant response and attitudes to those conditions. The basic architectural nature of the two building types is different in terms of controls, orientation, siting, and building envelope. A building designed with passive features, uses the building envelope and form of the building to modify climate, such as external shades, operable windows, narrow building plan, and orientation for maximum cross-ventilation. Mechanically-controlled buildings modify the climate through mechanical means, where the form of the building is essentially irrelevant. Naturally-ventilated buildings have dynamic conditions, while air-conditioned buildings maintain static environments. This suggests the need for separate standards.

A separate standard for naturally ventilated thermal environments would be one that recognizes that maintaining a single, optimum temperature is impossible and should not be the basis of the standard. Both the indirect, traditional method of acceptability and the direct measure of acceptability established operative temperature ranges that are wider than those in *Standard 55* for summer conditions. Naturally-ventilated classroom occupants found temperatures of 22.0 - 29.5°C acceptable, a range much wider than the 23 - 26°C of the *Standard 55* comfort zone. In the absence of data from actual subjective responses, Auliciems' adaptive model could be used since it closely predicts indoor optimum temperatures.

Another approach might include series of "performance credits" for architectural responses in load reducing strategies and adaptive opportunities, (e.g. operable windows, relaxed clothing standards) to promote the standard as one that not only specifies comfort, but energy-conserving practices as well. Air movement limits for draft risk be relaxed or removed, since people may be more tolerant of variable air movement in a naturally-ventilated environment. The standard however, should not be used as method for determining whether air-conditioning should be installed, for that would inherently predispose that naturally-ventilated designs are inferior, particularly when satisfaction to thermal criteria are not met. However, data from naturally-ventilated subjects can and should be used as a tool to inform the design of mechanically designed environments. As shown in Hawaii classrooms, occupants found higher temperature and humidity combinations satisfactory by direct acceptability and preference measures. Whether those combinations could be used as expectation-benchmarks about thermal comfort in air-conditioned buildings remains to be studied.

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CHAPTER 7

CONCLUSIONS and FUTURE WORK

7.1. Conclusions

The most significant conclusion of this study is that people in naturally-ventilated schools are comfortable in conditions that are *outside* of the comfort zone specifications of *Standard 55*. The fact that occupants were satisfied with conditions beyond the limits of the *Standard 55* is not a trivial point because of the amount of energy and resources spent to achieve comfort zone conditions in our buildings. By extension this offers schools an extraordinary opportunity to save long-term energy costs should they be well-designed, naturally-ventilated environments. This chapter discusses the key conclusions drawn from this study and offers suggestions for further work.

1. More than 75% of the indoor climate conditions in Hawaii classrooms did not meet the requirements of the *Standard 55* summer comfort zone. The distribution of ET*, Top, and SET* frequencies represents the distinct nature of the interior environment in naturally-ventilated and air-conditioned classrooms.
2. By direct measures of acceptability, naturally-ventilated and air conditioned occupants, found conditions acceptable, thus meeting and exceeding the 80% acceptability criterion of *Standard 55*. Results from indirect measures using the central 3 categories of the thermal sensation scale, did not meet the acceptability criterion. A significant number of people experiencing sensations of ±2, 3 still found these conditions to be acceptable. Direct measures of acceptability for naturally-ventilated classrooms covered a broad range of operative temperatures, similar to other tropical field studies, 22.0°C to 29.5°C.
3. Thermal neutrality occurred at 26.8°C ET* in naturally-ventilated buildings and 22.6°C ET*in air-conditioned buildings, using the thermal sensation responses

regressed with probit analysis. However, preferred temperatures were 2.5°C cooler than the observed naturally-ventilated neutrality and 0.6°C warmer than observed air-conditioned neutrality. The findings are supported by other tropical studies and suggest that neutral thermal sensations do not correlate to people's ideal or preferred thermal state.

4. Auliciems' adaptive model predicted observed neutralities closely, estimating to within 0.3°C of observations for all naturally-ventilated classrooms and 1.5°C for air-conditioned classrooms. Fanger's PMV did less well at predicting neutrality, estimating more than 2°C away from observed neutralities.
5. Clothing adjustments, one of the only adaptive mechanisms available to school occupants, occurred in both seasons, but more importantly during the course of the day. Observations noted students putting on warmer clothing (e.g. sweatshirts) in air-conditioned classes and then taking them off when outside.
6. Clothing insulation (estimated from *Standard 55*) for Hawaii naturally-ventilated occupants were 0.38 clo and 0.46 clo respectively. These clo levels were approximately 1.0 clo lower than office occupants of other field studies, because of relaxed dress norms in schools. Thermal sensations might have been lowered if students, wearing shorts, felt local discomfort on their legs. Chairs were estimated to add 0.10 to the clothing insulation of classroom occupants. The addition of the chair insulation may have contributed to the overestimation of PMV across both building types. Since students do not sit for as long a period as office workers, the additional chair insulation may have been unnecessary.
7. Discomfort from draft or excessive air movement was not a problem in classrooms. In fact, the problem in naturally-ventilated classrooms was *not enough* air movement. The majority of naturally-ventilated classrooms were beyond the prescriptions of the basic *Standard 55* comfort zone. Many of those classrooms were however, located within limits of the *extended* comfort zone, if the air movement is under individual control. However, most of the occupants of those classrooms expressed a desire for *more* air movement (while experiencing air velocities beyond the 0.2 m/s draft limit) and do not have any means of individual control of windows or fans for more air

movement. The Standard's draft limit, based on draft risk for air-conditioned environments, may be inappropriate for naturally-ventilated tropical classrooms.

8. Tolerance for a wide range of thermal conditions found by naturally-ventilated occupants and the distinct and dynamic conditions characterizing naturally-ventilated environments, suggest the need for a standard specifically for naturally-ventilated buildings. The basis of this standard would provide a *range* of acceptable thermal conditions. Naturally-ventilated classroom occupants found a wide range (22.0-29.5°C T_{op}) of conditions thermally acceptable.

7.2. Suggestions for Future Work

Work in this area may be expanded in a number of different ways. Two suggestions for further research emerge from this project.

1. The first involves further research in naturally-ventilated schools located in different climates, to establish larger database of acceptable ranges of temperatures and categories of adaptive opportunities. In this study, comparisons to comfort responses and physical conditions were limited to field studies of office buildings, because of the absence of current field studies in schools. A critical component of such research would be the contribution of information from subjective field assessment using direct measures of acceptability and thermal preference.
2. The second area of research involves closer examination of the effects of transient thermal comfort in schools. The school context offers an ideal context for the investigation of this topic. Subjects might carry thermal comfort cards containing traditional scales of measurement with them and mark the scales during designated time intervals, as they move in and out of classes throughout the day. Comparisons of thermal perceptions between naturally-ventilated and air-conditioned schools might reveal more information about our connection to the outdoor climate.

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Appendix A

Questionnaire

Classroom #: ______________________

Date & Time: ______________________

CLASSROOM THERMAL COMFORT SURVEY

Part 1. Personal Comfort

In this part of the survey we would like to know about your response to the physical conditions in this classroom **right now,** at this moment. In Part 2 we will ask about conditions that you may have experienced in the past. You will have an opportunity to write other comments at the end of this survey.

1. Please mark an (X) on the scale below at the place that best represents how you feel at this moment.

|--------+---------|--------+---------|--------+---------|--------+---------|--------+---------|--------+---------|--------+--------|

-3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5 3

cold cool slightly cool neutral slightly warm warm hot

2. Are the conditions (thermal) in this classroom acceptable to you **right now**?

1 ❑ acceptable
2 ❑ not acceptable

3. **Right now** I would prefer to be:

3 ❑ warmer
2 ❑ no change
1 ❑ cooler

4. Please check the box that best represents how you feel at this moment about the AIR MOVEMENT **right now** in this classroom.

1 ❑ acceptable
2 ❑ not acceptable

5. **Right now** I would prefer:

3 ❑ more air movement
2 ❑ no change
1 ❑ less air movement

6. Does the present rate of air movement (too little or too much) bother you in any way?

1 ❑ yes
2 ❑ no

7. If YES, explain how:

____

____

8. Please check the box that best represents how you feel at this moment about the HUMIDITY **right now** in this classroom.

1 ❑ acceptable
2 ❑ not acceptable

9. **Right now** I would prefer:

3 ❑ more moisture in the air (more humid)
2 ❑ no change
1 ❑ drier air (less humid)

10. Please check the box that best represents how you feel at this moment about the AIR QUALITY **right now** in this classroom.

7 ❑ very stale
6 ❑ moderately stale
5 ❑ slightly stale
4 ❑ neutral
3 ❑ slightly fresh
2 ❑ moderately fresh
1 ❑ very fresh

11. Please check the box that best represents how you feel at this moment about the AIR QUALITY **right now** in this classroom.

1 ❑ acceptable
2 ❑ not acceptable

12. Please check the box that best represents how you feel at this moment about the ACOUSTICS **right now** in this classroom.

1 ❑ acceptable
2 ❑ not acceptable

13. (General Comfort) How comfortable is your classroom right now?

6 ❑ very comfortable
5 ❑ moderately comfortable
4 ❑ slightly comfortable
3 ❑ slightly uncomfortable
2 ❑ moderately uncomfortable
1 ❑ very uncomfortable

Part 2. Environmental Conditions

This section asks questions about the environmental conditions in this classroom **since the beginning of the school semester.**

14. How often have you felt **too hot** in this classroom?

1 ❑ Never 2 ❑ Rarely 3 ❑ Sometimes 4 ❑ Usually 5 ❑ Always

15. If you have felt **too hot**, how much does it interfere with your class work?

1 ❑ Not at all 2 ❑ Somewhat 3 ❑ Moderately 4 ❑ Very much

16. How often have you felt **too cold** in this classroom?

1 ❑ Never 2 ❑ Rarely 3 ❑ Sometimes 4 ❑ Usually 5 ❑ Always

17. If you have felt **too cold**, how much does it interfere with your class work?

1 ❑ Not at all 2 ❑ Somewhat 3 ❑ Moderately 4 ❑ Very much

18. How often have you felt there is **too little air movement** in this classroom?

1 ❑ Never 2 ❑ Rarely 3 ❑ Sometimes 4 ❑ Usually 5 ❑ Always

19. If you have experienced **too little air movement**, how much does it interfere with your work?

1 ❑ Not at all 2 ❑ Somewhat 3 ❑ Moderately 4 ❑ Very much

20. How often have you felt there is **too much air movement** in this classroom?

1❑ Never 2❑ Rarely 3❑ Sometimes 4❑ Usually 5❑ Always

21. If you have experienced **too much air movement**, how much does it interfere with your work?

1❑ Not at all 2❑ Somewhat 3❑ Moderately 4❑ Very much

22. How often have you felt there are **distracting outside noises**?

1❑ Never 2❑ Rarely 3❑ Sometimes 4❑ Usually 5❑ Always

23. If you have experienced **distracting outside noises**, how much does it interfere with your class work?

1❑ Not at all 2❑ Somewhat 3❑ Moderately 4❑ Very much

Part 3. Indoor Air Quality

For each of the following types of potential problems with air quality conditions, please rate how much of a problem it is for you. Mark NA if the problem is **not applicable** to your classroom. (check one box per row)

	NA	NOT AT ALL	A LITTLE	MODERATE	BIG PROBLEM
24. Unpleasant odors	1❑	2❑	3❑	4❑	5❑
25. 'Stuffy' air	1❑	2❑	3❑	4❑	5❑
26. Dust	1❑	2❑	3❑	4❑	5❑

Part 4. Acoustical Conditions

Sometimes a variety of sounds are generated in the school environment. How often do *you* experience problems (e.g. distraction, annoyance) with the following sounds? (check one box per row)

	NA	NOT AT ALL	A LITTLE	MODERATE	BIG PROBLEM
27. Buzzing noise from lights	1❑	2❑	3❑	4❑	5❑
28. Noise from air-conditioning	1❑	2❑	3❑	4❑	5❑
29. Traffic noise from outdoors	1❑	2❑	3❑	4❑	5❑
30. School activities outside	1❑	2❑	3❑	4❑	5❑

Part 5. Clothing Responses

Check the box below that corresponds to each item of clothing which you are wearing RIGHT NOW. S**kip** items which you are not wearing.

CLOTHING

- .15 ❑ t-shirt
- .15 ❑ aloha shirt
- .17 ❑ knit sport shirt
- .13 ❑ tank top

- .25 ❑ long sleeve shirt
- .34 ❑ flannel long sleeve shirt
- .23 ❑ sleeveless dress
- .29 ❑ regular dress
- .14 ❑ skirt
- .23 ❑ jumper

- .15 ❑ pants
- .24 ❑ jeans
- .06 ❑ short shorts or lycra shorts or gym shorts
- .08 ❑ denim or knee-length shorts

- .10 ❑ vest
- .34 ❑ sweatshirt
- .25 ❑ sweater
- .36 ❑ jacket
- .02 ❑ cap

FOOTWWEAR

- .02 ❑ socks
- .02 ❑ stockings (pantyhose)

- .02 ❑ sandals
- .00 ❑ slippers/zoris
- .02 ❑ athletic shoes
- .10 ❑ boots

____

Part 6. General Background Information

31. Was the classroom you were in just before this class an air-conditioned space?

1 ❑ no 2 ❑ yes 3 ❑ not in class 4 ❑ don't know

32. Do you have air-conditioning at home?

1 ❑ not available 2 ❑ some rooms 3 ❑ all rooms

33. Do you use the air-conditioning at home during this time of year?

1 ❑ not available 2 ❑ never 3 ❑ occasionally 4 ❑ always

34. Do you ride to and from school in a vehicle with the air-conditioning in use during this time of year?

1 ❑ not available 2 ❑ never 3 ❑ occasionally 4 ❑ always

Part 7. Demographics

Please tell us a little about yourself by answering the following questions.

35. Gender: 1 ❑ Male 2 ❑ Female

36. Age: _________ years ________ months

37. Approximate height: _________ feet ________ inches

38. Approximate weight: ________ pounds

39. How long have you lived in Hawaii: _________ years ________ months

40. What would make you more comfortable in this classroom?

____

____

____

41. Is there anything else you would like to say about the environmental conditions in this classroom that has not been covered in this survey?

____

____

Thank you for your time in responding to this survey.

Appendix B

Building Indoor Climate Summaries

School A: Naturally-Ventilated

Hot Season: October 20, 1995

Cool Season: January 29, 1996

		Hot	Cool
Season		**Hot**	**Cool**
# of classrooms		1	1
# of visits		2	3
# of subjects		34	43
Air Temperature (deg C)			
	mean	27.0	22.6
	std dev	0.1	1.3
	min	27.0	21.1
	max	27.1	24.1
Mean Radiant Temperature (deg C)			
	mean	26.8	24.8
	std dev	0.1	0.2
	min	26.7	24.6
	max	26.8	25.0
Relative Humidity (%)			
	mean	57.4	51.3
	std dev	4.0	3.1
	min	53.9	47.5
	max	61.9	54.7
Air Velocity (m/s)			
	mean	0.28	0.22
	std dev	0.00	0.01
	min	0.27	0.21
	max	0.28	0.23
Carbon Dioxide (ppm)			
	mean	489	398
	std dev	22	31
	min	469	360
	max	514	432
Particles (um/min)			
	mean total	16,100	41,000
	mean .3um	7,100	19,400
	mean .5um	6,200	15,300
	mean 1.0um	2,800	6,300
	mean 5.0um	14	87

School B: Naturally-Ventilated

Cool Season: January 26, 1996

Season		**COOL**
# of classrooms		2
# of visits		3
# of subjects		20
Air Temperature (deg C)		
	mean	22.8
	std dev	0.4
	min	22.4
	max	23.3
Mean Radiant Temperature (deg C)		
	mean	24.5
	std dev	0.4
	min	24.0
	max	24.8
Relative Humidity (%)		
	mean	78.7
	std dev	2.0
	min	77.0
	max	81.5
Air Velocity (m/s)		
	mean	0.18
	std dev	0.04
	min	0.12
	max	0.21
Carbon Dioxide (ppm)		
	mean	480
	std dev	11
	min	463
	max	487
Particles (um/min)		
	mean total	106,800
	mean .3um	57,400
	mean .5um	41,000
	mean 1.0um	8,400
	mean 5.0um	83

School C: Naturally-Ventilated

Hot Season: October 20, 1995

 

Season		HOT
# of classrooms		1
# of visits		1
# of subjects		20
Air Temperature (deg C)		
	mean	27.2
	std dev	0.0
	min	27.2
	max	27.2
Mean Radiant Temperature (deg C)		
	mean	26.5
	std dev	0.0
	min	26.5
	max	26.5
Relative Humidity (%)		
	mean	52.5
	std dev	0.0
	min	52.5
	max	52.5
Air Velocity (m/s)		
	mean	0.40
	std dev	0.00
	min	0.40
	max	0.40
Carbon Dioxide (ppm)		
	mean	452
	std dev	0
	min	452
	max	452
Particles (um/min)		
	mean total	21,300
	mean .3um	8,800
	mean .5um	8,000
	mean 1.0um	4,400
	mean 5.0um	63

School D: Naturally-Ventilated

Hot Season: September 21 - 28, 1995

Cool Season: January 18 - 23, 1996

		HOT	COOL
Season		**HOT**	**COOL**
# of classrooms		8	8
# of visits		28	26
# of subjects		540	495
Air Temperature (deg C)			
	mean	28.5	26.4
	std dev	0.9	0.8
	min	26.6	24.9
	max	29.9	27.6
Mean Radiant Temperature (deg C)			
	mean	28.2	26.3
	std dev	0.8	0.8
	min	26.4	24.6
	max	29.4	27.5
Relative Humidity (%)			
	mean	62.3	69.0
	std dev	5.3	5.1
	min	52.2	60.9
	max	75.5	79.9
Air Velocity (m/s)			
	mean	0.36	0.34
	std dev	0.08	0.14
	min	0.21	0.10
	max	0.54	0.66
Carbon Dioxide (ppm)			
	mean	485	454
	std dev	14	54
	min	453	394
	max	516	657
Particles (um/min)			
	mean total	16,900	156,300
	mean .3um	7,300	87,700
	mean .5um	6,500	58,900
	mean 1.0um	3,200	9,500
	mean 5.0um	8	149

School E_1: Naturally-Ventilated

Hot Season: October 12 - 18, 1995

Cool Season: January 8 - 12, 1996

		HOT	COOL
Season		**HOT**	**COOL**
# of classrooms		10	8
# of visits		17	22
# of subjects		458	523
Air Temperature (deg C)			
	mean	29.3	26.4
	std dev	0.7	0.9
	min	28.5	24.6
	max	30.5	27.7
Mean Radiant Temperature (deg C)			
	mean	29.1	26.2
	std dev	0.7	0.9
	min	28.2	24.4
	max	30.3	27.5
Relative Humidity (%)			
	mean	57.3	63.2
	std dev	2.5	5.3
	min	51.3	51.0
	max	61.2	73.7
Air Velocity (m/s)			
	mean	0.37	0.34
	std dev	0.13	0.14
	min	0.20	0.11
	max	0.72	0.62
Carbon Dioxide (ppm)			
	mean	513	434
	std dev	26	57
	min	472	338
	max	562	638
Particles (um/min)			
	mean total	26,700	32,700
	mean .3um	11,900	25,800
	mean .5um	10,300	11,800
	mean 1.0um	4,500	128
	mean 5.0um	16	02

School E_2: Air-Conditioned

Hot Season: October 19, 1995

Cool Season: January 9, 1996

		HOT	COOL
Season		**HOT**	**COOL**
# of classrooms		2	2
# of visits		2	2
# of subjects		95	87
Air Temperature (deg C)			
	mean	24.3	23.4
	std dev	0.2	0.1
	min	24.0	23.2
	max	24.5	23.4
Mean Radiant Temperature (deg C)			
	mean	23.8	23.1
	std dev	0.5	0.1
	min	23.1	22.8
	max	24.3	23.2
Relative Humidity (%)			
	mean	54.4	65.1
	std dev	1.9	1.4
	min	52.3	63.5
	max	57.2	67.2
Air Velocity (m/s)			
	mean	0.25	0.19
	std dev	0.02	0.01
	min	0.21	0.18
	max	0.27	0.21
Carbon Dioxide (ppm)			
	mean	693	632
	std dev	52	12
	min	651	612
	max	773	642
Particles (um/min)			
	mean total	20,600	51,100
	mean .3um	9,300	29,900
	mean .5um	8,000	17,600
	mean 1.0um	3,300	3,600
	mean 5.0um	32	63

School F: **Air-Conditioned**

Hot Season: October 3 - 11, 1995

Cool Season: January 24 - 25, 30 - 31,
February 1, 1996

		HOT	COOL
Season		**HOT**	**COOL**
# of classrooms		7	6
# of visits		36	36
# of subjects		608	573
Air Temperature (deg C)			
	mean	23.4	22.5
	std dev	1.3	0.6
	min	19.8	21.2
	max	27.0	23.5
Mean Radiant Temperature (deg C)			
	mean	23.0	22.3
	std dev	1.3	0.7
	min	19.4	20.9
	max	26.9	23.5
Relative Humidity (%)			
	mean	57.4	63.8
	std dev	7.6	7.0
	min	43.1	51.8
	max	74.9	72.6
Air Velocity (m/s)			
	mean	0.14	0.14
	std dev	0.06	0.05
	min	0.07	0.07
	max	0.33	0.24
Carbon Dioxide (ppm)			
	mean	1606	1848
	std dev	437	800
	min	803	631
	max	2436	3117
Particles (um/min)			
	mean total	30,300	54,900
	mean .3um	13,600	26,300
	mean .5um	11,800	20,900
	mean 1.0um	4,900	7,600
	mean 5.0um	58	165